AMAP Arctic Climate Change Update 2024: **Key Trends and Impacts**

AMAP

Arctic Monitoring and Assessment Programme (AMAP)

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Tromsø, 2024

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Dedication

In memory of two great scientists and friends

This report is dedicated to two outstanding scientists who both played significant roles in major AMAP climate change assessments: Dr. Robert Correll as the leader of the first *Arctic Climate Impact Assessment* and Dr. Terry Prowse as a leader in the first *Arctic Freshwater Synthesis.*

Dr. Bob Corell was a towering figure in Arctic science and global climate leadership, whose legacy has profoundly shaped our understanding of a changing planet. A true pioneer, Bob spent more than half a century working in and for the Arctic, translating complex science into action and making the urgency of Arctic change understood by decision-makers around the world. As the leader of the first *Arctic Climate Impact Assessment*, published in 2005, he set a gold standard for collaboration, integrity, and scientific excellence. His work laid the foundation for generations of research and policy, bridging the often-fragmented worlds of science, governance, and society.

But Bob was far more than a brilliant scientist—he was a deeply kind and generous soul. His warmth, curiosity, and joy in conversation made him unforgettable. Whether sitting around a conference table or swapping stories with a glass of rum, he made everyone feel valued. He had an uncanny ability to bring people together—across disciplines, cultures, and generations. He believed in the power of collaboration and was a true champion of inclusivity, elevating Indigenous voices and early-career researchers long before it became a common priority. His support helped launch countless careers, and his encouragement has echoed across institutions and generations.

Above all, Bob was a mentor, a connector, and a friend. His laughter was infectious, his stories legendary, and his wisdom both deep and generously shared. He brought light and levity to the most complex challenges, always grounded in purpose and hope. We honor his immense contributions to science and society, but even more, we cherish the way he made us feel—seen, inspired, and motivated to do better. This update to the *Arctic Climate Impact Assessment* stands not only on the foundations he built but also in the spirit he embodied: collaborative, compassionate, and committed to making the world better for all who call the Arctic home.

"We do this work not just for the science—but for the people, for the future. That's what drives us."

— Dr. Robert W. Corell

Dr. Terry Prowse worked as a Research Scientist for Environment and Climate Change Canada (ECCC) for nearly 35 years. His research centered on cold regions hydrology, with a focus on river ice, lake ice and snow, as well as impacts of climate change on water resources. He made significant contributions to the AMAP program and the fields of circumpolar cold regions climate and hydrological science. His legacy is far-reaching, shaping research, policy, and education in Canada and globally.

Dr. Prowse was a pioneer in the study of the terrestrial cryosphere—encompassing snow, permafrost, and river and lake ice—advancing our understanding of the hydro-ecological and societal impacts of climate and cryospheric change. His leadership extended across scientific societies, advisory roles, editorial boards, and mentorship, where he guided numerous graduate students and early-career scientists. He championed collaboration and transdisciplinary approaches to tackling national and global water and climate challenges.

His contributions to major scientific assessments, led by organizations such as AMAP, WMO-CliC, IASC, ICARP, UNESCO-IHP, and the IPCC, earned him widespread recognition. Among his many accolades were governmental awards, an Honorary Doctorate from the University of Waterloo for his contributions to northern hydrology, and a shared Nobel Peace Prize as a lead author of the Polar Regions chapter in the 2007 IPCC assessment.

Dr. Prowse mentored multiple scientists in ECCC, supervised Master's and PhD students over the years and was a strong proponent of students gaining field experience. With over 28,000 citations and counting, Dr. Prowse's impact will continue to inspire future generations of hydrological, ecological and climate scientists dedicated to understanding and protecting our planet's cryospheric and water resources and associated freshwater ecosystems. AMAP remains deeply grateful for his enduring friendship, camaraderie, and dedication to advancing its mission.

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Special acknowledgment and gratitude go to Keith Alverson, Executive Director of the World Climate Research Programme (WCRP) Climate and Cryosphere Project (CliC), for leading the international peer review of this report, together with Narelle van der Wel, WCRP Secretariat Liaison to CliC.

Contents

Preface

This report presents the findings of the *Arctic Climate Change Update 2024: Key Trends and Impacts* prepared by the Arctic Monitoring and Assessment Programme (AMAP). This report is a follow-up to the *Arctic Climate Change Update 2021: Key Trends and Impacts* and is the second in a series of AMAP climate update reports that highlight key climate issues of concern and provide brief and timely updates on topics previously covered in depth in past AMAP assessments. The current report updates information on topics covered in the 2021 climate update report and also updates topics covered in previous AMAP assessments of Arctic Ocean acidification and climate-related changes in terrestrial hydrology. This report, like others in the series, is intended as a means for AMAP to provide current information on key climate topics of concern on a regular basis (every two to three years), while working simultaneously on longer, more comprehensive assessments.

Preparation of this report was coordinated by the AMAP Climate Expert Group (CEG). The CEG maintains an overview of climate issues and the coordination of climate-related activities and reports, ensuring that AMAP maintains momentum on climate work and can provide information on climate issues on a regular basis.

This 2024 report was prepared between 2022 and 2024 by an international group of 60 scientists, experts, and knowledgeable members of the Arctic Indigenous communities, as represented within the Arctic Council through the Permanent Participant organizations. Lead authors were selected by an open nomination process coordinated by AMAP in collaboration with several national and international organizations. A team of coordinating lead authors for the seven substantive chapters was responsible for scientific oversight and coordination of all work related to the preparation of this report.

An international peer review process was established by AMAP and coordinated by Keith Alverson, Executive Director of the Climate and Cryosphere Project (CliC) under the World Climate Research Programme (WCRP), assisted by Narelle van der Wel, liaison officer to CliC at WCRP. Peer reviewers were chosen from an extensive international nominations process to independently review the draft chapters of the report. Documentation is available from the AMAP Secretariat on this process and the outcome, including listings of the comments received from the peer reviewers and how they were addressed.

Information contained in this report is fully referenced and for most of the chapters is based mainly on research and monitoring efforts published since 2021. The report includes peer-reviewed material accepted for publication up until February 2024, and in some cases later. Unpublished monitoring information, including both *in situ* and satellite observations with well-established national and international standards and quality assurance / quality control protocols, is also included. All such references have been collected and are available upon request (at cost of reproduction) from the AMAP Secretariat. Care has been taken to ensure that no critical probability statements are based on these materials.

Access to reliable and up-to-date information is essential for the development of evidence-based decision-making regarding rapid and ongoing changes in the Arctic and their global implications. Accordingly, this technical report formed the basis for a product that focuses on the more policy-relevant and action-oriented conclusions and recommendations, namely, the *AMAP Climate Change Update 2024: Key Trends and Impacts Summary for Policy-makers* (Summary for Policy-makers). The Summary for Policy-makers was released in association with the 14th Meeting of the Arctic Council in May 2025. The lead authors have confirmed that the Summary for Policy-makers accurately and fully reflects the 2024 technical report. The present report constitutes the fully referenced scientific basis for all statements made in the Summary for Policy-makers. Both reports (the 2024 technical report and the associated Summary for Policy-makers) are available from the AMAP Secretariat and on the AMAP website (www.amap.no).

AMAP would like to express its appreciation to all experts who have contributed their time, effort, and data to this assessment, with particular gratitude to the chapter lead authors and members of the Climate Expert Group who coordinated the production of this report. Thanks are also due to the many referees and reviewers who contributed to the peer-review process and provided valuable comments that helped to ensure the quality of the report. A list of the main contributors is included at the start of each chapter. The list is not comprehensive. Specifically, it does not include the many national institutes, laboratories and organizations, and their staff that have been involved in the various countries. Apologies, and no lesser thanks are given to any individuals unintentionally omitted from the list.

The support of the Arctic nations, Arctic Indigenous Peoples, and non-Arctic countries implementing research and monitoring in the Arctic is vital to the success of AMAP. The AMAP work is essentially based on ongoing activities within these countries, including on the lands or territories of Indigenous Peoples. The nations, Permanent Participants, and other countries and organizations also provide the necessary support for most of the experts involved in the preparation of the AMAP assessments. In particular, AMAP would like to thank Canada, the Kingdom of Denmark, and the Norwegian Ministry of Foreign Affairs for their financial support to this work, and to sponsors of programs and projects that have delivered data for use in this report. The AMAP Working Group is pleased to present this report to the Arctic Council and the international science community.

John E. Walsh (Climate Expert Group Lead until February 2024); CEG co-leads: Johanna Mård, Rasmus E. Benestad, and (since September 2024) Julie Brigham-Grette

Sarah Kalhok Bourque (AMAP Chair)

Rolf Rødven (AMAP Executive Secretary)

Tromsø, October 2024

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1. Introduction

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Contributing authors: Jason E. Box, James Overland, Mark Parrington, Muyin Wang

1.1 The 2024 update report

This report by the Arctic Monitoring and Assessment Programme (AMAP) is the second in an anticipated series of climate update reports. It presents an update of findings in relation to various issues selected from the most recent climate update report, *AMAP Arctic Climate Change Update 2021: Key Trends and Impacts* (AMAP, 2021), as well partial updates of several previous climate-related assessments: *Snow, Water, Ice and Permafrost in the Arctic* (*SWIPA*) *2017* (AMAP, 2017a), *AMAP Assessment 2018: Arctic Ocean Acidification* (AMAP, 2018a), as well as *The Arctic Freshwater System in a Changing Climate* (CliC/AMAP/IASC, 2016), which synthesized the then-current understanding of Arctic freshwater sources, fluxes, storage and effects.

The present report updates information for various time periods depending on the date of the most recent coverage of the topic concerned. Thus, for Chapter 2, an expanded suite of Arctic climate indicators has been updated from 2021. Chapter 3 on Arctic extremes, Chapter 4 on wildfires, and Chapter 8 on Arctic/midlatitude weather linkages also update material from the 2021 report. Chapter 5 on the cryosphere updates material mainly from 2017; Chapter 6 on Arctic freshwater hydrology from 2016; and Chapter 7 on Arctic Ocean acidification from 2018.

1.2 Previous AMAP climate assessments

Mandated by the Arctic Council to monitor and assess the state of the Arctic environment and climate, AMAP produced its first assessment of Arctic climate change and its impacts as part of a comprehensive State of the Arctic Environment Report (AMAP, 1997, 1998). The findings of the 1998 assessment led the Arctic Council to initiate an independent and comprehensive assessment of Arctic climate change and its impacts – the Arctic Climate Impact Assessment (ACIA). This was undertaken by AMAP in cooperation with the Arctic Council Working Group on the Conservation of Arctic Flora and Fauna (CAFF) and the International Arctic Science Committee (IASC). The resulting *Arctic Climate Impact Assessment* (ACIA, 2005) and its derivative *Impacts of a Warming Arctic* (ACIA, 2004) documented Arctic-wide warming and ongoing changes in Arctic snow, water and ice conditions that were impacting Arctic ecosystems and human living conditions. It also highlighted the potential global impacts of Arctic climate change.

Focusing on climate-related changes in the Arctic cryosphere, AMAP published its third Arctic climate assessment in 2011: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere* (AMAP, 2011). This was followed by the fourth Arctic climate assessment: a follow-up *Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017* report (AMAP, 2017a), as noted above. These changes in the cryosphere were found to cause fundamental changes in the Arctic ecosystems, which will have important implications for Arctic livelihoods and living conditions. The two SWIPA assessments highlighted regional and global-scale climatic interactions caused by changes in the Arctic cryosphere and the cascading climate change impacts, while recognizing that climate change is not the only driver of change in the Arctic.

As a parallel activity to SWIPA 2017, three regional reports were prepared under the *Adaptation Actions for a Changing Arctic* (AACA) project to provide information on adaptation actions that could be taken based on assessments of drivers of change and resultant impacts. The three regions were the Barents area (AMAP, 2017b), the Baffin Bay / Davis Strait region (AMAP, 2018b), and the Bering-Chukchi-Beaufort region (AMAP, 2017c).

1.3 Purpose of climate update reports

Major climate assessments require substantial efforts and, consequently, a lengthy timeframe for their completion, resulting in production intervals of five years or more between assessments. The last overall climate assessment was the SWIPA 2017 assessment. Given the rapid changes occurring in the Arctic and globally, AMAP decided that a mechanism should be created to prepare shorter, more timely climate update reports to cover key issues of concern identified by AMAP climate experts, preferably on a biennial basis, which would serve to provide more frequent information on key aspects of climate change and their impacts in the Arctic.

The first climate update report, *AMAP Arctic Climate Change Update 2021: Key Trends and Impacts* (AMAP, 2021), covered 'climate issues of concern' that had been identified in the SWIPA 2017 assessment. Updates of issues identified in SWIPA 2017 covered in the 2021 climate update report included Arctic extremes, Arctic/midlatitude weather connections, time series of key Arctic climate indicators, and the evaluations of outcomes of the CMIP6 (Coupled Model Intercomparison Project Phase 6) models. The 2021 report also included an initial basis for a new, major assessment of the impacts of climate change on Arctic ecosystems, focusing on marine and terrestrial ecosystems, including connections to the coast, and associated feedbacks of these changes to the climate. Another chapter provided an initial consideration of societal implications of climate change, as a first step to a broader consideration of this issue in the assessment period 2023–2027.

As noted above, this second climate update report provides updates for the 2021 chapters covering the time series of key Arctic climate indicators, Arctic extremes, Arctic/midlatitude weather connections, and wildfires, as well as longer-term updates on the cryosphere, Arctic terrestrial hydrology, and Arctic Ocean acidification. This report has been prepared in parallel with the initial phases of two major climate-related assessments currently under way: the AMAP assessment of Societal Implications of Climate Change in the Arctic (SICCA) and the AMAP/CAFF assessment of Climate Change Impacts on Arctic Ecosystems and Associated Climate Feedbacks.

1.4 Geographical delineation

The geographical delineation of the Arctic as used in the SWIPA assessment and in this report is based on that adopted by AMAP (Figure 1.1). The 'AMAP area' essentially includes the terrestrial and marine areas north of the Arctic Circle (66°32'N), and north of 62°N in Asia and 60°N in North America, modified to include the marine areas north of the Aleutian Islands chain, Hudson Bay, and parts of the North Atlantic Ocean including the Labrador Sea. However, for certain chapters there has been some deviation from this delineation depending on the topic covered.

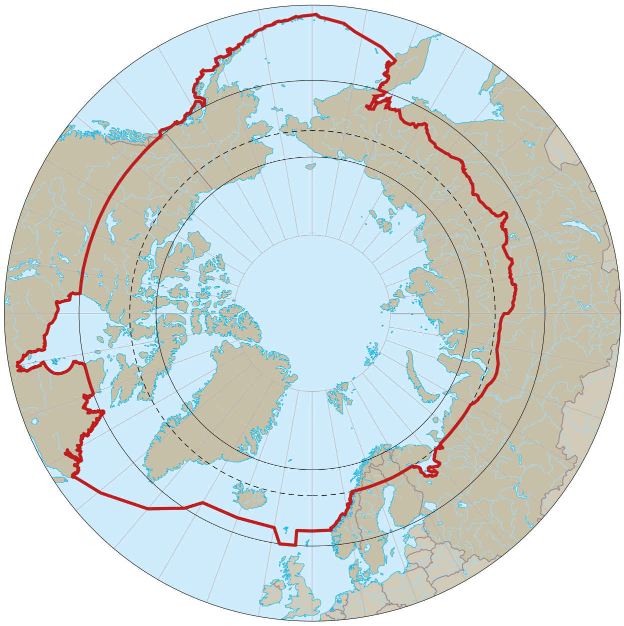

Figure 1.1 The Arctic, as defined by AMAP and as used in this report.

1.5 The process background

Preparation of the 2024 report involved over 56 scientists and experts from Arctic and non-Arctic countries. All were nominated by national and relevant international bodies and selected on the basis of scientific qualifications by appointed convening lead authors. These experts were charged with compiling and evaluating information from Arctic monitoring networks, published literature, and recent national and international research activities.

Each chapter was drafted by individuals with relevant expertise from different scientific disciplines and geographical areas. A lead authors group, comprising the convening lead authors for each chapter, was responsible for the organization and overall accuracy of the assessment.

This assessment report is fully referenced and peer reviewed. The assessment is based on the peer-reviewed scientific literature as well as on new results obtained using well-documented models and observational methods. The peer-reviewed observations, methods, and studies used in the assessment in many cases include contributions from Indigenous, traditional and local knowledge; it is recognized that this approach does not necessarily capture all relevant knowledge held by Arctic Indigenous Peoples, and other Arctic inhabitants.

Chapter authors have followed recommendations to promote the use of common terminology as far as possible. This included use of terminology associated with probability statements where discussion of future events and conditions needs to take into account the likelihood that these conditions or events will occur. To ensure consistency of the summarized material, the procedures used by ACIA and the two SWIPA reports (as refined from those of the Intergovernmental Panel on Climate Change) were used throughout this report (see Figure 1.2). Statements regarding the likelihood that particular events or conditions will occur reflect expert evaluation of peer-reviewed results, typically from multiple lines of evidence.

The statements and assessments presented in this report were subject to a comprehensive review process, which involved national experts that contributed data and information to the assessment. These national experts verified that the interpretation of their data was correct and acceptable to the primary sources. A rule-based, independent international peer-review process was established by AMAP and coordinated by the World Climate Research Program Climate and Cryosphere Project (CliC) and its Executive Director Keith Alverson to secure and document the integrity of the process. Documentation of the results of the peer-review process applied to this report is available on the AMAP website (www.amap.no).

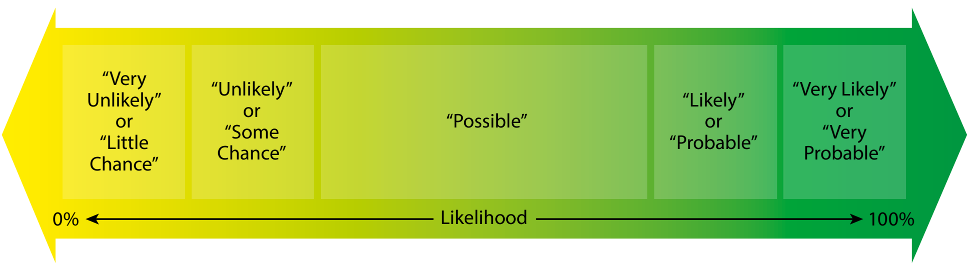

Figure 1.2 Five-tier lexicon describing the likelihood of expected change.

1.6 What will readers find within each chapter?

The report contains eight chapters including this introduction. A brief description of each chapter follows.

Chapter 2 presents an overview of Arctic climate change insights from an expanded collection of observational climate indicators, building on previous work (Box et al., 2019, 2021; AMAP, 2021), with the six added years marked by new record-setting years for air and permafrost temperatures, wildfires, regional sea-ice minima, and land-ice loss. It also includes information about future Arctic climate projections based on CMIP6 models.

Chapter 3 considers underlying conditions that are resulting in the occurrence of extreme events beyond previous records, i.e., events beyond anything that has happened historically, and documents several such recent extreme events in Arctic and subarctic areas. Many recent Arctic physical and biological extreme events are well beyond previous records. They vary by type, location, and season. In summer 2023 alone, there were six major events: record-shattering air temperatures, unprecedented wildfires, earlier than ever snow melt, exceptional Greenland ice melt, extreme sea temperatures, and low Alaskan salmon runs. Sixty-eight extreme weather events were recorded for 2022. These new behaviors represent an emergence phenomenon. Emergence occurs when multiple processes interact to produce new properties. The physics and biology of the Arctic can now be considered to be in a different state than fifteen years ago. These new states cannot be easily assigned forecast probabilities because they often have no historical analogues. Such diverse types of extremes form a consilience, the principle that evidence from independent, unrelated sources can converge as strong conclusions concerning Arctic change. Communities need to prepare for adaptation to such intermittent events.

Chapter 4 gives an overview of wildfires at Arctic and high northern latitudes. The chapter reviews recent research into the human- and climate-related drivers contributing to the observed year-to-year tendencies and variability, and how wildfires are impacting on the Arctic through landscape changes and the air quality / climate effects of wildfire smoke. Wildfires are a common feature of the Arctic landscape during summer months but are expected to increase in frequency and intensity as a result of increased fuel availability through poleward expansion of vegetation and permafrost thaw, warmer and drier conditions, and increased fire danger under climate change. Knowledge on ignition sources, which is one of the largest uncertainties in quantifying Arctic wildfires, continues to improve and will be improved further by incorporating more local knowledge, especially from Indigenous communities around the Arctic. The chapter also reviews the past two decades of satellite observations of Arctic and high latitude wildfires with a focus on large-scale persistent high latitude wildfires in 2021 and 2023.

Chapter 5 provides an update on findings regarding changes in the Arctic cryosphere components since the 2021 climate update report (AMAP, 2021) and, in the case of permafrost, since the SWIPA 2017 assessment (AMAP, 2017a). The chapter synthesizes recent knowledge on changes in the cryosphere, including key findings from the *Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2021), and its *Special Report on the Ocean and Cryosphere in a Changing Climate* (IPCC, 2019). The Arctic is warming much faster than the global mean and the resulting changes in the cryosphere, such as thawing permafrost, reductions in snow and sea-ice cover, and reductions in land ice, can exert positive feedback effects on local and global climate systems. The various components of the cryosphere are each addressed in this chapter at both pan-Arctic and regional scales. There is a particularly extensive discussion on permafrost, owing to the increased focus on this component, and the lack of update on this component in the 2021 report. Analyses were based on observational data as well as model simulations, including the outputs from CMIP6 models.

Chapter 6 provides a partial update on climate change impacts on the Arctic terrestrial freshwater system as a follow-up to SWIPA 2017 (AMAP, 2017a) and *The Arctic Freshwater System in a Changing Climate* (CliC/AMAP/IASC, 2016), including underlying scientific papers associated with that report. The chapter focuses on climate-water interactions and key processes within the terrestrial hydrological domain, including precipitation and snow cover, impacts of permafrost thaw on hydrology, river discharge, surface water (lakes), river ice, lake ice, and contributions from land-ice reductions, with emphasis on observed changes and key drivers, as well as projected changes. The chapter also provides a summary of impacts on ecosystems and society from changing hydrological processes, to serve as input to the AMAP/CAFF assessment of Climate Change Impacts on Arctic Ecosystems and Associated Climate Feedbacks as well as to the AMAP assessment of Societal Implications of Climate Change in the Arctic (SICCA).

Chapter 7 updates knowledge concerning new scientific understanding of Arctic Ocean acidification since the *AMAP Assessment 2018: Arctic Ocean Acidification* (AMAP, 2018a), as well as observed trends in the Arctic seawater carbonate system and model (CMIP6) projections of future trends. The greatest global decline in pH continues to be projected for the Arctic Ocean. This reflects impacts from multiple stressors such as surface ocean warming, organic carbon from land, loss of sea ice and atmospheric carbon dioxide (CO_2) uptake. How methane fluxes from the permafrost could impact ocean acidification is also addressed. Although projections show clear differences among Arctic sub-regions, model uncertainty is improved and shows an accelerated pace of ocean acidification as well as a deepening of the acidification signal. The chapter examines recent research into ecosystem hotspots and the response of key species to ocean acidification in the Arctic. The effects of ocean acidification are far reaching, with implications for changes in ecosystem function, biodiversity, and the structure of habitats, which in turn may challenge the population dynamics of species of critical importance to Indigenous livelihoods, health, and cultural practice. All model projection evaluations demonstrate that emission reductions can drastically slow the pace at which multiple drivers emerge or critical thresholds will be crossed. Intense mitigation strategies can also limit ecosystem exposure to potential warming and acidification stress during the 21st century.

Finally, Chapter 8 contains a brief update on the rapidly evolving state of research on Arctic/midlatitude connectivity, as a follow-up to the 2021 climate update report (AMAP, 2021). Arctic/midlatitude weather linkages remain a central concern, impacting millions of people. Processes include local forcing such as sea-ice loss and internal atmospheric variability. Arctic amplification, driven by global warming as manifest by loss of sea ice, warming temperatures, and thawing permafrost, is an ongoing process modifying atmospheric weather patterns. Advancements note the movement of the polar vortex over continents, and a theory of atmospheric blocking that helps to explain the location, timing and duration of Arctic/midlatitude weather connections.

1.7 Next steps

This report documents the continuing rapid climate-related physical and chemical changes in the Arctic, including the increasing occurrence and severity of extreme events, often beyond the bounds of previous such events. As a climate update report, it is intended to serve as a review of recent information on the topics covered rather than a major assessment. The information in this report is also intended to be of use to decision- and policy-makers to enable them to understand the current climate-related conditions and their scope as a basis for the development of policies to respond to these changes. To this end, a plain language Summary for Policy-makers has been prepared on the basis of the information in this report, which highlights the key findings and provides recommendations for further scientific work. It also contains policy recommendations addressed to Arctic states, Arctic Council Permanent Participants, and observer nations and organizations.

References

ACIA, 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press. 140 pp.

ACIA, 2005. Arctic Climate Impact Assessment: Scientific Report. Cambridge University Press. 1042 pp.

AMAP, 1997. Arctic Pollution Issues: A State of the Arctic Environment Report. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii+188 pp.

AMAP, 1998. The AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii+859 pp.

AMAP, 2011. Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii+538pp.

AMAP, 2017a. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv+269pp.

AMAP, 2017b. Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv+267pp.

AMAP, 2017c. Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv+255pp.

AMAP, 2018a. AMAP Assessment 2018: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. vi+187pp.

AMAP, 2018b. Adaptation Actions for a Changing Arctic: Perspectives from the Baffin Bay/Davis Strait Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xvi+354pp.

AMAP, 2021. AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, viii+148pp.

Box, J.E., W.T. Colgan, T.R. Christensen, N.M. Schmidt, M. Lund, F-J.W. Parmentier, R. Brown, U.S. Bhatt, E.S. Euskirchen, V.E. Romanovsky, J.E. Walsh, J.E. Overland, M. Wang, R.W. Corell, W.N. Meier, B. Wouters, S. Mernild, J. Mård, J. Pawlak and M.S. Olsen, 2019. Key indicators of Arctic climate change: 1971–2017. Environmental Research Letters, 14:045010. doi:10.1088/1748-9326/aafc1b

Box, J.E., U.S. Bhatt, T.R. Christensen, C. Derksen, S. Gerland, M. Granskog, K. Isaksen, J. Kohler, J. Mård, W.N. Meier, L. Mudryk, V.E. Romanovsky, A. Shiklomanov, S. Smith, I. Vanha-Majamaa, B. Wouters and D. Yang, 2021. Recent developments in Arctic climate observational indicators. In: AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. pp. 7-29. Arctic Monitoring and Assessment Programme (AMAP). Tromsø, Norway.

CliC/AMAP/IASC, 2016. The Arctic Freshwater System in a Changing Climate. WCRP Climate and Cryosphere (CliC) Project, Arctic Monitoring and Assessment Programme (AMAP), International Arctic Science Committee (IASC).

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (Eds.). Cambridge University Press, 755 pp. https://doi.org/10.1017/9781009157964

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.). Cambridge University Press. doi:10.1017/9781009157896

Box, J.E., R. Bellerby, R.E. Benestad, U.S. Bhatt, T.R. Christensen, C. Derksen, J. Francis, S. Gerland, K. Isaksen, J. Mård, J.L. McCarty, W.N. Meier, L. Mudryk, A. Shiklomanov, and S.L. Smith, 2024. Overview of multiple Arctic climate change indicators. In: AMAP Arctic Climate Change Update 2024: Key Trends and Impacts, pp. 5-12. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://doi.org/10.21352/bn0y-pv08

2. Overview of multiple Arctic climate change indicators

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Key findings

- *The Arctic climate system, as a cold-pole of the Earth's planetary heat engine, has undergone profound physical changes since the mid-1980s.*
- *The Arctic has warmed about three times as fast as that of the global average since 1979 owing to amplifying feedbacks in the climate system, but the exact estimate depends on the period chosen and is influenced by pronounced natural year-to-year variations.*
- *The greatest Arctic warming trends occur in the October-through-May 'cold season' that sets the stage for the June-through-September 'heating season' via thermal depletion of cold content in the ground and cryosphere (sea ice, snow cover, land ice, ground ice), meaning that less heat input is required for melting to ensue.*
- *Observation data showcase evidence of widespread loss of the Arctic cryosphere in all its forms (spring snow-cover extent, land ice, sea ice) as well as warming and thawing of permafrost.*
- *The Arctic is becoming wetter, with more precipitation falling as rainfall rather than snowfall, with an overall increase in precipitation totals.*
- *The Arctic Ocean is acidifying in response to CO_2 uptake, loss of sea-ice cover, ocean freshening and warming, and contributions of organic carbon from terrestrial sources.*
- *The Arctic is responding to changes in the climate system much more rapidly than any other region on Earth, and the changes in the far north are being felt far beyond the Arctic.*
- *The latest future Arctic climate projections suggest a more rapid Arctic warming and sea-ice loss by 2100 than previous projections, and consequently, greater and faster changes in the hydrological cycle, including Arctic glacier reduction and global sea-level rise.*

2.1 Introduction

Since 1979, the Arctic (here defined as the area north of 66.5°N) has warmed at least three times as fast as the global average (Rantanen et al., 2022). The decreasing temperature differential between the northern polar regions and the lower latitudes is increasing the persistence of weather extremes (Francis and Skific, 2015; Francis et al., 2020; Hoffmann et al., 2021) which, among other impacts, can elevate the risk of drought impacts for northern hemispheric breadbasket regions (Kornhuber et al., 2019). The amplified response of the Arctic versus global warming (e.g., Serreze et al., 2009; Previdi et al., 2021) results from numerous feedback processes mainly recognized through model studies, and which include changes in surface brightness (albedo) during the sunlit period, owing to losses of sea ice (Dai et al., 2019) and snow cover (Pulliainen et al., 2020); temperature profile feedbacks (Pithan and Mauritsen, 2014); increased downward infrared heating from increased humidity and clouds (Burt et al., 2016; Gong et al., 2017); increased poleward oceanic and atmospheric heat transport (Cai, 2005; Tsubouchi et al., 2020); and the effect of sea-ice thinning leading to less insulation between the warm ocean and cold atmosphere (Kurtz et al., 2011; Lang et al., 2017).

This chapter presents an overview of Arctic climate change insights from an expanded collection of observational climate indicators, building on Box et al. (2019, 2021) and AMAP (2021), with the six added years marked by new record-setting years for air and permafrost temperatures, wildfire, regional sea-ice minima, and land-ice loss. It also includes information about future Arctic climate projections.

2.2 Methodology

While homogeneous datasets for some variables begin before the 1980s, the focus here is on the 45-year period from 1979 to 2023 when more information from satellite observations is available and instrumental records are more continuous. The chosen period of analysis encompasses the pronounced Arctic warming *after* the mid-1980s (Overland et al., 2004; Przybylak and Wyszyński, 2020).

The results presented here are organized into sections addressing the atmospheric, terrestrial, and marine components of the Arctic climate system. These sections all refer to a single multi-indicator graphic (Figure 2.1) that illustrates selected indicators alongside one another.

Use of the term 'change', 'increase' or 'decrease' here is synonymous with the term 'trend' and refers to the magnitude of linear trends assessed by the standard least squares regression (Chatterjee and Hadi, 2006) temporal slope multiplied by the time duration. Statistical 'confidence' is measured by the probability that there is a real correlation between two time series after a Student's two-tailed t-test, estimated as 1 minus the probability (p) that there is an accidental match, i.e., $1 - p$.

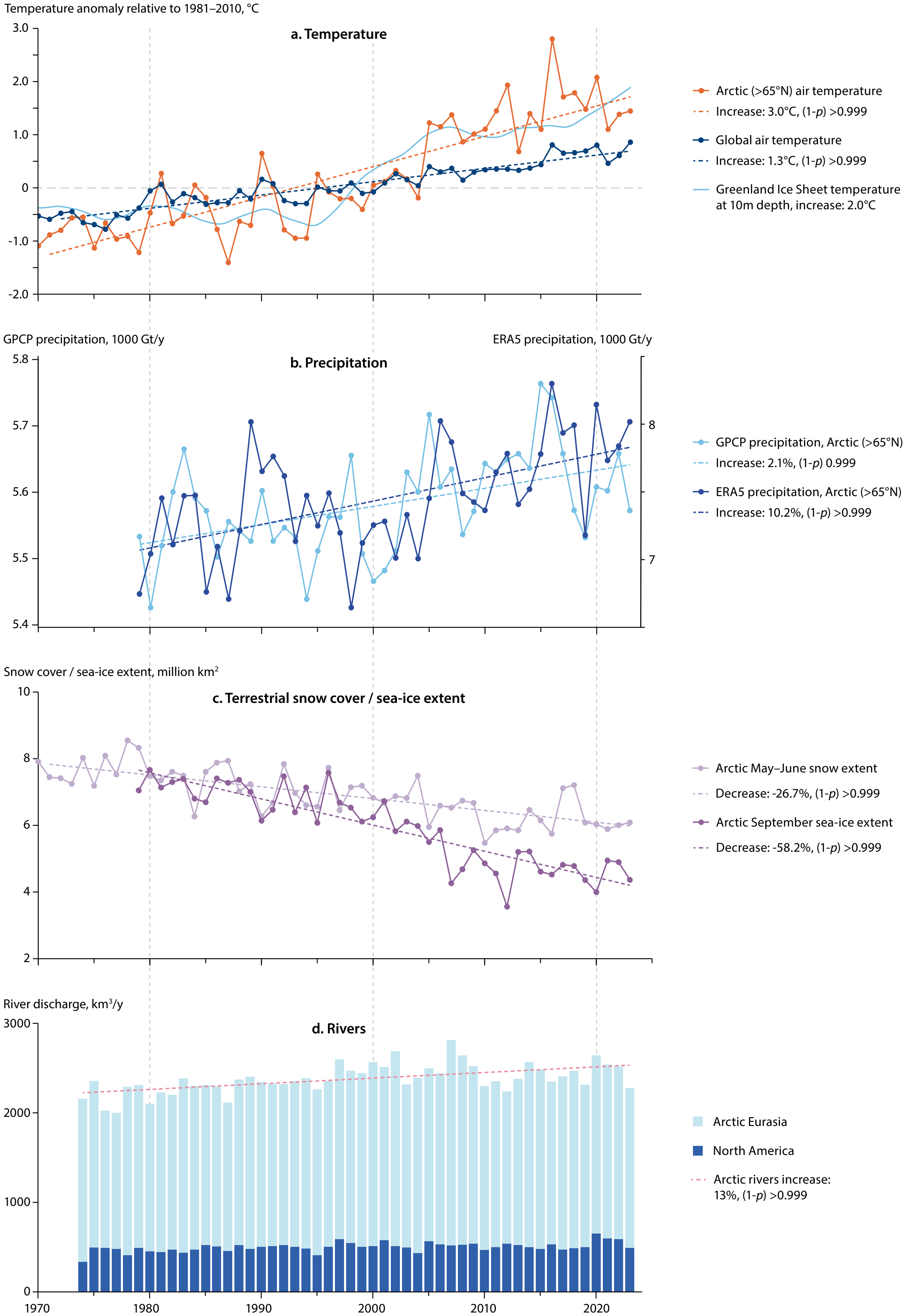
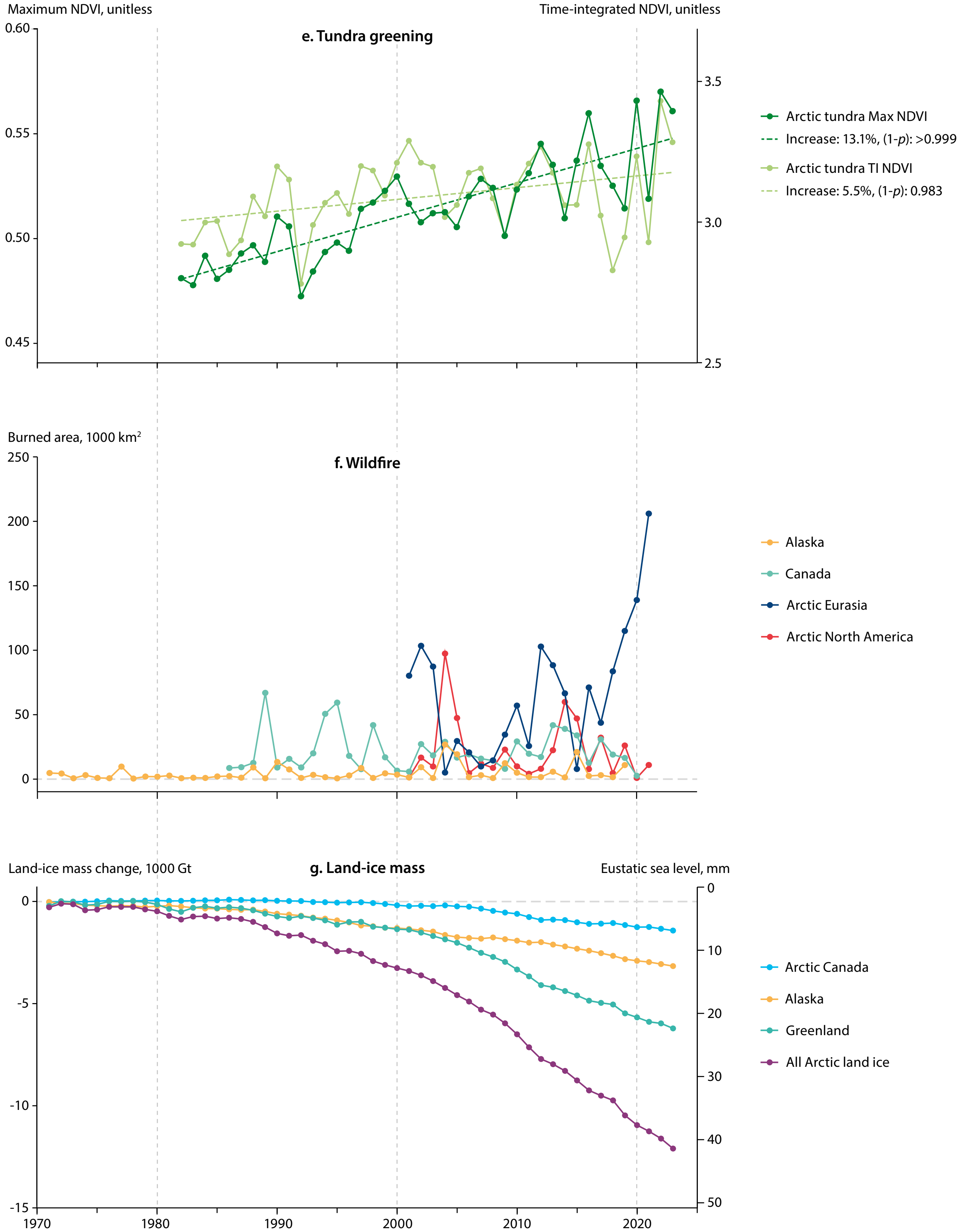


Figure 2.1 Arctic climate observational indicator records from as early as 1971. The 'increase' or 'decrease' metric refers to the change in the measured quantity over the various periods of record (see also Section 2.2). See box for data sources.



Data sources

The fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA5) monthly reanalysis (Hersbach et al., 2020) provides air temperature and precipitation data. The Global Precipitation Climatology Project (GPCP) version 2 data (Adler et al., 2003) are available from 1979 when satellite observations increased data accuracy, and for this reason the ERA5 data period to 1979 is excluded. Greenland Ice Sheet subsurface temperatures are after Vandecrux et al. (2024). Arctic river discharge data are after McClelland et al. (2024), see also Chapter 6. Arctic tundra greenness data are after Bhatt et al. (2017). Burned area data since 2000 are after Collection 6 Moderate Resolution Imaging Spectroradiometer (MODIS) MCD64 satellite observations (Giglio et al., 2018). See also Chapter 4. The Alaska burned area data are after Data Ref. 2.1. The Canada burned area data are after Data Ref. 2.2. Also discussed in Chapter 5 are the snow-cover data after Mudryk et al. (2020), the sea-ice extent data after Meier and Stewart (2019) and the Arctic land-ice mass balance data after Box et al. (2018) and Data Ref. 2.3 with the Greenland Ice Sheet mass balance data after Mankoff et al. (2021).

Satellite observations enable monitoring of vegetation 'greenness' using the Normalised Difference Vegetation Index (NDVI) metric (Bhatt et al., 2017). The maximum and time-integrated NDVI time series are standardized through dividing by their respective standard deviation (σ).

The European Global Reanalysis version five (ERA5) (Hersbach et al., 2020) and the Global Precipitation Climatology Project (GPCP) version 2 precipitation data (Adler et al., 2003), commonly used in regional precipitation assessment (Douville et al., 2021; IPCC, 2021), are both featured to indicate that metrics for Arctic precipitation have a substantial level of uncertainty.

An annual metric for Arctic above-melting temperatures is assessed using ERA5 data; each day the surface area with daily average temperature above 0°C is recorded and annual averages are presented.

The ocean acidification indicator was chosen to be the changes to the hydrogen ion concentration in seawater, conventionally expressed as pH, but presented here as H^+ to facilitate a trend analysis comparable with that of the other key Arctic climate indicators.

2.3 Atmospheric indicators

Since 1971, annual air temperatures have increased by 3.0°C for the Arctic defined as the area north of and including 65.5°N. Arctic warming in the 45 years since 1979 has been about three times that of the global average owing to amplifying feedbacks in the climate system, but the exact estimate depends on the period chosen and is influenced by pronounced year-to-year variations. See Figure 2.1a.

The rate of Arctic warming increased in the latter 18 years (2005–2023) owing to an increase in the number and duration of winter warm events over the central Arctic Ocean after 2004 (Graham et al., 2017b). See Figure 2.1a. The winter storms are accompanied by increased poleward transport of atmospheric moisture and heat over the Arctic Ocean (Boisvert and Stroeve, 2015; Park et al., 2015; Woods and Caballero, 2016; Graham et al., 2017a; You et al., 2022).

Arctic near-surface air temperature warming is concentrated across the marine environment (Figure 2.2) owing to sea-ice decline. The peak warming across the northern Barents Sea mirrors sea-ice decline (see Chapter 5), while north of Arctic Canada and Greenland where sea ice is thickest, little to no warming trend is evident.

Arctic air temperatures have increasingly exceeded the 0°C threshold (Figure 2.3). The increased area of above-freezing temperatures can be related to thawing permafrost (see Chapter 5), reductions in snow cover (see Chapter 5) and sea-ice extent, and a shift towards rainfall instead of snowfall across the Arctic (Figure 2.4). The increase in rainfall mirrors the decrease in snowfall. Snowfall has no overall pan-Arctic trend, yet appears to be increasing in southeast Greenland.

Arctic precipitation has increased significantly (Figure 2.1b), by between 2% and 10% in the 1979–2023 period. Another metric, the number of days with rainfall, also exhibits an increase (Figure 2.5). Increasing Arctic precipitation is an expected consequence of atmospheric warming. Increases are due to greater global warming and poleward moisture transport (Cai, 2005; Tsubouchi et al., 2020), enhanced Arctic amplification of warming, and the associated loss of sea ice.

The historical precipitation increase is dominated by more rainfall than snowfall (Figure 2.4) (McCrystall et al., 2021). The transition from a snow- to a rain-dominated Arctic in the summer and autumn is projected to occur decades earlier and at a lower level of global warming than previously thought, potentially under 1.5°C relative to pre-industrial times (1850–1900) (IPCC, 2021), with profound climatic, ecosystem and socio-economic impacts (McCrystall et al., 2021).

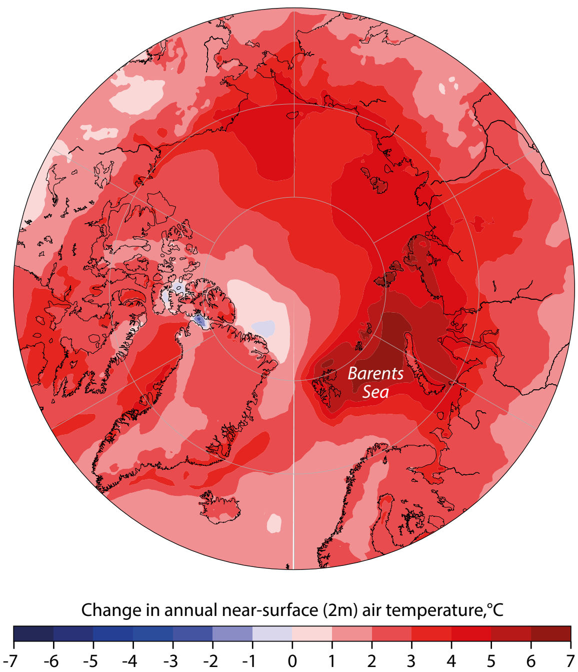


Figure 2.2 Arctic near-surface air temperature trends for the 45-year period 1979 to 2023. The trend metric is the linear regression temporal slope multiplied by the timespan in years. Source: ERA5 (Hersbach et al., 2020).

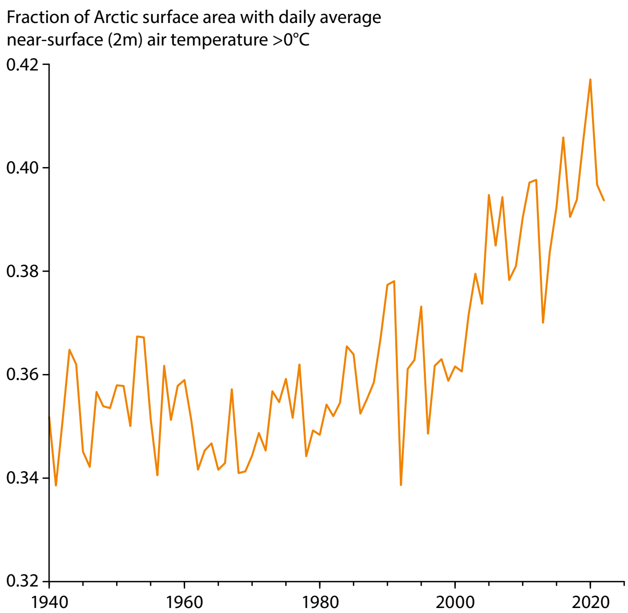


Figure 2.3 Surface area fraction north of 60°N with daily average near-surface air temperature above 0°C, over area-weighted ERA5 grid-boxes. Source: Benestad et al. (2024a).

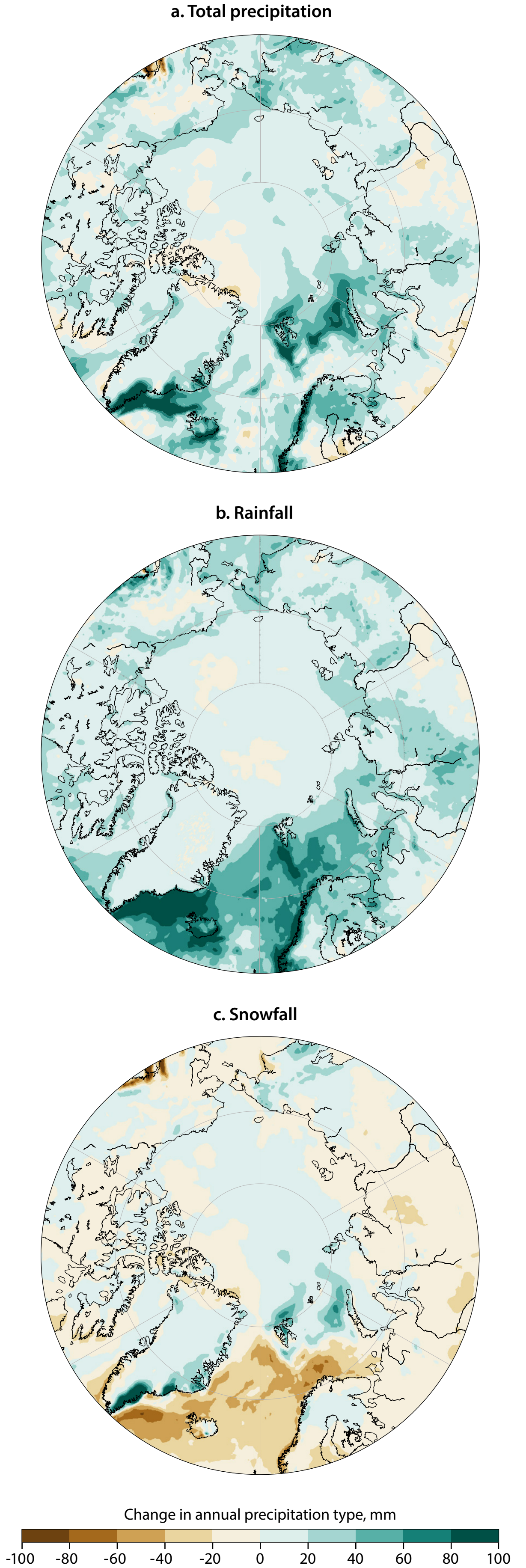


Figure 2.4 Trends for the 45-year period 1979 to 2023 in (a) Arctic total precipitation, with the liquid and solid components shown in terms of (b) rainfall and (c) snowfall. The trend is calculated as the trend slope per year multiplied by the timespan in years. Source: ERA5 (Hersbach et al., 2020).

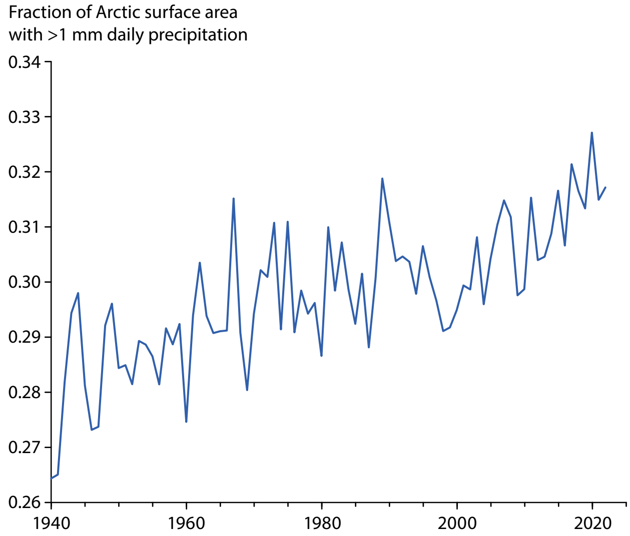


Figure 2.5 Surface area fraction north of 60°N with more than 1 mm daily precipitation. This provides an indication of the number of rainy days in the Arctic (see Benestad et al., 2024b). The total sum of precipitation and its trend (Figure 2.1b) is the product of the number of wet or snowy days and the mean precipitation intensity. Source: Benestad et al. (2024a).

2.4 Terrestrial indicators

Permafrost has continued to warm significantly, by 2–3°C since the 1970s (see Chapter 5), with ground temperatures reaching record high values at numerous monitoring sites in the latest year of this assessment, 2022 (Smith et al., 2023).

Permafrost thaw has been accompanied by landscape changes, such as increasing rates of coastal erosion, thaw slumping, active-layer detachments, and in poorly drained areas permafrost thawing creates collapse-scar wetlands and thermokarst lakes (see Chapter 5).

Subsurface snow and ice temperatures across the Greenland Ice Sheet in the period of instrumental observations since 1998 have increased by 2°C (Vandecrux et al., 2024). Consequently, the cold reservoir of the Greenland Ice Sheet is being thermally eroded, requiring less springtime or summer warming to bring the surface to the melting point.

Arctic spring (May through June) snow-cover extent on land has decreased by 27% over the 1979–2023 period (Figure 2.1c). A larger decrease (35%) is evident over the (larger) Eurasian area than across the North American Arctic (19%) (see Chapter 5).

Springtime snow loss (Figure 2.1c) is comparable in area to the loss of September sea ice, and occurs early in the warm season rather than late during the Arctic sunlit period. Hence, both contribute at different points during the Arctic summer to surface darkening, one of the leading causes of amplified Arctic warming (see Chapter 5 for an evaluation of the impact of warming on snow-cover decline).

Freshwater discharge to the Arctic Ocean from Arctic rivers is increasing, by 13% (or 309 km^3), about an average of 2381±161 km^3/y from 1974 to 2023 (Figure 2.1d). See also Chapter 6. The increase in freshwater discharge from land-ice loss is 1.6 times greater than the river discharge increase. See Figure 2.1g and Chapter 6.

Arctic vegetation greenness has increased significantly since 1982. The greenness correlates significantly with June through September rising air temperatures (Myneni et al., 1997; Jia et al., 2003; Box et al., 2019; Berner et al., 2020) which suggests overall continued Arctic greening with Arctic warming, despite limited areas instead exhibiting periods of 'browning'. See Figure 2.1e and Frost et al. (2023).

The possible increase in Arctic wildfires is likely to have been driven by a complex combination of rising Arctic air temperatures, reduced snow cover, increasing surface dryness, an expanding fire season and increasing human and lightning ignitions (e.g., Veraverbeke et al., 2017). See Figure 2.1f and Chapter 4.

The contribution to sea-level rise from the reduction of Arctic land ice (glaciers, ice caps, Greenland Ice Sheet) has been increasing. See also Chapters 5 and 6. Ice losses from Arctic glaciated areas account for most of the world's land-ice loss in the 1979–2023 period, totaling 10,000 Gt (Figure 2.1g, see also Chapter 5). The Greenland Ice Sheet and its peripheral glaciers account for half of the Arctic land-ice losses, amounting to roughly a third of the global land-ice contribution to sea-level rise over this period (Box and Colgan, 2017; AMAP, 2021; Otosaka et al., 2023).

The Arctic remains the largest regional source of global sea-level rise, with the rate of land-ice loss from Greenland exceeding that from Antarctica by nearly a factor of two (Otosaka et al., 2023).

2.5 Marine indicators

The September Arctic sea-ice extent declined significantly, by 58% in the period of continuous satellite observations from 1979 to present (Figure 2.1c). Arctic sea ice has also become thinner over recent decades. See Chapter 5 for details.

Delayed sea-ice freeze-up means that early snow falls onto open water rather than sea ice, thus leading to a decline in snow cover on sea ice. Declining sea-ice extent means that the summer open-water season has lengthened owing to earlier melt onset and retreat of the ice edge during spring and summer, followed by later freeze-up during autumn (Stroeve et al., 2016; Peng et al., 2018; Bliss et al., 2019). The open-water period has increased by up to 10 days per decade in some regions of the Arctic.

The Arctic Ocean is acidifying in response to increased ocean carbon dioxide (CO_2) uptake from the atmosphere, loss of sea-ice cover facilitating more gas exchange, ocean freshening and warming, and contributions of organic carbon from terrestrial sources. Ocean acidification negatively impacts marine life and activities, and the wellbeing and rights of Arctic Indigenous Peoples (see Chapter 7). The Arctic Ocean acidification rate has been three to four times higher than in other ocean basins over the past three decades (1994–2021) (Qi et al., 2022). Acidification has been observed in the Nordic Seas (Figure 2.6). The elevated Arctic Ocean acidification is mainly attributable to transport of anthropogenic carbon from the South, lowering further its buffer capacity owing to lower salinity due to sea ice and glacier melt and permafrost thaw, as well as to reduced sea-ice cover which promotes a more rapid partial equilibrium with atmospheric CO_2 increase. The acidification leads to an increase in hydrogen ion concentration and thus a decrease in pH and a decrease in calcium carbonate saturation states. See Chapter 7 for details.

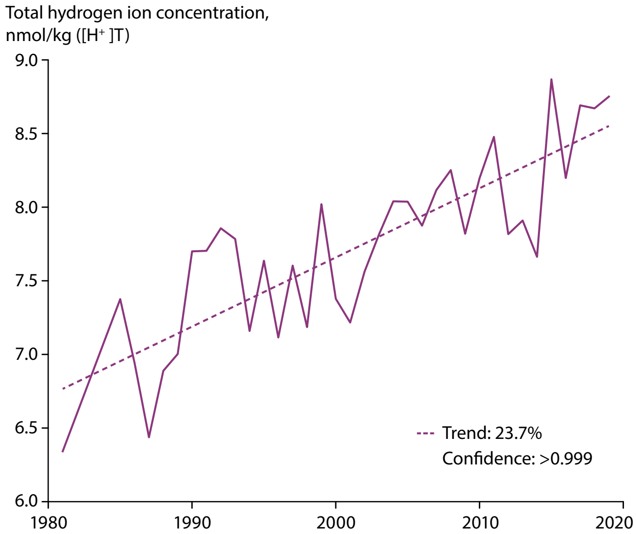


Figure 2.6 Acidification of the Nordic Seas from 39 years of observations (1981–2019) reported as an increase in total hydrogen ion concentration in order to evaluate a linear trend. Data from Fransner et al. (2022).

2.6 Future climate projections

The latest future Arctic climate projections suggest a more rapid Arctic warming this century than was the case in previous projections (McCrystall et al., 2021). Future projections indicate continued sea-ice decline (e.g., Notz and SIMIP Community, 2020; Bonan et al., 2021) while Arctic total precipitation (snowfall and rainfall) is projected to increase (Meredith et al., 2019). See Chapter 5 for details. Future permafrost thaw depth is projected to increase while permafrost extent is projected to decline, although there is much uncertainty regarding the magnitude and timing of the predicted response (Meredith et al., 2019; Fisher and Koven, 2020; Fox-Kemper et al., 2021; Peng et al., 2023).

2.7 Conclusions

The Arctic is responding to changes in the climate system much more rapidly than any other region on Earth, and these changes in the far north are being felt far beyond the Arctic.

Changes in more than ten observational indicators of Arctic climate, spanning up to a 52-year period (1971–2023) and which cover the transition to a rapidly warming Arctic, exhibit widespread and statistically significant trends including increases in air and permafrost temperatures, rainfall, and tundra greenness, and decreases in snow-cover duration and extent, reductions in sea-ice thickness and extent, and declining Greenland Ice Sheet and pan-Arctic glacial volumes (Figure 2.1). Areas with wildfire and permafrost degradation are sources of increased carbon emissions to the atmosphere.

Future climate projections indicate continued Arctic warming with amplified impacts on sea-ice decline, rainfall increase, permafrost thaw, and the likelihood for increased terrestrial carbon release to the atmosphere, driven by this warming. The latest generation of climate projections under the sixth phase of the Coupled Model Intercomparison Project (CMIP6) have improved simulations of the sea-ice average state and trends over the period of satellite observations (Davy and Outten, 2020; Notz and SIMIP Community, 2020), and improved simulations of past snow cover (Mudryk et al., 2020) and global precipitation (Scoccimarro and Gualdi, 2020), suggesting that simulations for other aspects of the hydrological cycle, such as Arctic precipitation, are also improved.

References

Text references

Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P.-P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin and E. Nelkin, 2003. The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present). Journal of Hydrometeorology, 4:1147-1167. doi:10.1175/1525-7541(2003)004<1147:tvgpcp>2.0.co;2

AMAP, 2021. Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 16 pp.

Benestad, R.E., C. Lussana and A. Dobler, 2024a. Global record-breaking recurrence rates indicate more widespread and intense surface air temperature and precipitation extremes. Science Advances, 10:45. doi:10.1126/sciadv.ado3712

Benestad, R.E., C. Lussana and A. Dobler, 2024b. A link between the global surface area receiving daily precipitation, wet-day frequency and probability of extreme rainfall. Discover Water, 4. doi:10.1007/s43832-024-00063-3

Berner, L.T., R. Massey, P. Jantz, B.C. Forbes, M. Macias-Fauria, I. Myers-Smith, T. Kumpula, G. Gauthier, L. Andreu-Hayles, B.V. Gaglioti, P. Burns, P. Zetterberg, R. D'Arrigo and S.J. Goetz, 2020. Summer warming explains widespread but not uniform greening in the Arctic tundra biome. Nature Communications, 11:4621. doi:10.1038/s41467-020-18479-5

Bhatt, U.S., D.A Walker, M.K Raynolds, P.A Bieniek, H.E. Epstein, J.C. Comiso, J.E. Pinzon, C.J Tucker, M. Steele, W. Ermold and J. Zhang, 2017. Changing seasonality of panarctic tundra vegetation in relationship to climatic variables. Environmental Research Letters, 12:055003. doi:10.1088/1748-9326/aa6b0b

Bliss, A.C., M. Steele, G. Peng, W.N. Meier and S. Dickinson, 2019. Regional variability of Arctic sea ice seasonal change climate indicators from a passive microwave climate data record. Environmental Research Letters, 14:045003. doi:10.1088/1748-9326/aafb84

Boisvert, L.N. and J.C. Stroeve, 2015. The Arctic is becoming warmer and wetter as revealed by the Atmospheric Infrared Sounder. Geophysical Research Letters, 42:4439-4446. doi:10.1002/2015gl063775

Bonan, D.B., F. Lehner and M.M. Holland, 2021. Partitioning uncertainty in projections of Arctic sea ice. Environmental Research Letters, 16:044002. doi:10.1088/1748-9326/abe0ec

Box, J.E. and W.T. Colgan, 2017. Sea level rise contribution from Arctic land ice: 1850-2100. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. pp. 219-229. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

Box, J.E., W.T. Colgan, B. Wouters, D.O. Burgess, S. O'Neel, L.I. Thomson and S.H. Mernild, 2018. Global sea-level contribution from Arctic land ice: 1971–2017. Environmental Research Letters, 13:125012. doi:10.1088/1748-9326/aaf2ed

Box, J.E., W.T Colgan, T.R. Christensen, N.M. Schmidt, M. Lund, F.-J.W. Parmentier et al., 2019. Key indicators of Arctic climate change: 1971–2017. Environmental Research Letters, 14:045010. doi:10.1088/1748-9326/aafc1b

Box, J.E., U.S. Bhatt, T.R. Christensen, C. Derksen, S. Gerland, M. Granskog, K. Isaksen, J. Kohler, J. Mård, W.N. Meier, L. Mudryk, V.E. Romanovsky, A. Shiklomanov, S. Smith, I. Vanha-Majamaa, B. Wouters and D. Yang, 2021. Recent developments in Arctic climate observational indicators. In: AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. pp. 7-29. Arctic Monitoring and Assessment Programme (AMAP). Tromsø, Norway.

Burt, M.A., D.A. Randall and M.D. Branson, 2016. Dark warming. Journal of Climate, 29:705-719. doi:10.1175/JCLI-D-15-0147.1

Cai, M., 2005. Dynamical amplification of polar warming. Geophysical Research Letters, 32:L22710. doi:10.1029/2005GL024481

Chatterjee, S. and A.S. Hadi, 2006. Regression Analysis by Example. John Wiley & Sons, 416 pp.

Dai, A., D. Luo, M. Song and J. Liu, 2019. Arctic amplification is caused by sea-ice loss under increasing CO_2. Nature Communications, 10:121. doi:10.1038/s41467-018-07954-9

Davy, R. and S. Outten, 2020. The Arctic surface climate in CMIP6: status and developments since CMIP5. Journal of Climate, 33:8047-8068. doi:10.1175/JCLI-D-19-0990.1

Douville, H., K. Raghavan, J. Renwick, R.P. Allan, P.A. Arias, M. Barlow, R. Cerezo-Mota, A. Cherchi, T.Y. Gan, J. Gergis, D. Jiang, A. Khan, W. Pokam Mba, D. Rosenfeld, J. Tierney, and O. Zolina, 2021. Water cycle changes. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, pp. 1055-1210. doi:10.1017/9781009157896.010

Fisher, R.A. and C.D. Koven, 2020. Perspectives on the future of land surface models and the challenges of representing complex terrestrial systems. Journal of Advances in Modeling Earth Systems, 12: e2018MS001453. doi:10.1029/2018ms001453

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen and Y. Yu, 2021. Ocean, cryosphere and sea level change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, pp. 1211-1362. doi:10.1017/9781009157896.011

Francis, J. and N. Skific, 2015. Evidence linking rapid Arctic warming to mid-latitude weather patterns. Philosophical Transactions of the Royal Society A, 373. doi:10.1098/rsta.2014.0170

Francis, J.A., N. Skific and S.J. Vavrus, 2020. Increased persistence of large-scale circulation regimes over Asia in the era of amplified Arctic warming, past and future. Scientific Reports, 10:14953. doi:10.1038/s41598-020-71945-4

Fransner, F., F. Fröb, J. Tjiputra, N. Goris, S.K. Lauvset, I. Skjelvan, E. Jeansson, A. Omar, M. Chierici, E. Jones, A. Fransson, S.R. Ólafsdóttir, T. Johannessen and A. Olsen, 2022. Acidification of the Nordic Seas. Biogeosciences, 19:979-1012. doi:10.5194/bg-19-979-2022

Frost, G.V., M.J. Macander, U.S. Bhatt, L.T. Berner, J.W. Bjerke, H.E. Epstein, B.C. Forbes, S.J. Goetz, M.J. Lara, R.Í. Magnússon, G.K. Phoenix, S.P. Serbin, H. Tømmervik, O. Tutubalina, D.A. Walker and D. Yang, 2023. Tundra greenness. In: State of the Climate in 2022. Bulletin of the American Meteorological Society, 104(9, Special Supplement), S305–S308. Article j. doi:10.1175/BAMS-D-23-0079.1

Giglio, L., L. Boschetti, D.P. Roy, M.L. Humber and C.O. Justice, 2018. The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment, 217:72-85. doi:10.1016/j.rse.2018.08.005

Gong, T., S. Feldstein and S. Lee, 2017. The role of downward infrared radiation in the recent Arctic winter warming trend. Journal of Climate, 30:4937-4949. doi:10.1175/JCLI-D-16-0180.1

Graham, R.M., A. Rinke, L. Cohen, S.R. Hudson, V.P. Walden, M.A. Granskog, W. Dorn, M. Kayser and M. Maturilli, 2017a. A comparison of the two Arctic atmospheric winter states observed during N-ICE2015 and SHEBA. Journal of Geophysical Research: Atmospheres, 122:5716-5737. doi:10.1002/2016jd025475

Graham, R.M., L. Cohen, A.A. Petty, L.N. Boisvert, A. Rinke, S.R. Hudson, M. Nicolaus and M.A. Granskog, 2017b. Increasing frequency and duration of Arctic winter warming events. Geophysical Research Letters, 44:6974-6983. doi:10.1002/2017GL073395

Hersbach, H., B. Bell, P. Berrisford, S. Hirahara, A. Horányi, J. Muñoz-Sabater, J. Nicolas et al., 2020. The ERA5 global reanalysis. Quarterly Journal of the Royal Meteorological Society, 146:1999-2049. doi:10.1002/qj.3803

Hoffmann, P., J. Lehmann, B. Fallah and F.F. Hattermann, 2021. Author Correction: Atmosphere similarity patterns in boreal summer show an increase of persistent weather conditions connected to hydro-climatic risks. Scientific Reports, 11:24242. doi:10.1038/s41598-021-03671-4

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (Eds.). Cambridge University Press, 2391 pp. doi:10.1017/9781009157896

Jia, G.J., H.E. Epstein and D.A. Walker, 2003. Greening of arctic Alaska, 1981–2001. Geophysical Research Letters, 30. doi:10.1029/2003gl018268

Kornhuber, K., D. Coumou, E. Vogel, C. Lesk, J.F. Donges, J. Lehmann and R.M. Horton, 2019. Amplified Rossby waves enhance risk of concurrent heatwaves in major breadbasket regions. Nature Climate Change, 10:48-53. doi:10.1038/s41558-019-0637-z

Kurtz, N.T., T. Markus, S.L. Farrell, D.L. Worthen and L.N. Boisvert, 2011. Observations of recent Arctic sea ice volume loss and its impact on ocean-atmosphere energy exchange and ice production. Journal of Geophysical Research: Oceans, 116. doi:10.1029/2010jc006235

Lang, A., S. Yang and E. Kaas, 2017. Sea ice thickness and recent Arctic warming. Geophysical Research Letters, 44:409-418. doi:10.1002/2016gl071274

Mankoff, K.D., X. Fettweis, P.L. Langen, M. Stendel, K.K. Kjeldsen, N.B. Karlsson, B. Noël, M.R. van den Broeke, A. Solgaard, W. Colgan, J.E. Box, S.B. Simonsen, M.D. King, A.P. Ahlstrøm, S.B. Andersen and R.S. Fausto, 2021. Greenland ice sheet mass balance from 1840 through next week. Earth System Science Data, 13:5001-5025. doi:10.5194/essd-13-5001-2021

McClelland, J.W., S.E. Tank, R.G.M. Spencer, A.I. Shiklomanov, S. Zolkos and R.M. Holmes, 2024. Arctic Great Rivers Observatory. Discharge Dataset, Version 20240125. https://arcticgreatrivers.org/

McCrystall, M.R., J. Stroeve, M. Serreze, B.C. Forbes and J.A. Screen, 2021. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nature Communications, 12:6765. doi:10.1038/s41467-021-27031-y

Meier, W.N. and J.S. Stewart, 2019. Assessing uncertainties in sea ice extent climate indicators. Environmental Research Letters, 14:035005. doi:10.1088/1748-9326/aaf52c

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019. Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964.

Mudryk, L., M. Santolaria-Otín, G. Krinner, M. Ménégoz, C. Derksen, C. Brutel-Vuilmet, M. Brady and R. Essery, 2020. Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. The Cryosphere, 14:2495-2514. doi:10.5194/tc-14-2495-2020

Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar and R.R. Nemani, 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature, 386:698-702. doi:10.1038/386698a0

Notz, D. and SIMIP Community, 2020. Arctic sea ice in CMIP6. Geophysical Research Letters, 47:e2019GL086749. doi:10.1029/2019gl086749

Otosaka, I.N., A. Shepherd, E.R. Ivins, N.-J. Schlegel, C. Amory, M.R. van den Broeke, M. Horwath et al., 2023. Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth System Science Data, 15:1597-1616. doi:10.5194/essd-15-1597-2023

Overland, J.E., M.C. Spillane, D.B. Percival, M. Wang and H.O. Mofjeld, 2004. Seasonal and regional variation of pan-Arctic surface air temperature over the instrumental record. Journal of Climate, 17:3263-3282. doi:10.1175/1520-0442(2004)017<3263:sarvop>2.0.co;2

Park, D.-S.R., S. Lee and S.B. Feldstein, 2015. Attribution of the recent winter sea ice decline over the Atlantic sector of the Arctic Ocean. Journal of Climate, 28:4027-4033. doi:10.1175/jcli-d-15-0042.1

Peng, G., M. Steele, A. Bliss, W. Meier and S. Dickinson, 2018. Temporal means and variability of Arctic sea ice melt and freeze season climate indicators using a satellite climate data record. Remote Sensing, 10:1328. doi:10.3390/rs10091328

Peng, X., T. Zhang, O.W. Frauenfeld, C. Mu, K. Wang, X. Wu, D. Guo, J. Luo, J. Hjort, J. Aalto, O. Karjalainen and M. Luoto, 2023. Active layer thickness and permafrost area projections for the 21st century. Earths Future, 11:e2023EF003573. doi:10.1029/2023ef003573

Pithan, F. and T. Mauritsen, 2014. Arctic amplification dominated by temperature feedbacks in contemporary climate models. Nature Geoscience, 7:181-184. doi:10.1038/ngeo2071

Previdi, M., K.L. Smith and L.M. Polvani, 2021. Arctic amplification of climate change: a review of underlying mechanisms. Environmental Research Letters, 16:093003. doi:10.1088/1748-9326/ac1c29

Przybylak, R. and P. Wyszyński, 2020. Air temperature changes in the Arctic in the period 1951–2015 in the light of observational and reanalysis data. Theoretical and Applied Climatology, 139:75-94. doi:10.1007/s00704-019-02952-3

Pulliainen, J., K. Luojus, C. Derksen, L. Mudryk, J. Lemmetyinen, M. Salminen, J. Ikonen, M. Takala, J. Cohen, T. Smolander and J. Norberg, 2020. Publisher Correction: Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature, 582:E18. doi:10.1038/s41586-020-2416-4

Qi, D., Z. Ouyang, L. Chen, Y. Wu, R. Lei, B. Chen, R.A. Feely, L.G. Anderson, W. Zhong, H. Lin, A. Polukhin, Y. Zhang, Y. Zhang, H. Bi, X. Lin, Y. Luo, Y. Zhuang, J. He, J. Chen and W.-J. Cai, 2022. Climate change drives rapid decadal acidification in the Arctic Ocean from 1994 to 2020. Science, 377:1544-1550. doi:10.1126/science.abo0383

Rantanen, M., A. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma and A. Laaksonen, 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, 3:168, doi:10.1038/s43247-022-00498-31

Scoccimarro, E. and S. Gualdi, 2020. Heavy daily precipitation events in the CMIP6 worst-case scenario: projected twenty-first-century changes. Journal of Climate., 33:7631-7642. doi:10.1175/JCLI-D-19-0940.1

Serreze, M.C., A.P. Barrett, J.C. Stroeve, D.N. Kindig and M.M. Holland, 2009. The emergence of surface-based Arctic amplification. The Cryosphere, 3:11-19. https://doi.org/10.5194/tc-3-11-2009

Smith, S.L., V.E. Romanovsky, K. Isaken, K. Nyland, N.I.S.D. Streletskiy and H.H. Christiansen, 2023. Permafrost (Arctic). In: State of the Climate in 2022. Bulletin of the American Meteorological Society, 104:S301-S305. doi:10.1175/BAMS-D-23-0079.1

Stroeve, J.C., A.D. Crawford and S. Stammerjohn, 2016. Using timing of ice retreat to predict timing of fall freeze-up in the Arctic. Geophysical Research Letters, 43:6332-6340. doi:10.1002/2016gl069314

Tsubouchi, T., K. Våge, B. Hansen, K.M.H. Larsen, S. Østerhus, C. Johnson, S. Jónsson and H. Valdimarsson, 2020. Increased ocean heat transport into the Nordic Seas and Arctic Ocean over the period 1993–2016. Nature Climate Change, 11:21-26. doi:10.1038/s41558-020-00941-3

Vandecrux, B., R.S. Fausto, J.E. Box, F. Covi, R. Hock, Å.K. Rennermalm, A. Heilig, J. Abermann, D. van As, E. Bjerre, X. Fettweis, P.C.J.P. Smeets, P. Kuipers Munneke, M.R. van den Broeke, M. Brils, P.L. Langen, R. Mottram and A.P. Ahlstrøm, 2024. Recent warming trends of the Greenland ice sheet documented by historical firn and ice temperature observations and machine learning. The Cryosphere, 18:609-631. doi:10.5194/tc-18-609-2024

Veraverbeke, S., B.M. Rogers, M.L. Goulden, R.R. Jandt, C.E. Miller, E.B. Wiggins and J.T. Randerson, 2017. Lightning as a major driver of recent large fire years in North American boreal forests. Nature Climate Change, 7:529-534. doi:10.1038/nclimate3329

Woods, C. and R. Caballero, 2016. The role of moist intrusions in winter Arctic warming and sea ice decline. Journal of Climate, 29:4473-4485. doi:10.1175/jcli-d-15-0773.1

You, C., M. Tjernström, A. Devasthale and D. Steinfeld, 2022 The role of atmospheric blocking in regulating arctic warming. Geophysical Research Letters, 49: e2022GL097899. doi:10.1029/2022gl097899

Data references

Data Ref. 2.1 AICC, 2020. Alaska burned area 1971 to 2019. Alaska Interagency Coordination Center (AICC). https://fire.ak.blm.gov/ (Accessed 2020).

Data Ref. 2.2 CWFIS, 2021. Canada and Northwest Territories burned area 1986 to 2020. Canadian Wildland Fire Information System (CWFIS). http://cwfis.cfs.nrcan.gc.ca (Accessed 2021).

Data Ref. 2.3 Box, J., 2023. Updated Arctic land ice mass balance. Glacier Mass Balance Intercomparison Exercise (GlaMBIE). https://github.com/jasonebox/GOA-2023 (Accessed 2023).

Overland, J., R.E. Benestad, J.E. Box, and J. Walsh, 2024. Arctic climate extremes. In: AMAP Arctic Climate Change Update 2024: Key Trends and Impacts, pp. 13-21. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://doi.org/10.21352/rafs-2a92

3. Arctic climate extremes

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Key findings

- *Recent increases in extreme events, especially those near and beyond previous records, are a major new index for Arctic and global climate change. These record-shattering, unprecedented events often have no known historical analogues and suggest that other climate surprises may be in store. Changes are continuing. Storms, heatwaves, wildfires, rain, sea-ice minima, ecosystem reorganizations, and different seasonal timing of physical and ecosystem events are examples noted both by weather services and by Indigenous local reports. Impacts are felt by many coastal communities. The diverse type, location and timing of recent (past five years) extreme events, taken together, allow a consilience interpretation (i.e., a strong conclusion based on multiple reasons) for a new Arctic climate.*
- *The interdependence and interaction of climate change, Arctic amplification, and natural variability is producing these new extremes. Global warming leads to temperature increases, permafrost thaw, and sea-ice loss / open water. These factors combine with the natural range of atmospheric and oceanic dynamics, such as jet stream meanders, blocking weather patterns, storms, and upper ocean heat content. This interdependence produces the new physical and ecological extremes, characterized by different types, locations, seasonality, and duration of events. The interaction of these processes, referred to as emergence, can now be said to be the cause of unprecedented impacts.*

3.1 Introduction

Arctic extremes are increasing and are often record-shattering (Walsh et al., 2020; Fischer et al., 2021; Overland, 2021). Such extremes represent new major indicators of climate change, because they show conditions beyond previous observations. They can be labeled as unprecedented events. Twenty years ago, the Arctic was more resilient to climate change than now, because sea ice had a broader extent and was three times thicker than today (Thoman, pers. comm.). These new extremes are mostly regional, singular events, occurring as a result of global change / local weather combinations. They are beyond those of linear temperature increases projected by climate models; such models can miss the complicated interaction of physical and ecological processes due to lack of spatial resolution and lack of physics.

The future is thus inherently unpredictable, especially after rare events that exceed previous records. Given the short record of events of the last half decade and their contrast with earlier years, statistical tests provide an insufficient characterization of change. Going forward depends on rationality and logic. It is important to imagine possible scenarios. Impacts on communities are large and complex, resulting from jet stream changes and linked through multiple processes to fisheries and melting of the Greenland Ice Sheet. Rather than being considered a regime shift, these changes are ongoing.

Examples of recent extreme events include the loss of sea ice and ecosystem reorganization in northern marine Alaska and the Barents Sea, heatwave extremes in Siberia, and loss of snow in Greenland. Their impacts result from an interaction between physical and ecological processes. These new states cannot easily be assigned occurrence probabilities because they often have no known historical analogues. Other climate surprises may be in store. It is difficult to interpret the importance of an extreme event that has not occurred before (Diffenbaugh et al., 2017), and noting such a difficulty is the purpose of this chapter. It is far from obvious how even to pose the question since nearly every extreme event is unique compared with previous data. Climate change is by definition statistically non-stationary. Moon et al. (2019) noted the expanding footprint of rapid Arctic change. Landrum and Holland (2020) concluded that the Arctic is already transitioning away from a cryosphere-dominated system. Taken together (consilience), multiple types of extremes can be considered an indicator of current rapid Arctic change compared to the more conventional approach of examining trends in single variables such as increasing temperatures.

3.2 Probabilistic reasoning and radical uncertainty

The term 'extreme event' is understood in one of two ways: based on how rare it was compared to the past, or based on how strong the impacts were. One approach, termed 'risk', is resolvable based on probability distributions. Formally, the distribution can be generated from historical data or model simulations. The probability density function shown in Figure 3.1 captures the likelihood of specified events resulting from a given temperature distribution and its changes. As with any bell curve, those events that fall near the center are most likely, and events that occur in lower and upper temperature extremes have smaller probability. Climate change can have different effects on the probability of extreme values of the distribution. For example, in Figure 3.1a a simple shift of the entire distribution towards a warmer climate leads to fewer extreme cold weather events and more hot weather and extreme hot weather events. Alternatively, in Figure 3.1b increased temperature variability without a shift in the mean could lead to more extreme cold and heat events, with a lower probability of mid-range temperature events.

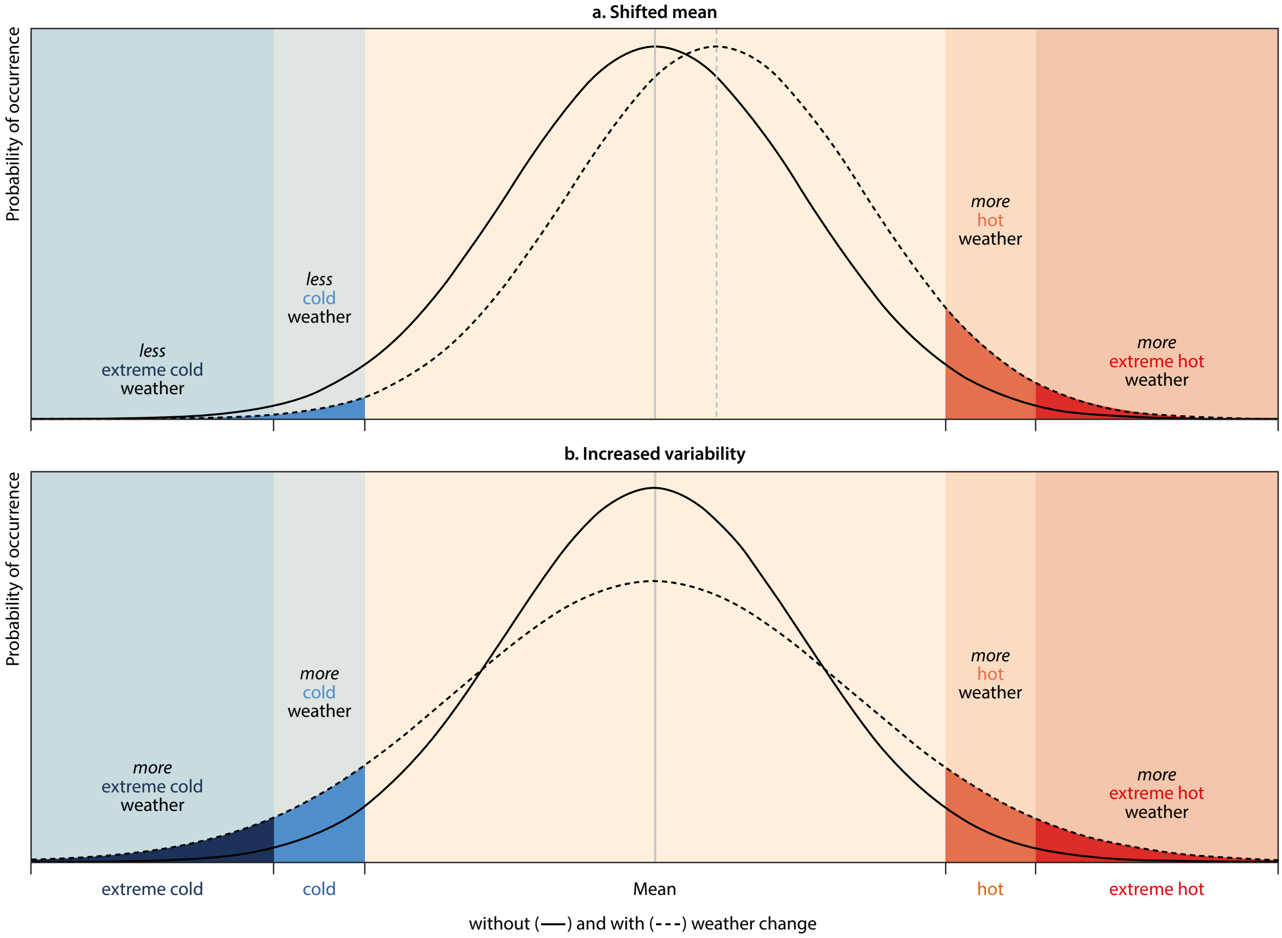

Figure 3.1 The effect of changes in temperature distribution on extremes. The two plots show different changes in temperature distribution between present and future climate and their effects on extreme values of the distributions: (a) effects of a simple shift of the entire distribution toward a warmer climate and (b) effects of an increased temperature variability with no shift of the mean. Source: IPCC (2012).

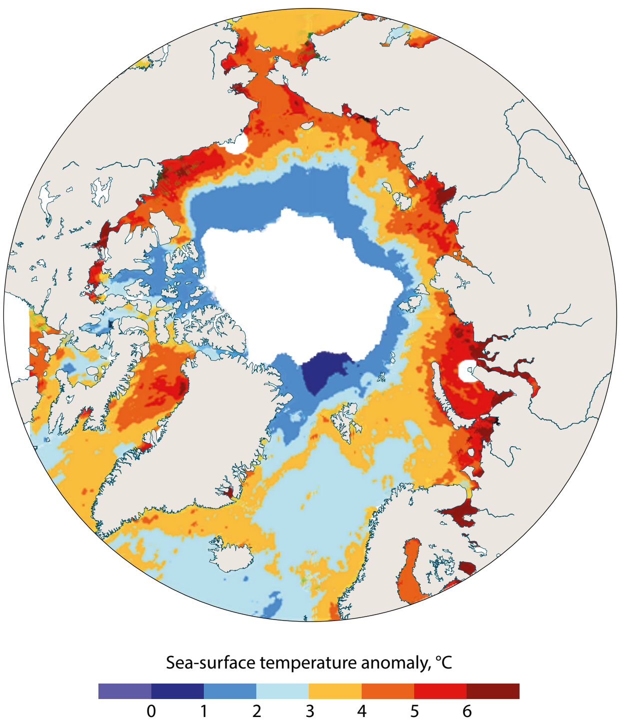

Figure 3.2 Maximum (1982–2020) sea-surface temperature anomaly (SSTA), derived using the 95th percentile threshold based on the 1982–2011 period and sustained for at least five consecutive days. Source: Huang et al. (2021).

Using this approach, marine heatwaves were described in the Arctic during 1982–2020 using three criteria and three independently produced daily sea-surface temperature (SST) products. Such a figure for the impact of climate change is shown from Huang et al. (2021; see Figure 3.2). The primary source of the data underlying Figure 3.2 was the NOAA DOISST v2.1 dataset, which is a global daily SST product with a resolution of 0.25° that blends in-situ and bias-corrected Advanced Very High Resolution Radiometer (AVHRR) SST measurements. The criteria were (a) that SST anomalies are greater than the 95th percentile threshold based on a 1982–2011 period, and (b) that the high anomalies are sustained for at least five consecutive days. This analysis indicated that the intensity, duration, frequency, and areal coverage of Arctic marine heatwaves increased during 1982–2020, and were greater in recent decades due to a warming climate. As illustrated in Figure 3.2, the maximum SST extremes are between 3°C and 5°C in the Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, Chukchi Sea, Beaufort Sea and Baffin Bay, and between 3°C and 4°C in the Norwegian Sea and Greenland Sea. These events were triggered in mid-July to early August during 1982 to 2020; they endured until mid-August during 1982–2000, until early September during 2000–2010, and until late September during 2010–2020.

At the opposite pole is radical uncertainty which is genuine unknown unknowns. It contrasts with historical randomness that is often termed as risk. These are states for which it is not possible to attach probabilities because it is not possible to conceive of these states. These are not low probability events, but unimaginable events given previous data. They are non-historical analogue situations. They are not likely to be the result of a long tail event arising from a low probability outcome from a known frequency distribution, but a result that was not previously expected.

For more than a half century the distribution approach has dominated decision science. However, statistical extrapolation methods, at present, generally do not conceivably have the information required to specify the distribution of new events, and consequences are thus uncertain. An alternative is to plan for positive outcomes and avoid outcomes that are worse. Many aspects of climate science are in this situation of having some prior knowledge of processes, but are comparatively data-poor in terms of what is actually trying to be predicted. The observed record provides only a limited sample of what is possible, and is moreover affected by sources of non-stationarity. In such a situation, using statistical methods that eschew physical reasoning and prior knowledge – "letting the data speak for itself" – is a recipe for disaster (Shepherd, 2021).

3.3 Types of unusual events

Reports on the ground are an important source of information. The 2017–2022 records from the Local Environmental Observer (LEO) Network represent a solicited group of observations from local residents, news articles, and topic experts, about unusual animal, environmental, and weather events in the Arctic. The LEO Network maintains a database that is searchable based on type of event and impact. In 2015, the LEO Network was selected as a model program of the Arctic Council to raise awareness and improve communication about climate change in the circumpolar region. Figure 3.3 illustrates the distribution of unusual events north of 60°N based on entries submitted between 2017 and 2022. Temperature extremes, changes in snow and sea ice, and shifts in seasonality are the most frequently reported observations. Ecosystems are impacted by changes in species range and animal die-offs.

A second source of information on extremes is a list of events for 2022 compiled by Benestad et al. (2023 updated; see Figure 3.4). Their summary is based on an enquiry collection undertaken by meteorological services connected to the Arctic. The total number of recorded events for 2022 was 68. The data include summer heatwaves in Greenland, Finland, Svalbard, Iceland, Alaska and Canada; rain events in Alaska and Norway; low sea ice in Russia in March; and cold events in Russia and the Yukon in December. Extreme storms can cause extensive societal impact. One of the most impactful Arctic extreme events in 2022 was a historically powerful storm that struck western Alaska in September. The storm originated as Typhoon Merbok in the subtropical North Pacific and transitioned to a very strong extratropical storm just prior to reaching the Bering Sea, where it had the lowest pressure (932 hPa) of any storm to form that early in autumn since at least 1950 (Thoman and The Conversation US, 2022). Typhoon Merbok caused severe coastal flooding across western Alaska, with extensive infrastructure damage along a 1000-km stretch of coast from Kuskokwim Bay to the Bering Strait. Some communities experienced their highest water levels in at least the last 100 years.

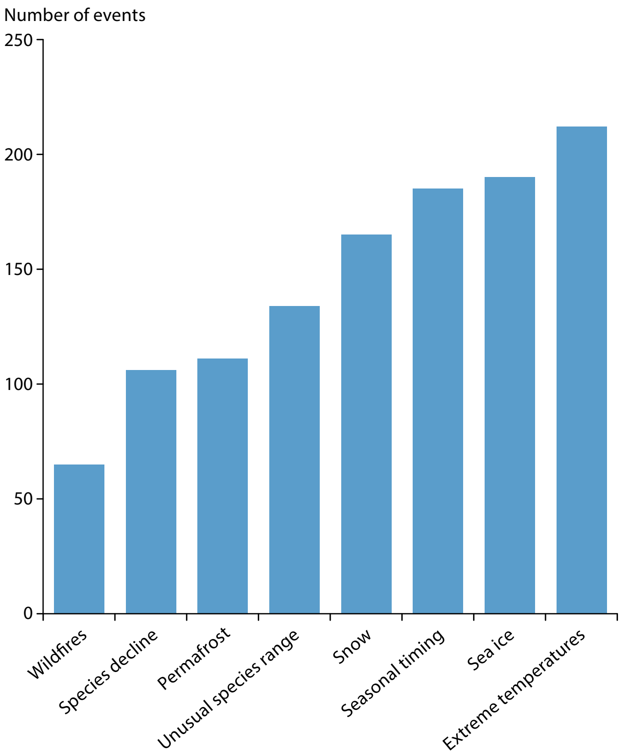

Figure 3.3 Observations of unusual or unexpected Arctic events submitted to the Local Environmental Observer (LEO) database in the period 2017–2022. Source: Data Ref. 3.1.

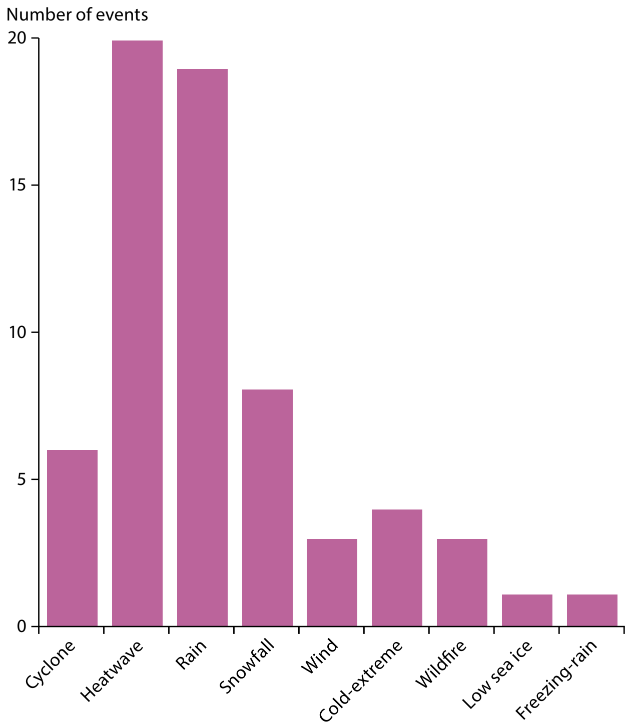

Figure 3.4 A summary of extreme event categories reported in the Arctic in 2022. Cyclones and wind events may overlap. The summary is based on events collected from meteorological services connected to the Arctic. Source: Benestad et al. (2023 updated).

3.4 Conceptual model: Influence of natural weather variability interacting with Arctic changes

The goal is to tie together biological/societal impacts of environmental events and extreme weather events to form joint causal accounts. Are there thresholds and tipping points of concern? New extremes are often forced by the interaction of background weather with ongoing atmosphere, ocean, and other Arctic changes, that then affect ecosystems and communities. Fluctuations outside resilience boundaries lead to detrimental impacts.

A conceptual model is suggested in Figure 3.5 whereby global warming from greenhouse gases increases as an ongoing thermodynamic response (a push) in Arctic changes, leading to temperature increases, permafrost thaw, and sea-ice loss / open water. These factors combine together with the natural range of atmospheric and oceanic dynamics (a pulse), such as jet stream meanders, blocking weather patterns, storms, and upper ocean heat content (Overland, 2021); their combination and interdependence produces new extremes. Arctic change provides precursors to major impacts. That new extremes apparently do not require circulation deviations to be much beyond their normal range is one reason suggested for the large number of recent impacts and the interannual and location variability of such events. These weather and climate extremes selectively influence ecosystems based on species-specific life history, such as the timing of reproduction and migration. Societal impacts follow directly from shifts in sea ice and ecosystem dynamics.

3.5 Recent examples of extremes that exceed previous records

3.5.1 Alaskan summer 2022 high variability

The total area affected by wildfires in Alaska reached 1 million acres on 18 June 2022, which was the earliest date of the 32 years of observation (Thoman, pers. comm. 2023). The two previous early dates, around 1 July for 2004 and 2015, had the largest seasonal burn area, suggesting that 2022 would continue to set records. However, this was prevented when drought conditions ended with record rainfall. For example, Utqiaġvik had 36 mm of rain fall on 26 July; exceeding the previous highest 24-hour precipitation on record of 32.5 mm on 21–22 July 1987. Anchorage had the highest rainfall on record at 184 mm in mid-July to mid-August. Alaska is a prime example of the range of potential extreme events.

3.5.2 Barents Sea extreme temperatures and Atlantification

Isaksen et al. (2022) found an unprecedented increase in annual mean 2001–2020 surface air temperature (SAT) over the northern Barents Sea of 5.4°C at Karl XII-øya on northeastern Svalbard and 4.4°C at Krenkel Observatory on Franz Josef Land. Both locations had large SAT values in autumn (SON) and winter (DJF). The warming was greater than hitherto known in this region and was exceptional even for the warming Arctic. The data show that the warming is linked, both in space and time, to the reduction in sea ice and increased SST; there is a

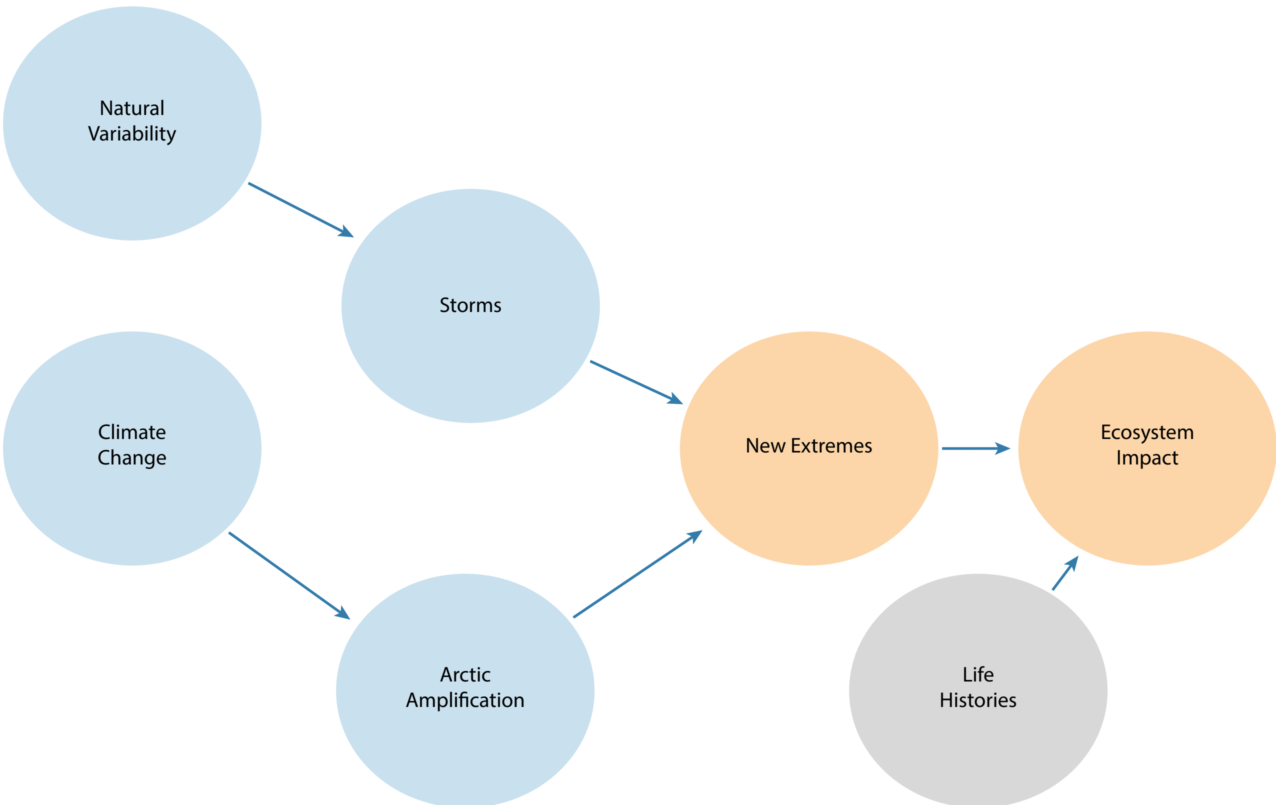

Figure 3.5 Conceptual model of extremes forced by atmosphere and ocean processes that interact with the ecosystem life histories. Climate change includes human influence. Climate change can affect natural variability; however, for this graphic the large range of natural background variability is emphasized. Source: modified from Overland (2021).

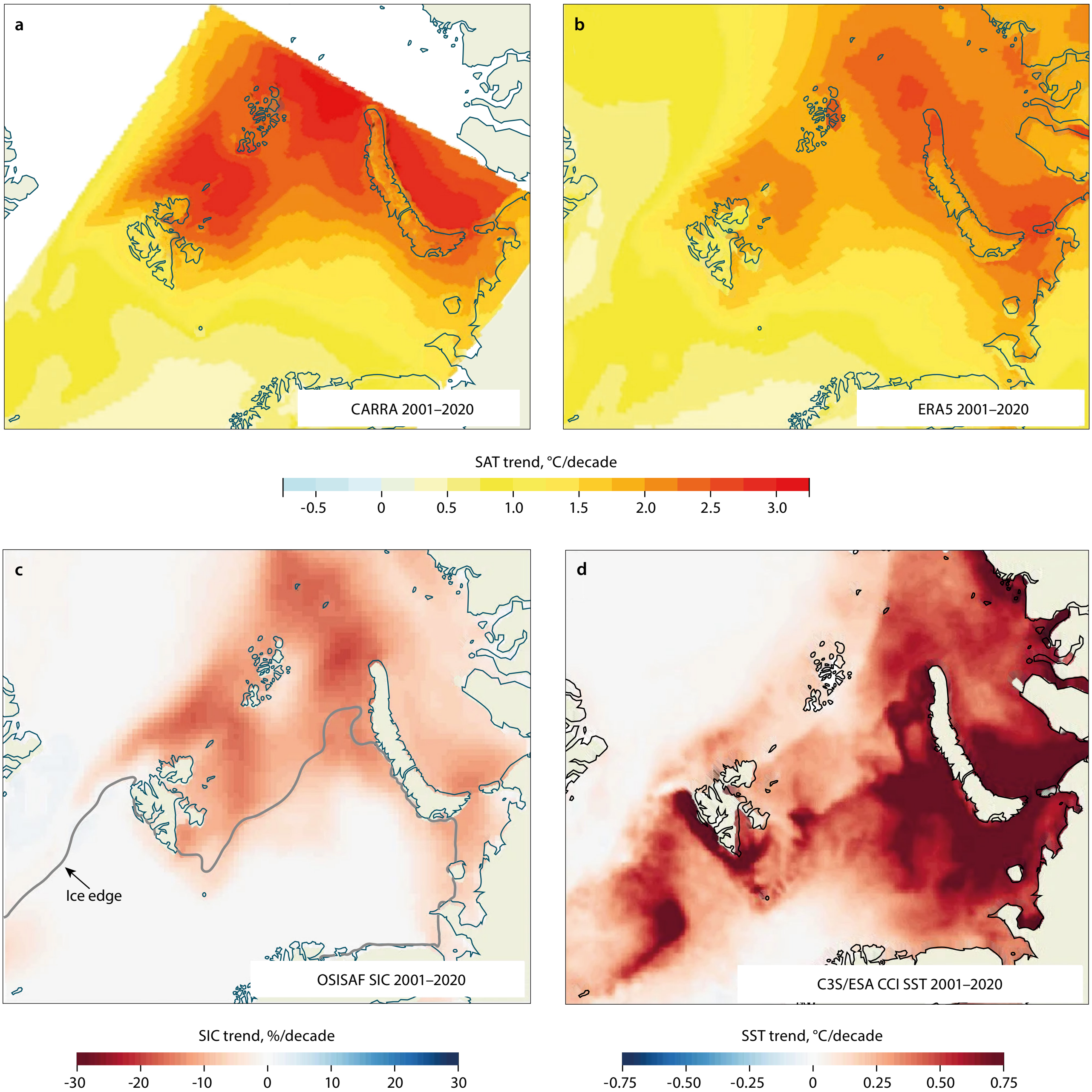

Figure 3.6 The spatial pattern of changes in surface air temperature (SAT), sea-ice concentration (SIC) and sea-surface temperature (SST) in the Barents Sea study area for the period 2001–2020. Plots (a) and (b) show annual SAT trends derived from CARRA and ERA5 reanalyses, plot (c) shows annual trends in SIC with the mean 15% SIC (ice edge) contour line marked in grey, and plot (d) shows annual SST trends. Source: Isaksen et al. (2022).

negative correlation between SAT and sea-ice loss at multiple stations of 0.94 in autumn and 0.97 in winter. The northern Barents Sea highlights the high temperatures of the 21st century, with a warming rate that is greater and longer lasting than during the “early 20th-century warming” (Førland et al., 2011). Figure 3.6 shows the spatial distribution of the annual rate of change for the Barents Sea over 2001–2020 for two reanalyses of SAT, sea-ice loss, and SST increase (Isaksen et al., 2022). Changes in SAT and sea ice are largest over the marginal ice zone north of the ice edge contour. Average June 2022 air temperature at Svalbard airport Longyearbyen was 6.0°C, which is 2.4°C above average and the warmest ever recorded. A major factor for warm temperatures in northern Svalbard over these decades was the increased presence of low sea-level pressure over the central Barents Sea giving easterly warm winds to the north of the low-pressure center. Northeast (i.e., from the NE) wind circulation contributes most to the warming (Wickström, pers. comm. 2023). Current conditions lead to rain-on-snow events in Svalbard (Jonassen, pers. comm. 2023). Despite the clear 20-year trend, it is also important to note the large interannual variability.

The cumulative sea-ice melting across Svalbard between 1 June and 31 July 2022 was 1.5 times larger than the previous record in 2018. The melting was caused by persistent warm winds blowing into the area from the south. From 1 May through 25 July 2022, parts of the Svalbard archipelago experienced air temperatures that averaged up to 1.8°C higher than usual. A significant pulse of warm air starting on 15 July produced Svalbard’s highest recorded melt volume two days later on 17 July (Wickström, pers. comm. 2023).

A major increase in SST occurred in the eastern Barents Sea and the northward coastal current along the west coast of Svalbard: the two branches of the Norwegian Atlantic Current. This is an indication of the *Atlantification* of the southern Barents Sea, a transition from more Arctic Ocean properties to those of the inflowing Atlantic waters. A strong warming (up to 0.8°C per decade) occurred in the southeastern region just outside the mean ice zone with an increasing influence of saltier Atlantic water (Polyakov et al., 2017). This warming of the surface water causes a retreat in sea ice in winter and an absence of sea ice in summer. The loss of winter sea ice means that the surface layer of cold freshwater from melting sea ice in summer is not replenished. This causes a weaker contrast between the temperature layers in the ocean and a stronger mixing of Atlantic water. Atlantification in this area is almost complete (Lind et al., 2018) and is having ecosystem consequences. For example, Barents Sea phytoplankton blooms have moved 5° further north compared to 1989 (Neukermans et al., 2018). Fish communities have also moved northward, with impacts on those seabirds, seals and whales that depend directly on these fish populations (Fossheim et al., 2015).

3.5.3 Community observations of extreme events in the northern Bering Sea

Unprecedented minimum winter sea-ice coverage occurred in the Bering Sea during 2017/2018 and 2018/2019, with sea-ice extent 70% lower than the climatological mean for 1950–2000, and with major impacts on ecosystem dynamics and human food security lasting at least through 2021 (Overland et al., 2024). Ecosystem impacts were immediately observed including multi-year changes in biological energy flow and structure, the presence of harmful algal blooms, loss of sea-ice algae and large lipid-rich zooplankton, loss of juvenile crab, northward expansion of commercially fished Pacific cod (*Gadus macrocephalus*) and Alaska pollock (*Gadus chalcogrammus*), reductions in all species of northern salmon runs, an unusual mortality event for three species of ice-associated seal (Boveng et al., 2020), and five consecutive years of multi-species seabird mortality.

In the Alaskan part of the northern Bering Sea / Bering Strait region, the non-commercial acquisition and utilization of diverse marine wildlife are essential to the nutritional, cultural, and economic wellbeing of coastal communities (Figure 3.7) (Huntington et al., 2020; Brinkman et al., 2022). The recent regional reduction in the duration, extent, and quality of sea ice continues to cascade into maritime changes, directly resulting in widespread concern by coastal residents. Additional concerns beyond the direct impacts of sea-ice loss are shifts in the geographical distribution of marine species (e.g., Stejneger's beaked whale *Mesoplodon stejnegeri*), the establishment of invasive species (e.g., Hanasaki crab *Paralithodes brevipes*), and reports of toxic algae in pinnipeds and cetaceans at levels that indicate potential health concerns. Recent changes represent an ecological shock: no coastal community remains untouched by the suite of changes. The peoples of the Bering Strait region are a part of the marine ecosystem; food security and wildlife health concerns must be addressed in collaborative, integrated, and public ways. The previous four years (2021–2024) show a return to more typical sea-ice extents. However, conditions during 2018–2019 suggest the possible return of low sea ice in the next two decades.

3.5.4 Siberian heatwave/wildfires

Siberia experienced a heatwave of extreme monthly temperatures of +6°C anomalies from January through May 2020, culminating in near daily temperature records at the Arctic station of Verhojansk in mid-June (Overland and Wang, 2021). The proximate cause for the warm extremes from January through April was the record strength of the stratospheric polar vortex and tropospheric jet stream. The stratospheric polar vortex and high geopotential heights to the south combined to provide strong zonal winds from the west that reduced the potential penetration of cold air from the north. An index of vortex strength is the Arctic Oscillation; averaged over January–April, the Arctic Oscillation set extreme positive records in 1989, 1990 and 2020 (baseline starting in 1950). The strength and stability of the stratospheric polar vortex over the central Arctic contributed to the winter–spring persistence of the heatwave in Siberia during 2020 (Overland and Wang, 2021). May–June temperatures were related to high tropospheric geopotential heights over Asia. An open question is whether these dynamic events are becoming more persistent. Such record events will not occur every year but it may be expected that they will recur over the next decades due to internal atmospheric variability added to a continued global warming.

Figure 3.7 Examples of diverse non-commercial marine resources essential to the nutritional, cultural, and economic wellbeing of coastal communities in the northern Bering Sea / Bering Strait region. From left to right the images show sculpin, walrus, and clams from the walrus' stomach. Photo credits: G. Sheffield.

Extreme wildfires also occurred in Canada during summer 2023 (Thoman et al., 2023). A more complete discussion of wildfires is provided in Chapter 4.

3.5.5 Greenland ice melt

On 14 August 2021, rainfall was witnessed for the first time at Summit station near the highest point of the Greenland Ice Sheet (Ramirez, 2021; Box et al., 2022) and was accompanied by high surface melt spatial extent. Satellite measurements revealed a rapid retreat of the snowline to higher elevations, exposing a large extent of relatively dark bare ice. Exceptional heating of the ice sheet occurred due to the heat transfer from condensation and the elevated air temperature during the August episode of warm air and rainfall arriving in what is often termed an 'atmospheric river'. The frequency of moist atmospheric rivers reaching Greenland is increasing (Mattingly et al., 2016), probably driven by more highly-amplified (i.e., more north-south extent) jet-stream patterns (Francis and Skific, 2015).

In September 2022, Greenland experienced exceptional heat and rainfall due to a series of atmospheric wind/temperature transport events from the south (see Figure 3.8). In 2022, temperatures in September were the highest on record; up to 8°C higher than average. The ice sheet saw record melt, with at least 23% of its area impacted at the peak of the first heatwave. Rainfall was much higher than average across southern and western areas of the ice sheet.

During these heatwaves, temperatures were above freezing at several locations on the Greenland Ice Sheet. For example, a high altitude (2883 m elevation) automated weather station at the southern dome of the ice sheet recorded 39 hours with temperatures above 0°C. Previously, the only periods with temperatures above 0°C at this station were much shorter: four hours in 2003 and one hour in 2016. Another location, in western Greenland, saw 325 hours with temperatures above 0°C during September. Melt had occurred here in 18 previous years out of a 28-year record, for an average of 57 hours. The exceptional heat further impacted the ice sheet by reducing the snow albedo by up to 15%. Ice crystals vary in shape, and heat rounds the otherwise sharp ice crystal edges reducing their albedo and accelerating melting. Melt in Greenland ice is tied to sea-level rise (see Chapter 2, Figure 2.1g).

3.6 Summer 2023 and winter 2023/2024

Extreme events continue. Thoman et al. (2023) reported six major extreme events during summer 2023: Arctic-wide summer air temperatures shattered records; unprecedented Canadian wildfires; early Canadian and Siberian snow melt; Greenland snow melt in late June; SSTs in the Barents, Kara, Laptev, and Beaufort Seas 5–7°C above normal in August; and extreme low Alaskan salmon runs. The events noted by Thoman et al. (2023) were verified by the Arctic Regional Climate Centre network (ArcRCC, 2023). Figure 3.9 shows that extreme summer heat events are regional.

Major events in winter 2023/2024 were listed by ArcRCC (2024). They include extreme winds in northern Canada in November 2023; snow in Alaska and northern Canada in December 2023; warm temperatures in northern Canada in January 2024; cold temperatures in eastern Siberia in February 2024; and drought in Iceland during winter 2024.

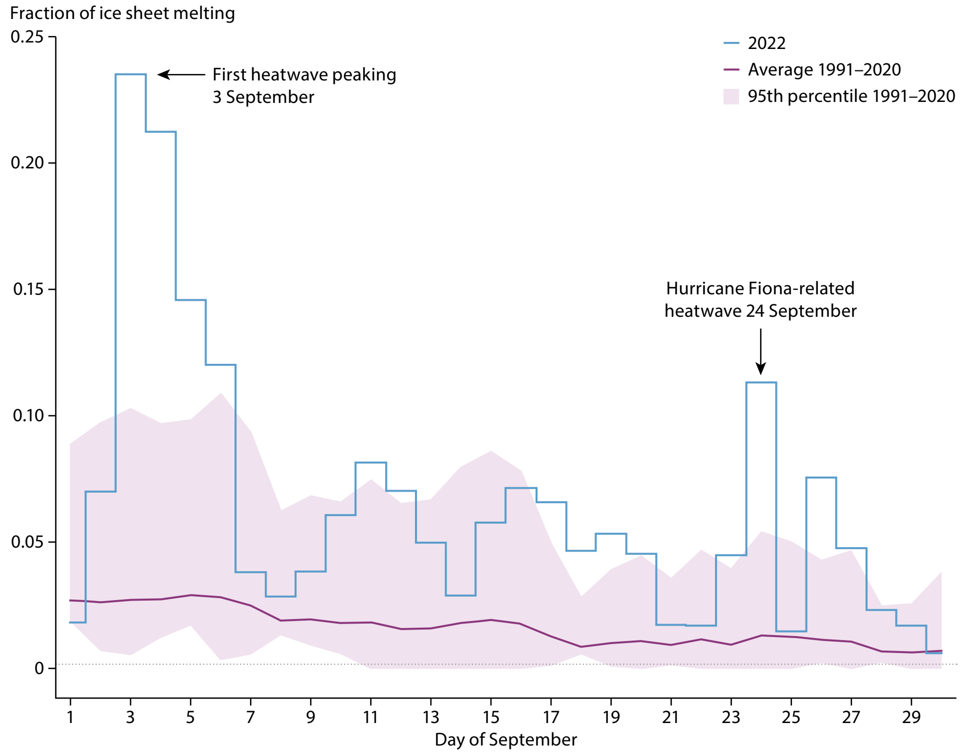

Figure 3.8 Melt area (daily fraction of the ice sheet melted) of the Greenland Ice Sheet and peripheral glaciers during 2022 compared to the average for the 1991–2020 reference period, and the range of values seen over the reference period (5th to 95th percentile). Source: CS3 (2023).

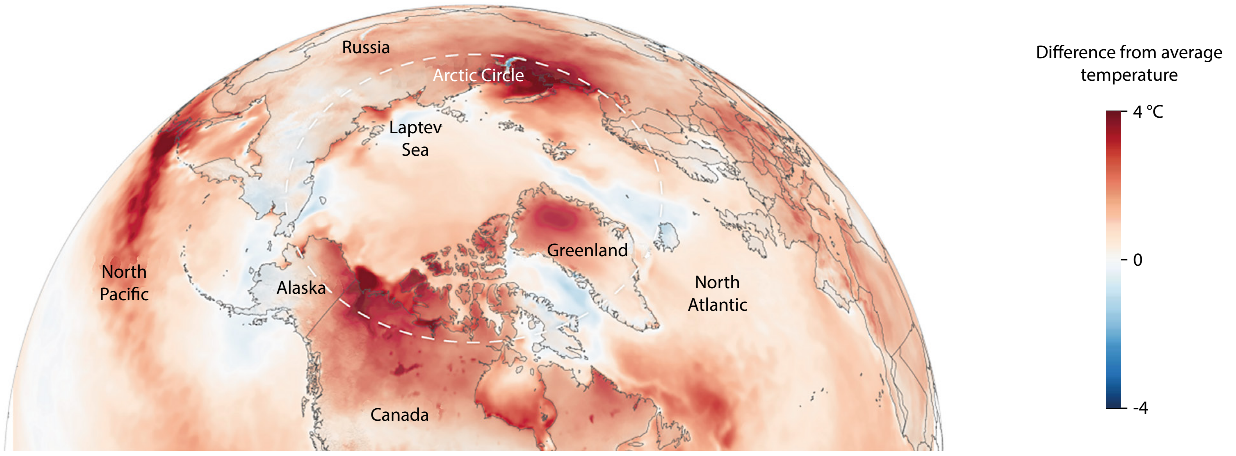

Figure 3.9 Summer 2023 Arctic temperature extremes. Source: Thoman et al. (2023).

3.7 Impact-based projections

The increase in future uncertainty due to lack of robust extrapolation does not mean that planning is less important. One way forward for adaptation to future extremes is through scenario/narrative approaches (Shortridge et al., 2017). For example, proposed impacts on the ecosystem are extrapolated backwards through species life histories to identify causal factors for change (e.g., temperature, storms, sea ice, permafrost). Such impacts could include wildfires, flooding, ecosystem shifts, biological pests, and changes in snow-water equivalent, storm intensity, fisheries, and marine mammals. Such approaches emphasize identification of potential major impacts and their causes, as well as strategies that are adaptable and robust. The way forward should include engagement of Indigenous Peoples and Indigenous Knowledge.

3.8 Summary: a new Arctic

The assessment of the Intergovernmental Panel on Climate Change (IPCC) concluded that, "It is unequivocal that human influence has warmed the atmosphere, ocean and land" (IPCC, 2021). Particularly for large-scale changes, there are robust anthropogenic signals that have been identified through multiple lines of evidence. Multiple unprecedented extreme events now add additional information to the climate change story.

It is undeniable that there was an overwhelming collection of extreme events in the Arctic during the previous five years. Such unprecedented events tend to be short-lived, occur in multiple regions, and are multivariate. Arctic data meet the criteria for both emergence and consilience. Emergence occurs when a complex entity has properties or behaviors that its parts do not have on their own, and emerge when they interact as a wider whole, such as Arctic amplification with natural meteorological and oceanographic variability (see Figure 3.5). Consilience is the principle that evidence from independent, unrelated sources can converge on a strong conclusion. That is, when multiple sources of evidence agree, the conclusion for Arctic change is strengthened. Based on the range of extreme events shown in this chapter, the Arctic emerges as being in a new physical state beyond that implied by previous indicators and processes, and that these multiple Arctic changes serve as an ongoing indicator of global change. Some changes represented by events are nearly complete, such as the Atlantification of the Barents Sea (e.g., warming, salinification, and ecosystem shifts). Most other Arctic regions are subject to intermittent events. Unpredictable behaviors are seen as an emergent phenomenon. The observed record provides a limited sample of what is possible, and recent observations are manifestly non-stationary.

Going forward, information necessary to guide communities in terms of adaptation responses requires continuing monitoring every year, physical reasoning, and judicious use of existing process knowledge. It is important to adopt policies and strategies that are robust to alternative futures. Such futures cannot be calculated, only framed by avoiding the worst outcomes. Implementing successful conservation for the climate-altered future requires proactive application of adaptation approaches. Futures must be assumed different from what has been experienced, and these futures are deeply uncertain (Shepherd, 2021). Expectations are for social and ecological change, requiring monitoring and balancing risks and opportunities. A fundamental necessity is understanding ecosystem and community changes with goals based on community values. Maintaining processes that generate heterogeneity in habitats, genes, and biological structures should be prioritized (Moore and Schindler, 2022). Strategies that enable adaptation and change in species and ecosystems that minimize climate impacts will happen at local to regional scales such as the northern Bering Sea, Barents Sea, and parts of maritime Canada.

Historically, attribution of the causes of the large environmental changes, including in temperatures, sea and land ice, and biological impacts, is a formidable task because it is difficult to separate the signal due to anthropogenic greenhouse gases from the background of large natural climate variability. Observational evidence now shows multiple ongoing extreme examples that are well beyond previous records. They are not likely to be the result of a long tail event arising from a very low probability outcome from a known frequency distribution, termed 'black swan' events (Shepherd, 2021). New states cannot easily be assigned probabilities because they often have no known historical analogues. Their occurrence suggests that climate surprises are in store for the future.

References

Personal communications

Jonassen, M., University Centre, Svalbard

Thoman, R., University of Alaska Fairbanks

Wickström, S., University Centre, Svalbard

Text references

ArcRCC, 2023. ACF Fall 2023. The 12th session of the Arctic Climate Forum (ACF-12). Arctic Regional Climate Centre network (ArcRCC). https://www.arctic-rcc.org/acf-fall-2023

ArcRCC, 2024. ACF Spring 2024. The 13th session of the Arctic Climate Forum (ACF-13). Arctic Regional Climate Centre network (ArcRCC). https://www.arctic-rcc.org/acf-spring-2024

Benestad, R., R.L. Thoman, Jr., J.L. Cohen, J. Overland, E. Hanna, G.W.K. Moore, M. Rantanen, G.N. Petersen and M. Webster, 2023. Extreme weather and climate events in 2022. In: State of the Climate in 2022. Bulletin of the American Meteorological Society, 104:S285-S287, doi:10.1175/10.1175/BAMS-D-23-0079.1

Boveng, P.L., H.L. Ziel, B.T. McClintock and M.F. Cameron, 2020. Body condition of phocid seals during a period of rapid environmental change in the Bering Sea and Aleutian Islands, Alaska. Deep-Sea Research II, 181-182:104904. doi:10.1016/j.dsr2.2020.104904

Box, J.E., A. Wehrlé, D. van As, R.S. Fausto, K.K. Kjeldsen, A. Dachauer, A.P. Ahlstrøm and G. Picard, 2022. Greenland ice sheet rainfall, heat and albedo feedback impacts from the mid-August 2021 atmospheric river. Geophysical Research Letters, 49:e2021GL097356. doi:10.1029/2021GL097356

Brinkman, T., B. Charles, B. Stevens, B. Wright, S. John, B. Ervin, J. Joe, G. Ninguelook, K. Heeringa, J. Nu, T. Chapin and S. Rasmus, 2022. Changes in sharing and participation are important predictors of the health of traditional harvest practices in indigenous communities in Alaska. Human Ecology, 50:681-695. doi:10.1007/s10745-022-00342-4

C3S, 2023. Greenland heatwaves. In: European State of the Climate 2022. Copernicus Climate Change Service (C3S). https://climate.copernicus.eu/esotc/2022/greenland-heatwaves

Diffenbaugh, N.S., D. Singh, J.S. Mankin, D.E. Horton, D.L. Swain, D. Touma, A. Charland, Y. Liu, M. Haugen, M. Tsiang and B. Rajaratnam, 2017. Quantifying the influence of global warming on unprecedented extreme climate events. Proceedings of the National Academy of Sciences USA, 114:4881-4886, doi:10.1073/pnas.1618082114

Fischer, E., S. Sippel and R. Knutti, 2021. Increasing probability of record-shattering climate extremes. Nature Climate Change, 11:689-695. doi:10.1038/s41558-021-01092-9

Førland, E.J., R.E. Benestad, I. Hanssen-Bauer, J.E. Haugen and T.E. Skaugen, 2011. Temperature and precipitation development at Svalbard 1900–2100. Advances in Meteorology, 2011:893790. doi:10.1155/2011/893790

Fossheim, M., R. Primicerio, E. Johannesen, R.B. Ingvaldsen, M.M. Aschan and A.V. Dolgov, 2015. Recent warming leads to a rapid borealization of fish communities in the Arctic. Nature Climate Change, 5:673-677. doi:10.1038/nclimate2647

Francis, J. and N. Skific, 2015. Evidence linking rapid Arctic warming to mid-latitude weather patterns. Philosophical Transactions of the Royal Society A, 373:20140170. doi:10.1098/rsta.2014.0170

Huang, B., Z. Wang, X. Yin, A. Arguez, G. Graham, C. Liu, T. Smith and H.-M. Zhang, 2021. Prolonged marine heatwaves in the Arctic: 1982–2020. Geophysical Research Letters, 48:e2021GL095590. doi:10.1029/2021GL095590

Huntington, H.P., S.L. Danielson, F.K. Wiese, M. Baker, P. Boveng, J.J. Citta, A. De Robertis, D.M.S. Dickson, E. Farley, J.C. George, K. Iken, D.G. Kimmel, K. Kuletz, C. Ladd, R. Levine, L. Quakenbush, P. Stabeno, K.M. Stafford, D. Stockwell and C. Wilson, 2020. Evidence suggests potential transformation of the Pacific Arctic ecosystem is underway. Nature Climate Change, 10:342-348. doi:10.1038/s41558-020-0695-2

IPCC, 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.). Cambridge University Press, 582 pp.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32, doi:10.1017/9781009157896.001

Isaksen, K., Ø. Nordli, B. Ivanov, M.A.Ø. Køltzow, S. Aaboe, H.M. Gjelten, A. Mezghani, S. Eastwood, E. Førland, R.E. Benestad, I. Hanssen-Bauer, R. Brækkan, P. Sviashchennikov, V. Demin, A. Revina and T. Karandasheva, 2022. Exceptional warming over the Barents area. Scientific Reports, 12:9371. doi:10.1038/s41598-022-13568-5

Landrum, L. and M.M. Holland, 2020. Extremes become routine in an emerging new Arctic. Nature Climate Change, 10:1108-1115. doi:10.1038/s41558-020-0892-z

Lind, S., R.B. Ingvaldsen and T. Furevik, 2018. Arctic warming hotspot in the northern Barents Sea linked to declining sea-ice import. Nature Climate Change, 8:634-639. doi:1038/s41558-018-0205-y

Mattingly, K.S., C.A. Ramseyer, J.J. Rosen, T.L. Mote and R. Muthyala, 2016. Increasing water vapor transport to the Greenland ice sheet revealed using self-organizing maps. Geophysical Research Letters, 43:9250-9258. doi:10.1002/2016gl070424

Moon, T.A., I. Overeem, M. Druckenmiller, M. Holland, H. Huntington, G. Kling, A.L. Lovecraft, G. Miller, T. Scambos, C. Schädel, E.A.G. Schuur, E. Trochim, F. Wiese, D. Williams and G. Wong, 2019. The expanding footprint of rapid Arctic change. Earths Future, 7:212-218. doi:10.1029/2018EF001088

Moore, J. and D. Schindler, 2022. Getting ahead of climate change for ecological adaptation and resilience. Science, 376:1421-1426. doi:10.1126/science.abo3608

Neukermans, G., L. Oziel and M. Babin, 2018. Increased intrusion of warming Atlantic water leads to rapid expansion of temperate phytoplankton in the Arctic. Global Change Biology, 24:2545-2553. doi:10.1111/gcb.14075

Overland, J.E., 2021. Rare events in the Arctic. Climatic Change, 168:27. doi:10.1007/s10584-021-03238-2

Overland, J.E. and M. Wang, 2021. The 2020 Siberian heat wave. International Journal of Climatology, 41:E2341-E2346. doi:10.1002/joc.6850

Overland, J.E., E. Siddon, G. Sheffield, T. Ballinger and C. Szuwalski, 2024. Transformative ecological and human impacts from climate change and diminished sea ice in the northern Bering Sea. Weather, Climate, and Society, 16:303-313. doi:10.1175/WCAS-D-23-0029.1

Polyakov, I., A.V. Pnyushkov, M.B. Alkire, I.M. Ashik, T M. Baumann, E.C. Carmack, I. Goszczko, J. Guthrie, V.V. Ivanov, T. Kanzow, R. Krishfield, R. Kwok, A. Sundfjord, J. Morison, R. Rember and A. Yulin, 2017. Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. Science, 356:285-291. doi:10.1126/science.aai8204

Ramirez, R., 2021. Rain fell at the normally snowy summit of Greenland for the first time on record. https://edition.cnn.com/2021/08/19/weather/greenland-summit-rain-climate-change/index.html

Shepherd, T.G., 2021. Bringing physical reasoning into statistical practice in climate change science. Climatic Change, 169:2. doi:10.1007/s10584-021-03226-6

Shortridge, J., S. Guikema and B. Zaitchik, 2017. Robust decision making in data scarce contexts: addressing data and model limitations for infrastructure planning under transient climate change. Climatic Change, 140:323-337. doi:10.1007/s10584-016-1845-4

Thoman, R. and The Conversation US, 2022. Why Typhoon Merbok Was So Powerful when It Hit Alaska. Scientific American. 19 September 2022. www.scientificamerican.com/article/why-typhoon-merbok-was-so-powerful-when-it-hit-alaska

Thoman, R.L., M.L. Druckenmiller and T.A. Moon, 2023. The Arctic smashed so many terrifying records in 2023, what can we even say? Science Alert. https://www.sciencealert.com/the-arctic-smashed-so-many-terrifying-records-in-2023-what-can-we-even-say

Walsh, J.E., T.J. Ballinger. E.S. Euskirchen, E. Hanna, J. Mård, J.E. Overland, H. Tangen and T. Vihma, 2020. Extreme weather and climate events in northern areas: A review. Earth-Science Reviews, 209:103324. doi:10.1016/j.earscirev.2020.103324

Data references

Data Ref. 3.1 Local Environmental Observer (LEO) Network. https://www.leonetwork.org/en

Parrington, M., J.L. McCarty, J. Aalto, M.A. Crowley, M.D. Flannigan and M.R. Turetsky, 2024. Arctic and high-latitude wildfires. In: AMAP Arctic Climate Change Update 2024: Key Trends and Impacts, pp. 23-29. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://doi.org/10.21352/q5d0-kg43

4. Arctic and high-latitude wildfires

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Key findings

- *Increased numbers of wildfires have been observed in the Arctic region in recent decades due to the fast rate of change in the climate at high northern latitudes driving changes in fuel availability (e.g., poleward expansion of vegetation and permafrost thaw), fire danger (i.e., drier vegetation and fuels, and warmer conditions), and fire behavior following ignition.*
- *Fire occurrence in the Arctic, and more generally at high northern latitudes (north of 60°N), is a common feature each summer but with a high degree of year-to-year variability reflecting human, biogeographical, and hydrometeorological influences. In general, the majority of observed fires occur in regions with human activities and where soil moisture and precipitation levels are below the climatological mean.*
- *Knowledge of ignition sources for Arctic wildfires has improved in recent years, with better understanding and observational evidence of human-caused and natural ignitions. Improved capabilities for detecting holdover fires and lightning ignitions, and incorporation of Indigenous knowledge are both essential to understanding wildfires in the Arctic under a changing climate.*
- *Emerging research and novel monitoring technologies (e.g., new satellites and developments using artificial intelligence) are providing further insight into the relative roles of human and non-human ignition sources, available fuel types (including peat and high carbon soil) and fuel conditions, as well as into fire behavior across the region which is essential to monitoring/modeling current/future vulnerability of the Arctic and high northern latitudes to wildfires.*

4.1 Introduction

Wildfires in the Arctic have received widespread media attention around the world in recent years as well as within the scientific community. Wildfires are a relatively common feature of the high northern latitude boreal forests, especially during summer, and have shown some degree of poleward migration over the past two decades, particularly during the summers of 2019 and 2020 (C3S, 2020, 2021), 2023 (C3S, 2024; Jain et al., 2024) and 2024. At high northern latitudes (i.e., latitudes north of 60°N), wildfires are not uncommon and have shown a high degree of spatial and temporal variability in recent years (Masrur et al., 2018) and in projected future manifestations of wildfires (e.g., Krawchuk et al., 2009; UNEP, 2022). A detailed synthesis of wildfires in the Arctic was presented by McCarty et al. (2021), covering the drivers, future climate change impacts, estimated emissions, fire management, and knowledge gaps for pan-Arctic and pan-boreal fires. A study of extreme wildfires around the world between 2003 and 2023 based on satellite observations showed that the largest (more than four-fold) regional increase was in the northeast Arctic (Cunningham et al., 2024). Spatial variability in the pyrogeography of pan-Arctic and pan-boreal wildfires is influenced by varying responses to environmental drivers and interactions with anthropogenic and other factors, which recent studies have started to identify in more detail (e.g., Scholten et al., 2024). Arctic wildfires in recent years have burned persistently through the summer months and covered vast areas. Figure 4.1 shows example satellite imagery of active fire fronts extending over many kilometers in Russia's Sakha Republic during July 2020. This chapter presents an overview of recent research on Arctic wildfires, including changes in wildfire risk, climate interactions and air quality impacts, and a brief synthesis of observed wildfire emissions in recent years.

4.2 Wildfire risk

The Arctic climate has been warming at three times the rate of the global average (i.e., the Arctic amplification) (AMAP, 2021; see also Chapter 2). The warming climate, and associated impacts on precipitation and soil moisture, increases the likelihood (or risk) of landscape fires through increased flammability of the vegetation (Descals et al., 2022), with higher risk also leading to the potential for larger-scale and more persistent fires after there has been an ignition. Thawing of permafrost can also expose further fuel, including peat and areas with high soil carbon (Post and Mack, 2022), further complicating wildfire behavior, estimation of emissions, and climate feedbacks. Although the underlying vegetation conditions may be ideal for widespread fires, the actual occurrence at the large scale is related to the synoptic meteorological conditions which can also be related to the position of the polar jet stream (e.g., Mann, 2019; Strigunova et al., 2022). For example, the influence of the polar jet stream on early seasonal snowmelt was a factor in the scale of the fires observed in both Arctic and subarctic regions of Siberia during 2019, 2020, and 2021 (Scholten et al., 2022). Further, boreal and subarctic areas are currently experiencing and are likely to continue to experience heightened fire weather conditions, as increased temperature, decreased relative humidity, and increased Vapour Pressure Deficit (i.e., whereby high VPD values caused by high temperatures and a dry airmass over an extended period result in drier fuels) are driving wildland fire trends (Lehtonen et al., 2016; Ellis et al., 2021; Jain et al., 2021; Scholten et al., 2024). Furthermore, a potential increase and poleward shift in high-latitude lightning activity as a result of climate change could lead to increased wildfire ignitions in the Arctic, which are projected to more than double under the RCP8.5 scenario (Chen et al., 2021a; OECD, 2023), in line with recent findings for extra-tropical wildfires (Janssen et al., 2023).

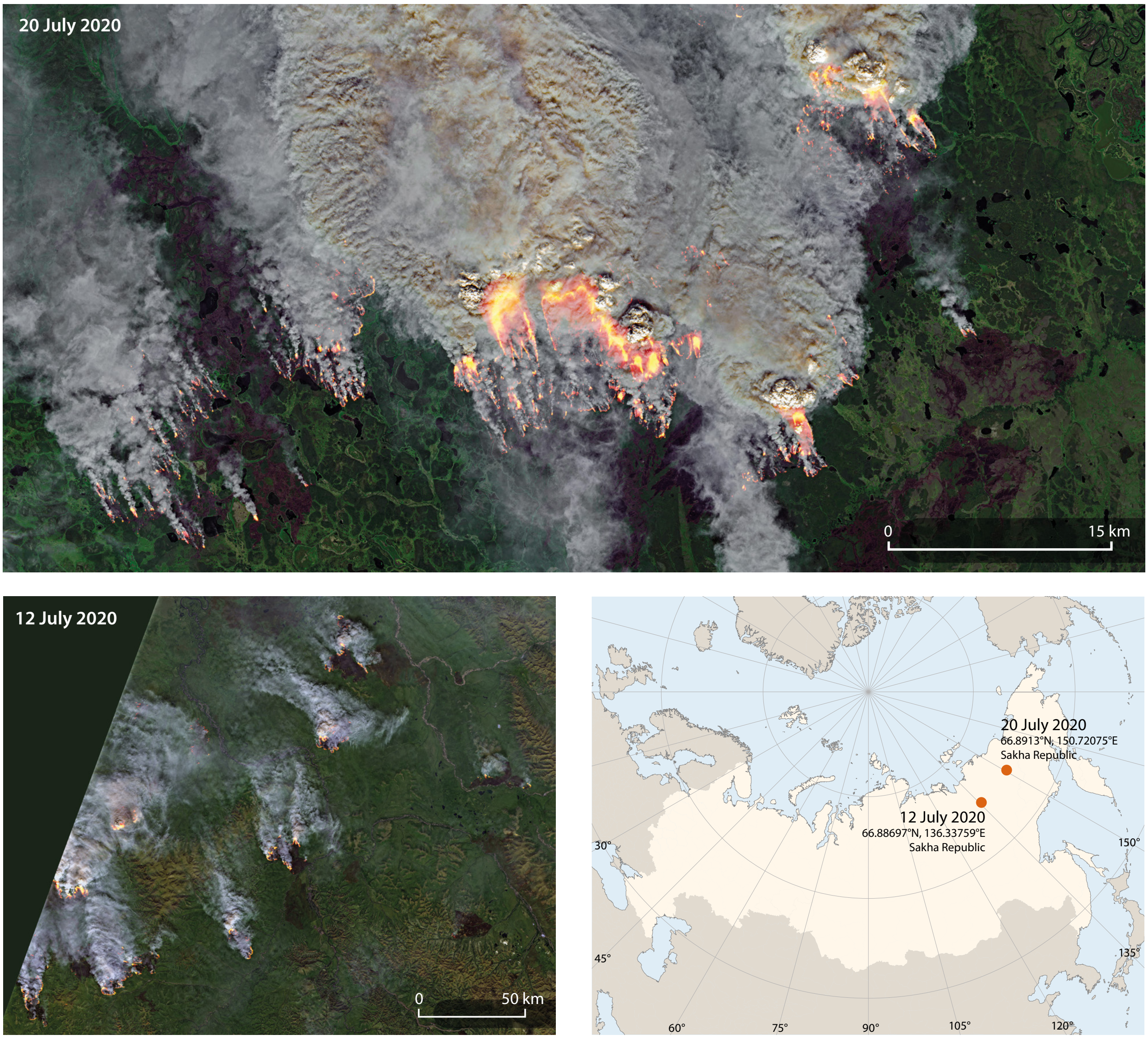

Figure 4.1 Multiple wildfires around the Arctic Circle during July 2020 in the Sakha Republic, Russia. Enhanced natural colors/infra-red (IR) mix with IR hotspots. Contains modified Copernicus Sentinel data processed by Pierre Markuse.

4.3 Interactions with climate

The impacts of Arctic warming on the environment, and their relationship with wildfire activity in the region are complex. For example, a general 'greening' trend of the Arctic (Berner et al., 2020; Myers-Smith et al., 2020) with poleward expansion of vegetation (Vowles and Björk, 2019), and permafrost thaw (Heijmans et al., 2022) can lead to more non-herbaceous surface fuels being available to burn (Arndt et al., 2019; Mekonnen et al., 2021) – with region-specific impacts that could both impede and facilitate fire spread across shrubby areas in the Low Arctic (Frost et al., 2020). With regards to permafrost thaw, fire activity influences the rate at which this happens in complex ways (Holloway et al., 2020). Fires alter the surface albedo (French et al., 2016; Webb et al., 2021) and accelerate permafrost thaw and thermokarst formation (Holloway et al., 2020; Chen et al., 2021b) primarily by combusting the litter, moss, peat layers, and other burnable biomass that insulate frozen soil. Post-fire changes in vegetation in permafrost regions can alter the soil thermal regime and lead to thawing due to loss of shading, loss of the insulating layer, and change in landscape-level snow-cover extent that impacts terrestrial albedo feedbacks for the Arctic and boreal regions (Webb et al., 2021). Post-fire vegetation may also alter the rate of carbon sequestration, and play a role in fire self-regulation if it is less flammable (e.g., Mack et al., 2021). In contrast, while fire has been identified as a major driver of permafrost thaw (Gibson et al., 2018), an open question in this respect is whether this will cause stronger positive feedbacks on the climate, such as through the release of carbon and greenhouse gases (carbon dioxide and methane) that had been locked in the ground in peat (Turetsky et al., 2020; Schuur et al., 2022), leading to changes in biomes and post-fire vegetation regrowth (Kharuk et al., 2022). Some of the thaw-driven carbon released to the atmosphere will be reabsorbed by increased vegetation productivity (Mekonnen et al., 2021). Further to the impacts on climate, permafrost thaw is also likely to have complex impacts on fire danger. In areas with ice-poor permafrost, thaw can lead to drier soils and fuels and may possibly promote tree productivity (Ogden et al., 2023). However, in areas underlain by ice-rich permafrost, thaw can lead to subsidence and localized flooding that may have the opposite effect on fire danger.

4.4 Wildfires and air quality

In addition to the biogeophysical changes to the landscape, wildfires at high latitudes are of concern for the Arctic region due to the impact of smoke transport on air quality and climate. Particulate matter, especially $PM_{2.5}$ (particulate matter with a mean diameter of less than 2.5 µm), is of particular concern owing to its role in degrading air quality, with potentially severe health impacts for Arctic communities (Schmale et al., 2018). Such impacts are not confined to physical symptoms and there is growing evidence of mental health impacts related to displacement and smoke exposure following wildfires which can lead to more cases of anxiety and post-traumatic stress disorder (e.g., Humphreys et al., 2022). Particulate matter such as black (and brown) carbon, or soot, is also a short-lived climate forcer, with potential contributions to local increases in air temperature and deposition to snow/ice packs, altering the albedo and increasing melt rates (AMAP, 2015; DeRepentigny et al., 2022). Wildfires emit a wide range of atmospheric pollutants which can influence regional atmospheric chemistry and result in additional air quality and environmental impacts. Arctic wildfires are known sources of atmospheric mercury (Dastoor et al., 2022) and volatile organic compounds (Wizenberg et al., 2023). The potential for air quality and climate impacts of wildfire smoke is generally much greater with closer proximity to wildfire occurrence, as has been reported for larger population centers of Alaska (Hahn et al., 2021) and the Sakha Republic (Tomshin and Solovyev, 2022). A study focused on the eight Arctic countries found that $PM_{2.5}$ from wildfires mostly affects remote populations close to the fires (Silver et al., 2024). However, health impacts across these countries were seen to decrease across the region, despite increasing regional levels of $PM_{2.5}$ from wildfires, due to the northward shift of wildfires, particularly in Siberia, and thus reduced impacts on the more densely populated areas (Silver et al., 2024). Wildfires at extra-tropical, and even tropical latitudes, also have the potential to affect the High Arctic and to impact larger urban centers in the boreal and temperate zones through long-range transport. Long-range smoke transport tends to occur at high altitudes due to increased atmospheric lifetimes of pollutants and stronger winds, and potential surface impacts are reduced. Many examples of long-range smoke transport into the Arctic region have been covered in the scientific literature, including spring-time transport from Southeast Asia (Dupont et al., 2012), summer-time transport from boreal regions (e.g., Stohl et al., 2006; Paris et al., 2009), and surface deposition at elevation on the Greenland Ice Sheet (Thomas et al., 2017).

4.5 Monitoring techniques and datasets

Earth observation satellites have been providing global-scale measurements related to wildfires since the 1970s. Many different sensors have provided information on burned areas and the radiative energy of active fires, such as the Moderate Resolution Imaging Spectroradiometer (MODIS, on the NASA Terra and Aqua satellites), the Visible Infrared Imaging Radiometer Suite (VIIRS, on NOAA satellites), and the Sea and Land Surface Temperature Radiometer (SLSTR, on the European Copernicus Sentinel-3 satellites) instruments currently providing the wildfire observations from polar-orbiting satellites. Of particular note is the two-decade dataset of active fire observations provided by the MODIS instruments on the NASA Terra and Aqua satellites, which provide measurements during mid-morning and early afternoon each day. The active fire observations are available in near-real-time, allowing for a rapid assessment of the scale of Arctic wildfires through the observed fire radiative power (FRP) and estimated emissions of smoke pollutants (including particulate matter, volatile organic compounds, carbon and greenhouse gases). A number of datasets provide long-term information on fire emissions using these satellite observations. This report considers estimated fire emissions of carbon from the combined Terra and Aqua MODIS observations by the Global Fire Assimilation System v1.2 (GFASv1.2; Kaiser et al., 2012), from the Copernicus Atmosphere Monitoring Service (CAMS).

4.6 Wildfire occurrence and emissions

The geographical distribution of high latitude wildfires varies from year to year. Figure 4.2 shows some of the approximate shifts in wildfire occurrence within the Arctic Circle and illustrates the shift from North America between 2003 and 2009 to Eurasia in the 2010s and 2020s (with most fires occurring in 2019 and 2020). Figure 4.3 shows the annual total estimated wildfire carbon emissions from the Arctic and subarctic latitudes. The scale of the fire emissions from Arctic latitudes in 2019 and 2020 (~35 and 60 million tonnes of carbon, respectively) clearly stands out, with the 2021 and 2022 emissions returning to more typical values, below 20 million tonnes of carbon. Table 4.1 summarizes the Arctic and subarctic wildfire emissions for each of the past three decades. For the Arctic, subarctic and combined regions, the mean annual total emissions increased in each subsequent decade, with the total estimated emissions for 2020–2024 already higher than the total for 2003–2009. The post-2020 reduction in emissions reflects the return to less intense regional temperature and soil moisture anomalies at Arctic latitudes in Eurasia (McCarty et al., 2021; C3S, 2022). However, summer 2021 was notable for large-scale wildfires at subarctic boreal latitudes in both North America and Eurasia simultaneously, leading to the highest estimated fire

Table 4.1 Estimated carbon emissions from wildfires north of 60°N for the years available in each of the past three decades based on Terra and Aqua MODIS active fire observations assimilated in the Global Fire Assimilation System (GFASv1.2). Source: Copernicus Atmosphere Monitoring Service / European Centre for Medium-Range Weather Forecasts (Data ref. 4.1).

Region	Mean (sum) annual total wildfire carbon emissions, 10^6 t C		
	2003–2009	2010–2019	2020–2024
Arctic (66.6–90°N)	7.9 (55.3)	10.4 (103.9)	24.7 (123.6)
Subarctic (60–66.6°N)	61.9 (433.5)	94.1 (941.4)	142.0 (709.8)
Arctic + Subarctic (60–90°N)	69.8 (488.8)	104.5 (1045.3)	166.7 (833.4)

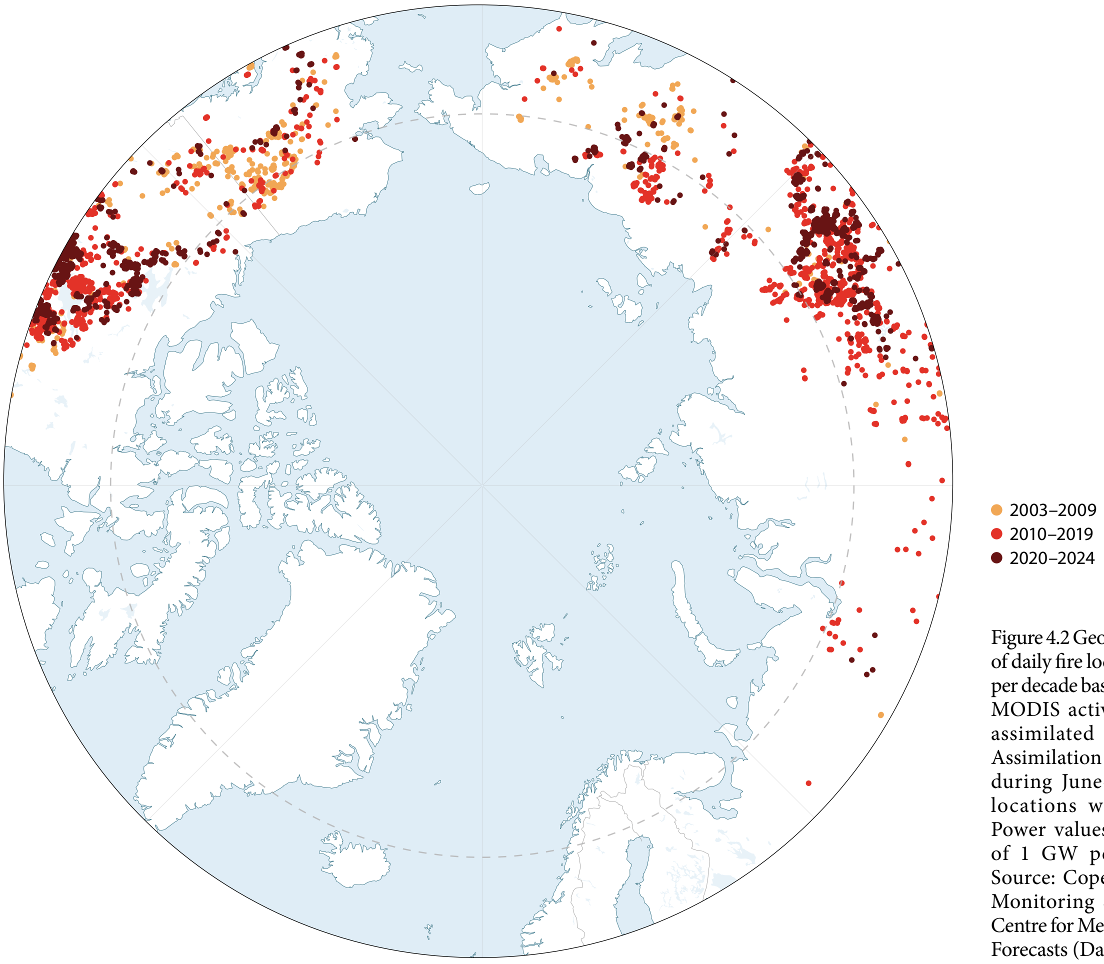

Figure 4.2 Geographical distribution of daily fire locations north of 60°N per decade based on Terra and Aqua MODIS active fire observations assimilated in the Global Fire Assimilation System (GFASv1.2) during June-July-August. Only locations with Fire Radiative Power values above a threshold of 1 GW per day are shown. Source: Copernicus Atmosphere Monitoring Service / European Centre for Medium-Range Weather Forecasts (Data ref. 4.1).

emissions anomaly of the past two decades worldwide (Zheng et al., 2023). The 2021 fires occurred in a widespread area of anomalously low soil moisture centered on the Sakha Republic of Russia, which resulted in persistent fires for several weeks and a significant long-range transport episode of smoke across the Arctic Ocean and North Pole (C3S, 2022). Summer 2022 saw significantly reduced numbers of wildfires and associated emissions in the Eurasian Arctic region with fire mostly occurring in Alaska and the Yukon and the Northwest Territories of Canada (C3S, 2023). High-latitude wildfires increased in 2023 following a prolonged period of persistent large-scale wildfires which burned across Canada between May and September, producing high-profile long-range transport of smoke to the temperate regions of Canada and the United States (Jain et al., 2024). Many of the wildfires in Canada, particularly in the Northwest Territories, occurred at high latitudes north of 60°N and produced emissions that were estimated to account for 20% to 30% of the global total wildfire emissions for the year (C3S, 2024; Jain et al., 2024; Kolden et al., 2024). The early summer of 2024 witnessed an increase in the number and estimated emissions of wildfires in the Arctic Circle, particularly in the Sakha Republic. The monthly total estimated emissions for June 2024 were the third highest, behind 2019 and 2020, of the past two decades and followed a period of anomalously high surface air temperatures and low soil moisture in that region. Additional high latitude wildfires also occurred in early summer 2024 in subarctic regions of North America, notably Alaska, Yukon Territory, Northwest Territories and northeastern British Columbia.

Emerging research on Arctic fires has been to identify the potential for fires from one year to re-emerge as an ignition source for wildfires and/or a continuing wildfire in the following year (McCarty et al., 2020; Scholten et al., 2021; Xu et al., 2022). The occurrence of holdover fires (sometimes referred to as overwintering fires), and their contribution to larger fires in the Arctic is challenging to quantify. Recent research into the application of satellite observations has shown improved prospects for identifying such fires, indicating a contribution of between 3% and 7% of the burned area in eastern Siberia (Xu et al., 2022) and a correlation of the occurrence following years with the highest burned area values (McCarty et al., 2021; Scholten et al., 2022).

As Arctic temperatures continue to increase at a faster rate than the rest of the planet, the prospect of large-scale persistent wildfires, such as those of 2019 and 2020 (C3S, 2020, 2021) will remain high. One positive factor of the raised profile of Arctic wildfires is acknowledging the role of Indigenous knowledge of fire behavior and fire management practices. A review of the relationship between Indigenous Peoples and wildfires across boreal North America (Christianson et al., 2022) provides historical context for this and indicates the need for better integration of Indigenous practices in understanding fires and improving management and decision-making around wildfires.

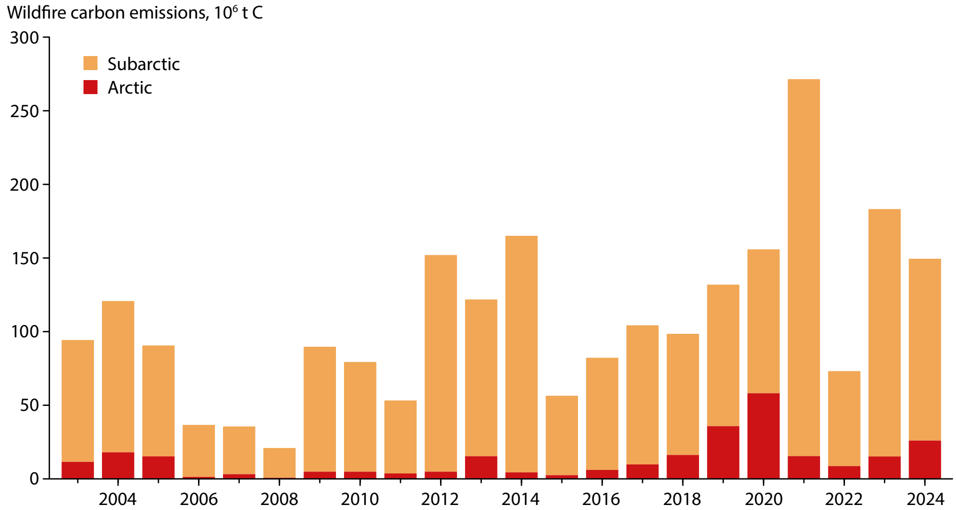

Figure 4.3 Annual total estimated carbon emissions from wildfires north of 60°N from 2003 to 2024, showing the relative contributions of subarctic (60–66.6°N) and Arctic (66.6–90°N) fires based on Terra and Aqua MODIS active fire observations assimilated in the Global Fire Assimilation System (GFASv1.2). Source: Copernicus Atmosphere Monitoring Service / European Centre for Medium-Range Weather Forecasts (Data ref. 4.1).

4.7 Conclusions

The occurrence and impacts of wildfires in the Arctic reflect the culmination of many complex interactions between human, biogeographical, and hydrometeorological factors. With the current rate of climate change, close monitoring of the Arctic region is essential for gaining a better understanding of the processes involved. Much knowledge has been accumulated on fuel types and conditions, fire types (surface, crown, or ground fires) and the role of surface and atmospheric climate states in relation to Arctic fires. Furthermore, monitoring is essential for evaluating the health and climate impacts of wildfire smoke originating from and transported to Arctic regions.

Fire regimes, which can generally be defined in terms of fire frequency, seasonality, type, typical size and severity, and ignition types (Hanes et al., 2019), are complex and require multi-disciplinary research. Integrated modeling of future wildfires in the boreal and Arctic regions will, likewise, need to account for socio-biogeographical and hydrometeorological variables in addition to natural and human-caused drivers of fire ignitions. Fire regimes will vary across Arctic and boreal landscapes and research needs, including modeling frameworks, for addressing these knowledge gaps must be able to take these complexities into consideration. For example, what is considered an extreme fire for Greenland, such as the 2017 and 2019 wildfires (Evangeliou et al., 2019), might not be considered extreme for tundra regions of North America and Siberia. Similarly, fire management and stewardship practices vary across Arctic and boreal landscapes. Improving how the scientific community monitors, quantifies, and integrates the changing policy and management landscapes of cultural Indigenous burning, prescribed fires, fire prevention / fuel breaks / suppression, and wildfire dynamics in diverse Arctic and boreal landscapes will be necessary to build improved next-generation models of biogeophysical processes that may be used to inform decision-makers and local communities.

References

Text references

AMAP, 2015. AMAP Assessment 2015: Black carbon and ozone as Arctic climate forcers. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii+116 pp.

AMAP, 2021. AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. viii+148pp.

Arndt, K.A., M.J. Santos, S. Ustin, S.J. Davidson, D. Stow, W.C. Oechel, T.T.P. Tran, B. Graybill and D. Zon, 2019. Arctic greening associated with lengthening growing seasons in Northern Alaska. Environmental Research Letters, 14:125018. doi:10.1088/1748-9326/ab5e26

Berner, L., R. Massey, P. Jantz, B.C. Forbes, M. Macias-Fauria, I. Myers-Smith, T. Kumpula, G. Gauthier, L. Andreu-Hayles, B.V. Gaglioti, P. Burns, P. Zetterberg, R. D'Arrigo and S.J. Goetz, 2020. Summer warming explains widespread but not uniform greening in the Arctic tundra biome. Nature Communications, 11:4621. doi:10.1038/s41467-020-18479-5

C3S, 2020. European State of the Climate 2019. Copernicus Climate Change Service (C3S), Full report: https://climate.copernicus.eu/ESOTC/2019

C3S, 2021. European State of the Climate 2020, Copernicus Climate Change Service (C3S), Full report: climate.copernicus.eu/ESOTC/2020

C3S, 2022. European State of the Climate 2021. Copernicus Climate Change Service (C3S), Full report: climate.copernicus.eu/ESOTC/2021

C3S, 2023. European State of the Climate 2022. Copernicus Climate Change Service (C3S), Full report: climate.copernicus.eu/ESOTC/2022

C3S, 2024. European State of the Climate 2023. Copernicus Climate Change Service (C3S), Full report: climate.copernicus.eu/ESOTC/2023

Chen, Y., D.M. Romps, J.T. Seeley, S. Veraverbeke, W.J. Riley, Z.A. Mekonnen and J.T. Randerson, 2021a. Future increases in Arctic lightning and fire risk for permafrost carbon. Nature Climate Change, 11:404-410. doi:10.1038/s41558-021-01011-y

Chen, Y., M.J. Lara, B.M. Jones, G.V. Frost and F.S. Hu, 2021b. Thermokarst acceleration in Arctic tundra driven by climate change and fire disturbance. One Earth, 4:1718-1729. doi:10.1016/j.oneear.2021.11.011

Christianson, A.C., C.R. Sutherland, F. Moola, N.G. Bautista, D. Young and H. MacDonald, 2022. Centering indigenous voices: The role of fire in the boreal forest of North America. Current Forestry Reports, 8:257-276. doi:10.1007/s40725-022-00168-9

Cunningham, C.X., G.J., Williamson and D.M.J.S. Bowman, 2024. Increasing frequency and intensity of the most extreme wildfires on Earth. Nature Ecology and Evolution, 8:1420-1425. doi:10.1038/s41559-024-02452-2

Dastoor, A., S.J. Wilson, O. Travnikov, A. Ryjkov, H. Angot, J.H. Christensen, F. Steenhuisen and M. Muntean, 2022. Arctic atmospheric mercury: Sources and changes. Science of The Total Environment, 839:156213. doi:10.1016/j.scitotenv.2022.156213

DeRepentigny, P., A. Jahn, M.M. Holland, J.E. Kay, J. Fasullo, J.-F. Lamarque, S. Tilmes, C. Hannay, M.J. Mills, D.A. Bailey and A.P. Barre, 2022. Enhanced simulated early 21st century Arctic sea ice loss due to CMIP6 biomass burning emissions. Science Advances, 8:30 doi:10.1126/sciadv.abo2405

Descals, A., D.L.A. Gaveau, A. Verger, D. Sheil, D. Naito and J. Peñuelas, 2022. Unprecedented fire activity above the Arctic Circle linked to rising temperatures. Science, 378:532-537. doi:10.1126/science.abn9768

Dupont, R., B. Pierce, J. Worden, J. Hair, M. Fenn, P. Hamer, M. Natarajan, T. Schaack, A. Lenzen, E. Apel, J. Dibb, G. Diskin, G. Huey, A. Weinheimer, Y. Kondo and D. Knapp, 2012. Attribution and evolution of ozone from Asian wild fires using satellite and aircraft measurements during the ARCTAS campaign. Atmospheric Chemistry and Physics, 12:169-188. doi:10.5194/acp-12-169-2012

Ellis, T.M., D.M.J.S. Bowman, P. Jain, M.D. Flannigan and G.J. Williamson, 2021. Global increase in wildfire risk due to climate-driven declines in fuel moisture. Global Change Biology, 28:1544-1559. doi:10.1111/gcb.16006

Evangeliou, N., A. Kylling, S. Eckhardt, V. Myroniuk, K. Stebel, R. Paugam, S. Zibtsev and A. Stohl, 2019. Open fires in Greenland in summer 2017: transport, deposition and radiative effects of BC, OC and BrC emissions. Atmospheric Chemistry and Physics, 19:1393-1411. doi:10.5194/acp-19-1393-2019

French, N.H., M.A. Whitley and L.K. Jenkins, 2016. Fire disturbance effects on land surface albedo in Alaskan tundra. Journal of Geophysical Research: Biogeosciences, 121:841-854. doi:10.1002/2015JG003177

Frost, G.V., R.A. Loehman, L.B. Saperstein, M.J. Macander, P.R. Nelson, D.P. Paradis and S.M Natali, 2020. Multi-decadal patterns of vegetation succession after tundra fire on the Yukon-Kuskokwim Delta, Alaska. Environmental Research Letters, 15:025003. doi:10.1088/1748-9326/ab5f49

Gibson, C.M., L.E. Chasmer, D.K. Thompson, W.L. Quinton, M.D. Flannigan and D. Olefeldt, 2018. Wildfire as a major driver of recent permafrost thaw in boreal peatlands. Nature Communications, 9:3041. doi:10.1038/s41467-018-05457-1

Hahn, M.B., G. Kuiper, K. O'Dell, E.V. Fischer and S. Magzamen, 2021. Wildfire smoke is associated with an increased risk of cardiorespiratory emergency department visits in Alaska. GeoHealth, 5:e2020GH000349. doi:10.1029/2020GH000349

Hanes, C.C., X. Wang, P. Jain, M.-A. Parisien, J.M. Little and M.D. Flannigan, 2019. Fire-regime changes in Canada over the last half century. Canadian Journal of Forest Research. 49:256-269. doi:10.1139/cjfr-2018-0293

Heijmans, M.M.P.D., R.Í. Magnússon, M.J. Lara, G.V. Frost, I.H. Myers-Smith, J. van Huissteden, M.T. Jorgenson, A.N. Fedorov, H.E. Epstein, D.M. Lawrence and J. Limpens, 2022. Tundra vegetation change and impacts on permafrost. Nature Reviews Earth & Environment, 3:68-84. doi:10.1038/s43017-021-00233-0

Holloway, J.E., A.G. Lewkowicz, T.A. Douglas, X. Li, M.R. Turetsky, J.L. Baltzer and H. Jin, 2020. Impact of wildfire on permafrost landscapes: A review of recent advances and future prospects. Permafrost and Periglacial Processes, 31:371-382. doi:10.1002/ppp.2048

Humphreys, A., E.G. Walker, G.N. Bratman and N.A. Errett, 2022. What can we do when the smoke rolls in? An exploratory qualitative analysis of the impacts of rural wildfire smoke on mental health and wellbeing, and opportunities for adaptation. BMC Public Health, 22:41. doi:10.1186/s12889-021-12411-2

Jain, P., D. Castellanos-Acuna, S.C.P. Coogan, J.T. Abatzoglou and M.D. Flannigan, 2021. Observed increases in extreme fire weather driven by atmospheric humidity and temperature. Nature Climate Change, 12:63-70. doi:10.1038/s41558-021-01224-1

Jain, P., Q.E. Barber, S. Taylor, E. Whitman, D. Castellanos Acuna, Y. Boulanger, R.D. Chavardès, J. Chen, P. Englefield, M. Flannigan, M.P. Girardin, C.C. Hanes, J. Little, K. Morrison, R.S. Skakun, D.K. Thompson, X. Wang and M.-A. Parisien, 2024. Drivers and impacts of the record-breaking 2023 wildfire season in Canada. Nature Communications, 15:6764. doi:10.1038/s41467-024-51154-7

Janssen, T.A.J., M.W. Jones, D. Finney, G.R. van der Werf, D. van Wees, W. Xu and S. Veraverbeke, 2023. Extratropical forests increasingly at risk due to lightning fires. Nature Geoscience, 16:1136-1144. doi:10.1038/s41561-023-01322-z

Kaiser, J.W., A. Heil, M.O. Andreae, A. Benedetti, N. Chubarova, L. Jones, J.-J. Morcrette, M. Razinger, M.G. Schultz, M. Suttie and G.R. van der Werf, 2012. Biomass burning emissions estimated with a global fire assimilation system based on observed fire radiative power. Biogeosciences, 9:527-554. doi:10.5194/bg-9-527-2012

Kharuk, V.I., M.L. Dvinskaya, S.T. Im, A.S. Golyukov and K.T. Smith, 2022. Wildfires in the Siberian Arctic. Fire, 5:106. doi:10.3390/fire5040106

Kolden, C.A., J.T. Abatzoglou, M.W. Jones and P. Jain, 2024. Wildfires in 2023. Nature Reviews Earth & Environment, 5:238-240. doi:10.1038/s43017-024-00544-y

Krawchuk, M.A., M.A. Moritz, M.-A. Parisien, J. Van Dorn and K. Hayhoe, 2009. Global pyrogeography: The current and future distribution of wildfire. PLoS ONE 4:e5102. doi:10.1371/journal.pone.0005102

Lehtonen, I., A. Venäläinen, M. Kämäräinen, H. Peltola and H. Gregow, 2016. Risk of large-scale fires in boreal forests of Finland under changing climate. Natural Hazards and Earth System Sciences, 16:239-253. doi:10.5194/nhess-16-239-2016

Mack, M.C., X.J. Walker, J.F. Johnstone, H.D. Alexander, A.M. Melvin, M. Jean and S.N. Miller, 2021. Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees. Science, 372:280-283. doi:10.1126/science.abf3903

Mann, M.E., 2019. The weather amplifier. Scientific American, 320:42-49. www.jstor.org/stable/27265110

Masrur, A., A.N. Petrov and J. DeGroote, 2018. Circumpolar spatio-temporal patterns and contributing climatic factors of wildfire activity in the Arctic tundra from 2001–2015. Environmental Research Letters, 13:014019. doi:10.1088/1748-9326/aa9a76

McCarty, J.L., T.E.L. Smith and M.R. Turetsky, 2020. Arctic fires re-emerging. Nature Geoscience, 13:658-660. doi:10.1038/s41561-020-00645-5

McCarty, J.L., J. Aalto, V.-V. Paunu, S.R. Arnold, S. Eckhardt, Z. Klimont, J.J. Fain, N. Evangeliou, A. Venäläinen, N.M. Tchebakova, E.I. Parfenova, K. Kupiainen, A.J. Soja, L. Huang and S. Wilson, 2021. Reviews and syntheses: Arctic fire regimes and emissions in the 21st century. Biogeosciences, 18:5053-5083. doi:10.5194/bg-18-5053-2021

Mekonnen, Z.A., W.J. Riley, L.T. Berner, N.J. Bouskill, M.S. Torn, G. Iwahana, A.L. Breen, I.H. Myers-Smith, M.G. Criado, Y. Liu, E.S. Euskirchen, S.J. Goetz, M.C. Mack and R.F. Grant, 2021. Arctic tundra shrubification: a review of mechanisms and impacts on ecosystem carbon balance. Environmental Research Letters, 16:5. doi:10.1088/1748-9326/abf28b

Myers-Smith, I.H., J.T. Kerby, G.K. Phoenix, J.W. Bjerke, H.E. Epstein, J.J. Assmann, C. John, L. Andreu-Hayles, S. Angers-Blondin, P.S.A. Beck, L.T. Berner, U.S. Bhatt, A.D. Bjorkman, D. Blok, A. Bryn, C.T. Christiansen, J.H.C. Cornelissen, A.M. Cunliffe, S.C. Elmendorf, B.C. Forbes, S.J. Goetz, R.D. Hollister, R. de Jong, M.M. Loranty, M. Macias-Fauria, K. Maseyk, S. Normand, J. Olofsson, T.C. Parker, F.-J.W. Parmentier, E. Post, G. Schaepman-Strub, F. Stordal, P.F. Sullivan, H.J.D. Thomas, H. Tømmervik, R. Treharne, C.E. Tweedie, D.A. Walker, M. Wilmking and S. Wipf, 2020. Complexity revealed in the greening of the Arctic. Nature Climate Change, 10:106-117. doi:10.1038/s41558-019-0688-1

OECD, 2023. Understanding wildfire risk in a changing climate. In: Taming Wildfires in the Context of Climate Change. Organisation for Economic Co-operation and Development (OECD). OECD Publishing, Paris. doi:10.1787/ff787015-en

Ogden, E.L., S.G. Cumming, S.L. Smith, M.R. Turetsky and J.L. Baltzer, 2023. Permafrost thaw induces short-term increase in vegetation productivity in northwestern Canada. Global Change Biology, 29:5352-5366. doi:10.1111/gcb.16812

Paris, J.-D., A. Stohl, P. Nédélec, M.Yu. Arshinov, M.V. Panchenko, V.P. Shmargunov, K.S. Law, B.D. Belan and P. Ciais, 2009. Wildfire smoke in the Siberian Arctic in summer: source characterization and plume evolution from airborne measurements. Atmospheric Chemistry and Physics, 9:9315-9327. doi:10.5194/acp-9-9315-2009

Post, E. and M.C. Mack, 2022. Arctic wildfires at a warming threshold. Science, 378:470-471. doi:10.1126/science.ade9583

Schmale, J., S.R. Arnold, K.S. Law, T. Thorp, S. Anenberg, W.R. Simpson, J. Mao and K.A. Pratt, 2018. Local Arctic air pollution: a neglected but serious problem. Earth's Future, 6:1385-1412. doi:10.1029/2018EF000952

Scholten, R.C., R. Jandt, E.A. Miller, B.M. Rogers and S. Veraverbeke, 2021. Overwintering fires in boreal forests. Nature, 593:399-404. doi:10.1038/s41586-021-03437-y

Scholten, R.C., D. Coumou, F. Luo and S. Veraverbeke, 2022. Early snowmelt and polar jet dynamics co-influence recent extreme Siberian fire seasons. Science, 378:1005-1009. doi:10.1126/science.abn4419

Scholten, R.C., S. Veraverbeke, Y. Chen and J.T. Randerson, 2024. Spatial variability in Arctic–boreal fire regimes influenced by environmental and human factors. Nature Geoscience, 17:866-873. doi:10.1038/s41561-024-01505-2

Schuur, E.A.G., B.W. Abbott, R. Commane, J. Ernakovich, E. Euskirchen, G. Hugelius, G. Grosse, M. Jones, C. Koven, V. Leshyk, D. Lawrence, M.M. Loranty, M. Mauritz, D. Olefeldt, S. Natali, H. Rodenhizer, V. Salmon, C. Schädel, J. Strauss, C. Treat and M. Turetsky, 2022. Permafrost and climate change: carbon cycle feedbacks from the warming Arctic. Annual Review of Environment and Resources, 47:343-371. doi:10.1146/annurev-environ-012220-011847

Silver, B., S.R. Arnold, C.L. Reddington, L.K. Emmons and L. Conibear, 2024. Large transboundary health impact of Arctic wildfire smoke. Communications Earth and Environment, 5:199. doi:10.1038/s43247-024-01361-3

Stohl, A., E. Andrews, J.F. Burkhart, C. Forster, A. Herber, S.W. Hoch, D. Kowal, C. Lunder, T. Mefford, J.A. Ogren, S. Sharma, N. Spichtinger, K. Stebel, R. Stone, J. Ström, K. Tørseth, C. Wehrli and K.E. Yttri, 2006. Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004. Journal of Geophysical Research: Atmospheres, 111:D22. doi:10.1029/2006JD007216

Strigunova, I., R. Blender, F. Lunkeit and N. Žagar, 2022. Signatures of Eurasian heat waves in global Rossby wave spectra. Weather and Climate Dynamics, 3:1399-1414. doi:10.5194/wcd-3-1399-2022

Thomas, J.L., C.M. Polashenski, A.J. Soja, L. Marelle, K.A. Casey, H.D. Choi, J.-C. Raut, C. Wiedinmyer, L.K. Emmons, J.D. Fast, J. Pelon, K.S. Law, M.G. Flanner and J.E. Dibb, 2017. Quantifying black carbon deposition over the Greenland ice sheet from forest fires in Canada. Geophysical Research Letters, 44:7965-7974. doi:10.1002/2017GL073701

Tomshin, O. and V. Solovyev, 2022. Features of the extreme fire season of 2021 in Yakutia (Eastern Siberia) and heavy air pollution caused by biomass burning. Remote Sensing, 14:4980. doi:10.3390/rs14194980

Turetsky, M.R., B.W. Abbott, M.C. Jones, K.W. Anthony, D. Olefeldt, E.A.G. Schuur, G. Grosse, P. Kuhry, G. Hugelius, C. Koven, D.M. Lawrence, C. Gibson, A.B.K. Sannel and A.D. McGuire, 2020. Carbon release through abrupt permafrost thaw. Nature Geoscience, 13:138-143. doi:10.1038/s41561-019-0526-0

UNEP, 2022. Spreading like Wildfire: The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. United Nations Environment Programme (UNEP). www.unep.org/resources/report/spreading-wildfire-rising-threat-extraordinary-landscape-fires

Vowles, T. and R.G. Björk, 2019. Implications of evergreen shrub expansion in the Arctic. Journal of Ecology, 107:650-655. doi:10.1111/1365-2745.13081

Webb, E.E., M.M. Loranty and J.W. Lichstein, 2021. Surface water, vegetation, and fire as drivers of the terrestrial Arctic-boreal albedo feedback. Environmental Research Letters, 16:084046. doi:10.1088/1748-9326/ac14ea

Wizenberg, T., K. Strong, D.B.A. Jones, E. Lutsch, E. Mahieu, B. Franco and L. Clarisse, 2023. Exceptional wildfire enhancements of PAN, C_2H_4, CH_3OH, and HCOOH over the Canadian High Arctic during August 2017. Journal of Geophysical Research: Atmospheres, 128:e2022JD038052. doi:10.1029/2022JD038052

Xu, W., R.C. Scholten, T.D. Hessilt, Y. Liu and S. Veraverbeke, 2022. Overwintering fires rising in eastern Siberia. Environmental Research Letters, 17:045005. doi:10.1088/1748-9326/ac59aa

Zheng, B., P. Ciais, F. Chevallier, H. Yang, J.G. Canadell, Y. Chen, I.R. van der Velde, I. Aben, E. Chuvieco, S.J. Davis, M. Deeter, C. Hong, Y. Kong, H. Li, H. Li, X. Lin, K. He and Q. Zhang, 2023. Record-high CO_2 emissions from boreal fires in 2021. Science, 379:6635. doi:10.1126/science.ade0805

Data references

Data ref. 4.1. Copernicus Atmosphere Monitoring Service Global Fire Assimilation System (GFAS) v1.2, 2003-present day dataset and documentation. Available at: https://ads.atmosphere.copernicus.eu/datasets/cams-global-fire-emissions-gfas?tab=overview

Wang, M., S.L. Smith, J.E. Box, S. Gerland, K. Isaksen, W.N. Meier, L. Mudryk, S.M. Natali, V.E. Romanovsky, Q. Shu and M. Sigmond, 2024. Cryosphere. In: AMAP Arctic Climate Change Update 2024: Key Trends and Impacts, pp. 31-56. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://doi.org/10.21352/g8qd-6h14

5. Cryosphere

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Key findings

- *Since 1980, the Arctic cryosphere has diminished both on land (permafrost and snow) and over the ocean (sea ice). The melt season has lengthened while the freeze season has shortened.*
- *Permafrost has warmed and thawed over the past four decades, which has led to landscape change especially where permafrost is ice-rich. Permafrost degradation is expected to continue in response to increasing air temperature but there is less certainty regarding the magnitude and timing of the response.*
- *Snow-cover extent has declined substantially in spring and autumn based on a combination of multiple snow products, which is consistent with earlier assessments. A larger declining trend was found in Eurasia than in North America. Seasonal maximum snow-water equivalent is projected to decrease across much of the Arctic, but regional increases are expected in eastern Siberia and the Canadian Arctic Archipelago. Projected spring snow extent and snow mass both show a nearly linear response to the increase in global mean near-surface temperature regardless of the emission scenarios employed in the climate model (CMIP6) simulations.*
- *The largest sea-level rise contributions are glacier melt from Greenland, Alaska, and Arctic Canada, resulting from amplified Arctic warming and increasing atmospheric rivers reaching Greenland. The rates of Arctic glacier ice loss have increased for all regions in each successive decade since the 1970s.*
- *Over the 43-year record (1980–2023), the decline in sea-ice extent is greater in September (month of the annual minimum extent) than in March (month of the annual maximum extent). Decadal variability is also more pronounced in September than in March. The largest decline in these months occurred in the period 1993–2006.*
- *Sea-ice thickness shows large regional variability based on satellite data for 2011–2022. A sea ice-free Arctic summer is projected by mid-century based on CMIP6 models under the moderate to high greenhouse gas emissions scenarios, consistent with previous climate model projections.*

5.1 Introduction

The cryosphere, which refers to the frozen parts of the Earth's surface, including glaciers, ice caps, ice sheets, permafrost, sea ice, and snow, plays a crucial role in the Earth's climate system and is of significant importance for the planet's ecosystems, human societies, and local to global climate. Since the 1980s, the Arctic cryosphere has been diminishing, and the timing of the melt-freeze cycle has changed: with earlier melt and later freeze. This has resulted in major changes in the physical and chemical environment of the Arctic, a shift in conditions for living species, and potentially an alteration in the role of the Arctic in the global climate system (AMAP, 2017). Climate-forced population displacement, including community relocation, is expected to be one of the greatest climate adaptation challenges for Alaska Native communities (Bronen et al., 2020) and people more generally across the Arctic.

This chapter provides an update on findings regarding changes in the Arctic cryosphere components since AMAP's Arctic Climate Change Update 2021: Key Trends and Impacts (AMAP, 2021a) and, in the case of permafrost, since AMAP's Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017 assessment (AMAP, 2017). The chapter synthesizes recent knowledge on changes in the cryosphere, including key findings from the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (AR6; IPCC, 2021), and its Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019). As discussed in Chapter 2, the Arctic is warming much faster than the global mean (Rantanen et al., 2022) and the resulting changes in the cryosphere, such as thawing permafrost, reductions in snow and ice cover, and reductions in land ice can exert positive feedback effects on local and global climate systems. The various components of the cryosphere are each addressed in the following sections.

5.2 Permafrost

Permafrost is defined as earth materials (soil or rock, and organic matter) that remain below 0°C for two or more consecutive years (IPA, 1998). Extensive regions of the Arctic landscape are underlain by permafrost. Permafrost has an important influence on landscape stability, hydrological systems, and ecosystems (Schuur and Mack, 2018; Smith et al., 2022). Recent evidence indicates that permafrost is warming and thawing in response to climate change (e.g., Biskaborn et al., 2019; Box et al., 2021; Gulev et al., 2021; Smith et al., 2022, 2023). Thawing of permafrost, especially when ice-rich, can lead to ground instability including surface subsidence, which has implications for infrastructure integrity (Hjort et al., 2022). Changes in permafrost can also have impacts on traditional activities, including access to land, and can pose risks to travel, health and food security (e.g., Hausner et al., 2021; Hancock

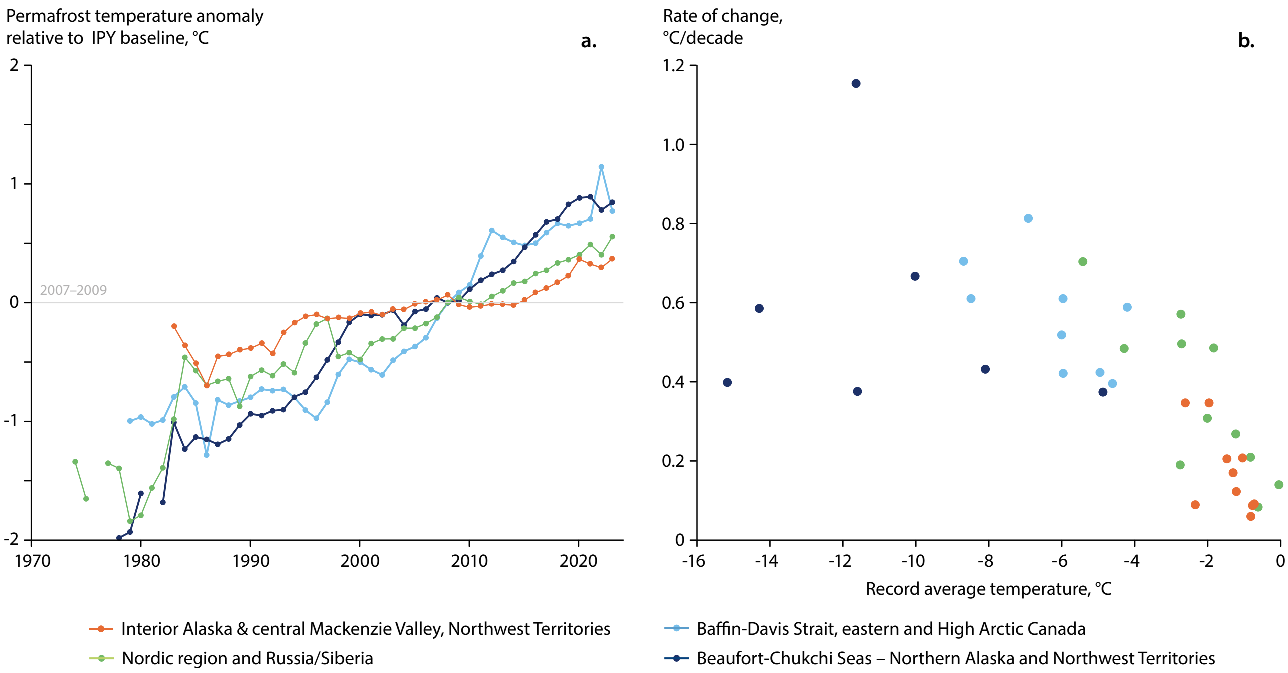


Figure 5.1 (a) Average departures of permafrost temperature (measured in the upper 20–30 m) from a baseline established during the International Polar Year (IPY 2007–2009) for four Arctic regions and (b) rates of permafrost temperature change vs average temperature for the entire available record for individual sites in each of the four regions. See Smith et al. (2023) for data sources and location of sites. Note: some sites were established after 2000.

et al., 2022). Permafrost can also store large amounts of carbon which can be mobilized as the ground thaws, resulting in the release of greenhouse gasses with feedback to the climate system (e.g., Miner et al., 2022; Schuur et al., 2022).

Knowledge of permafrost conditions and their evolution under a changing climate is therefore critical for assessing impacts on the natural and built environments and to inform the response to these impacts. This section synthesizes observed changes in permafrost thermal state and active layer thickness, as well as other evidence of changing permafrost conditions. New knowledge regarding the causes of these changes is discussed and recent projections of future conditions are summarized.

5.2.1 Indicators of changing permafrost conditions

5.2.1.1 Permafrost temperatures

Permafrost temperatures measured in boreholes up to 20–30 m deep are indicators of changing thermal state. Measurements have been made across the Arctic for more than four decades at some sites. Clear evidence of increases in permafrost temperature have been reported in earlier assessments (AMAP, 2017; Biskaborn et al., 2019; Box et al., 2021; Smith et al., 2022). Time series updated to 2021–2023 show that permafrost is warming in all regions of the Arctic, with temperatures over the past decade generally being among the highest recorded (Figure 5.1a; see also Chapter 2).

Regional rates of temperature change (Figure 5.1b) vary from 0.19°C/decade in the warm (generally above -2°C) permafrost in the discontinuous zone of Interior Alaska and the central Mackenzie Valley in the Northwest Territories, to 0.59°C/decade for colder permafrost in the Beaufort-Chukchi seas region (Table 5.1) for the period 1978 to 2023. This is reflected in the grouping evident in Figure 5.1b, with temperature increases generally greater in colder permafrost than in warmer permafrost. These results are in general agreement with the findings of IPCC AR6 (Gulev et al., 2021), based on data up to 2019. Within each region, there is spatial variation in the magnitude of permafrost warming (e.g., Smith et al., 2022). The highest rates of warming (>0.5°C/decade) are found in the Canadian High Arctic, northern Alaska and Svalbard, and the

Table 5.1 Number of sites, mean temperature, and rate of permafrost temperature change for the four regions shown in Figure 5.1 for the period 1978 to 2023. Maximum and minimum rates for each region are based on rates determined for individual sites.

Region	Number of sites	Mean temperature, °C	Rate of change, °C/decade		
			Regional	Maximum	Minimum
Baffin-Davis Strait	7	-10.95	0.47	1.20	0.38
Beaufort-Chukchi Seas	9	-6.23	0.59	0.81	0.40
Interior Alaska, central Mackenzie Valley	10	-1.37	0.19	0.35	0.06
Barents	11	-2.15	0.41	0.70	0.08

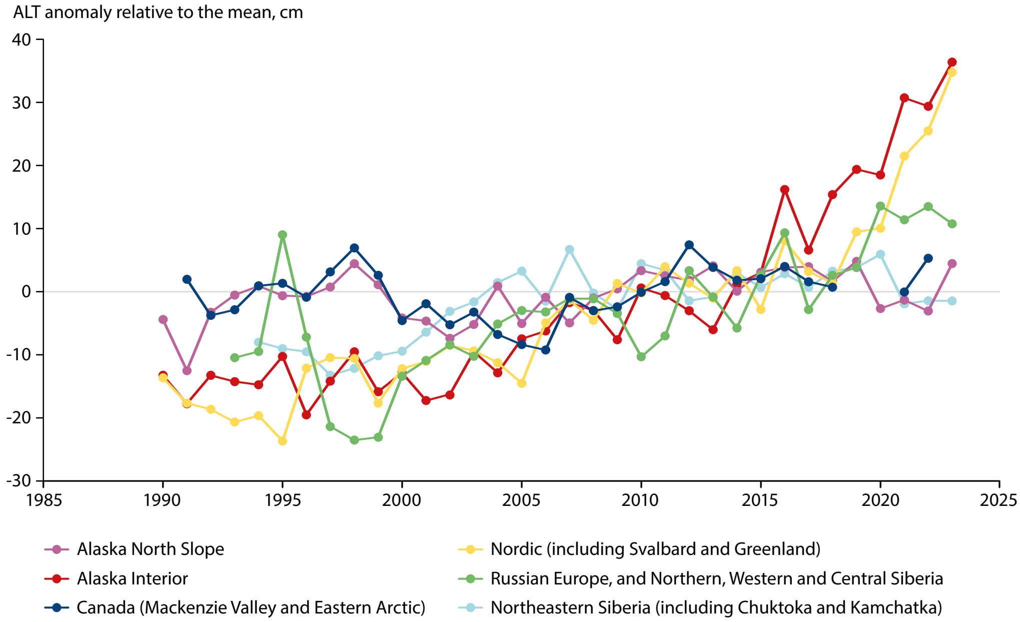


Figure 5.2 Regional active layer thickness (ALT) anomalies relative to the record mean for the available period between 1990 and 2023 for most sites. Data are from the Circumpolar Active Layer Monitoring (CALM) Network (Data Ref. 5.1). Note: for some sites there was limited data collection for 2020–2022. See Table 5.2 for a regional description and additional information on the number of sites per region, and the CALM website for individual site information including record length.

western Russian Arctic (Box et al., 2019; Etzelmüller et al., 2020; Vasiliev et al., 2020; Isaksen et al., 2022; Malkova et al., 2022; Smith et al., 2024). Shorter records (2014–2021) from northern Greenland also indicate similar rates of warming (Strand et al., 2022). In northern Norway, warming of up to 0.5°C/decade has been observed (Etzelmüller et al., 2023; Smith et al., 2023). In warmer permafrost at temperatures close to 0°C, such as that found in the discontinuous permafrost zone of northwestern North America, the Nordic region (e.g., southern Norway), Iceland, warmer regions of the Russian European north, and northwest Siberia, increases in temperature have been minimal (Smith et al., 2019, 2023; Isaksen et al., 2022; Malkova et al., 2022; Etzelmüller et al., 2023). This is especially true of ice-rich permafrost where energy (i.e., latent heat) is required to melt ground ice but results in little change in ground temperature (Romanovsky et al., 2017). Exceptions include sites where ice contents are low, including those underlain by bedrock.

5.2.1.2 Active layer thickness

Active layer thickness (ALT) – the thickness of the seasonally thawed layer above permafrost – has been determined across the Arctic since 1991 by the Circumpolar Active Layer Monitoring Network (CALM; Nelson et al., 2021). At most sites, ALT is determined by mechanical probing. In the Mackenzie Valley in northwestern Canada, thaw tubes are used, while interpolation of shallow temperatures is used at some Nordic sites to determine ALT. Regional anomalies for ALT based on data from 88 sites (Figure 5.2) indicate far greater interannual variability compared to deeper permafrost temperatures. Trends are also highly variable spatially, with ALT increasing over time in some regions but showing little change in others (Table 5.2).

Trends are evident in the interior Alaskan, Nordic, and Russian Arctic sites (Figure 5.2), with large increases in ALT observed in the Russian European North and western and central Siberia, averaging 1.4 cm/y and up to >3 cm/y at some sites (Kaverin et al., 2021; Malkova et al., 2022). Large increases in ALT have also been observed at Nordic sites, averaging 1.8 cm/y but with considerable interannual variability (Etzelmüller et al., 2020; Strand et al., 2021). The highest increases in the Nordic region, greater than 5 cm/y, were observed in southern Norway. The increased thaw in Norway and Iceland has also led to talik formation (a layer of unfrozen ground within permafrost) at some sites (Etzelmüller et al., 2023). In Alaska, the increases in ALT have been greatest in the interior (average 0.9 cm/y;

Table 5.2 Rate of change in active layer thickness in six Arctic regions based on data from the Circumpolar Active Layer Monitoring (CALM) Network (Data Ref. 5.1), with the latest data in 2023 where available.

Region	Rate of change in ALT, cm/y[a]		Number of sites[b]
	Average	Range	
Alaska North Slope	0.2	-0.1 to 0.4	25
Alaska Interior	0.9	0 to 3.3	5
Canada (Mackenzie Valley and Eastern Arctic)	0.0	-1.0 to 0.7	7
Nordic (including Svalbard and Greenland)	1.8	0.5 to 7.5	7
Russian European North, and western and central Siberia	1.4	0 to 3.7	20
Northeastern Siberia (including Chukotka and Kamchatka)	0.3	-1.0 to 1.4	24

[a]Active layer thickness is determined by mechanical probing in most sites. The exceptions are Canadian sites which use thaw tubes, and three Nordic sites which use ground temperature measurements. [b]Sites are largely located in unconsolidated material, except for two sites in weathered bedrock with patchy till. Sites included have at least 10 years of data ending in 2018 or later.

Smith et al., 2023), with greater increases after 2013 (Figure 5.2). Positive but smaller trends (average 0.3 cm/y) have been observed in northeastern Siberia (Table 5.2) (Abramov et al., 2021). For the Mackenzie Valley and North Slope of Alaska, ALT trends have averaged 0–0.1 cm/y (Smith et al., 2023).

The negligible or small changes in ALT observed at some sites are partly due to the latent heat required to melt ground ice, which results in smaller increases in shallow ground temperature (i.e., sensible heat). However, in some cases, small increases in ALT can occur even though thaw progresses deeper into the ground over time (O'Neill et al., 2023). This is due to ground subsidence and the soil consolidation that accompanies the thawing in ice-rich permafrost. The amount of permafrost thaw at ice-rich sites is therefore obscured when ALT measurements are made using the ground surface position each year as the reference datum rather than a fixed datum (Streletskiy et al., 2017; Vasiliev et al., 2020; Abramov et al., 2021; Smith et al., 2022; O'Neill et al., 2023). Ground surface subsidence has recently been documented at some sites in North America. In northwestern Canada in the Mackenzie Valley and Delta region, significant subsidence was recorded at 21 sites from 1991 to 2018 at a median rate of 0.4 cm/y and a maximum rate of 1.4 cm/y, based on data collected from thaw tubes (O'Neill et al., 2023). Similar rates were found in northern Alaska based on assessments of elevation change derived from differential GPS measurements. Between 2003 and 2015, subsidence of 0.4–1.0 cm/y was observed at three sites in the Utqiaġvik area (Streletskiy et al., 2017), and observations between 2000 and 2018 at three sites in the Outer Coastal Plain and Northern Foothills indicate 0.7–0.8 cm/y of subsidence (Nyland et al., 2021). At a site further south near Healy, 1.2 cm/y of subsidence was observed between 2009 and 2018 (Rodenhizer et al., 2020). In the Canadian High Arctic, subsidence of 3.3–7.5 cm/y was observed between 2003 and 2016 in ice-wedge polygon troughs, indicating significant permafrost degradation over the 12-year period (Farquharson et al., 2019).

5.2.1.3 Landscape change

Thawing of ice-rich permafrost can lead to differential subsidence of the ground surface resulting in thermokarst topography. Thermokarst can be associated with mass movements, including retrogressive thaw slumps, collapse of ice-cored peat plateaus and palsas, and the formation of thermokarst lakes. In addition to the local-scale observation of ground subsidence, thaw-driven landscape changes have been documented over larger areas through analysis of satellite and airborne remotely sensed imagery (Bernhard et al., 2020; Nitze et al., 2021; Witharana et al., 2022; Yang et al., 2023), providing additional evidence of changes in permafrost conditions. These changes in the landscape can further exacerbate permafrost thaw, for example, by removing material and changing surface boundary conditions (e.g., Smith et al., 2022).

Degradation of permafrost in organic terrain, such as peatlands and palsas, has recently been documented in North America and Scandinavia (Olvmo et al., 2020; Douglas et al., 2021; Gibson et al., 2021; Veremeeva et al., 2021; Chen et al., 2022). Gibson et al. (2021) found, for example, that for an area of over 370,000 km^2 in the central and southern Mackenzie Valley, 70% of the peatland area was affected by permafrost thaw. A decline in the extent of permafrost in palsa areas, accompanied by increased ground subsidence, has also been documented in Sweden since the 1960s (de la Barreda-Bautista et al., 2022).

Change in lake area can also be an indicator of ground thaw. Observations in Siberia and Alaska include increases in lake area as permafrost degrades and thermokarst lakes form and/or enlarge as the ground subsides, and reductions in lake area associated with thaw-induced lake drainage (Swanson, 2019; Lindgren et al., 2021; Veremeeva et al., 2021; Chen et al., 2022; Webb et al., 2022). In northwest Alaska, widespread subsurface drainage since 2015 is thought to have been driven by talik development (Jones et al., 2022).

Degradation of ice wedges and thermo-erosion have been documented in North America and Siberia (Farquharson et al., 2019; Gagnon and Allard, 2020; Burn et al., 2021; Morgenstern et al., 2021; Jorgenson et al., 2022a). Field-based studies in Nunavik in northern Quebec, Canada, indicate that between 1989 and 2018, widespread ice-wedge degradation occurred with ice wedge tops becoming consistently deeper (Gagnon and Allard, 2020). Widespread ice-wedge degradation in northeastern Alaska has been detected through analysis of imagery, with the proportion of ice wedges undergoing degradation increasing from 2% in 1950 to 19% in 2018 (Jorgenson et al., 2022a). Increases in thermokarst area, density and size have also occurred. In Canada's High Arctic on Banks Island, increases in ponding resulting from ice-wedge thaw on hilltops affected an area of at least 1500 km^2 over a 32-year period (1985–2017) (Fraser et al., 2018).

Intensification of thaw slumping associated with permafrost degradation has been widely documented (Nitze et al., 2018; Lewkowicz and Way, 2019; Ward Jones et al., 2019; Kokelj et al., 2021; Bernhard et al., 2022a,b). On Banks Island, a 60-fold increase in the number of retrogressive thaw slumps was observed between 1984 and 2015, with over 4000 being initiated over this period (Lewkowicz and Way, 2019). A 300% increase in retrogressive thaw slumps-affected area over the past two decades has been documented in northern Siberia (Runge et al., 2022). Bernhard et al. (2022a) reported a 43-fold increase in thaw slumping in the Taymyr Peninsula over the past two decades. Imagery analysis at ten sites across the Arctic revealed significant changes in volume and area in retrogressive thaw slumps over a 5-year period (2012–2017), with an increase in material mobilized for 1853 retrogressive thaw slumps of 77 m^3/y/km^2 (Bernhard et al., 2022b).

5.2.1.4 Coastal erosion

In addition to permafrost thaw, Arctic coasts are vulnerable to several other factors associated with a changing climate, including sea-level rise and changing sea-ice conditions (Irrgang et al., 2022), which makes attribution of coastal erosion complex. In most regions of the Arctic coast, the average 21st century erosion rates are more than 50% greater than during the latter three to four decades of the 20th century, particularly for permafrost in unlithified material (sediments) (Jones et al., 2020; Irrgang et al., 2022). Along sections of the Alaskan Beaufort Sea coast, erosion rates in the most recent decade have quadrupled (Jones et al., 2018, 2020; Gibbs et al.,

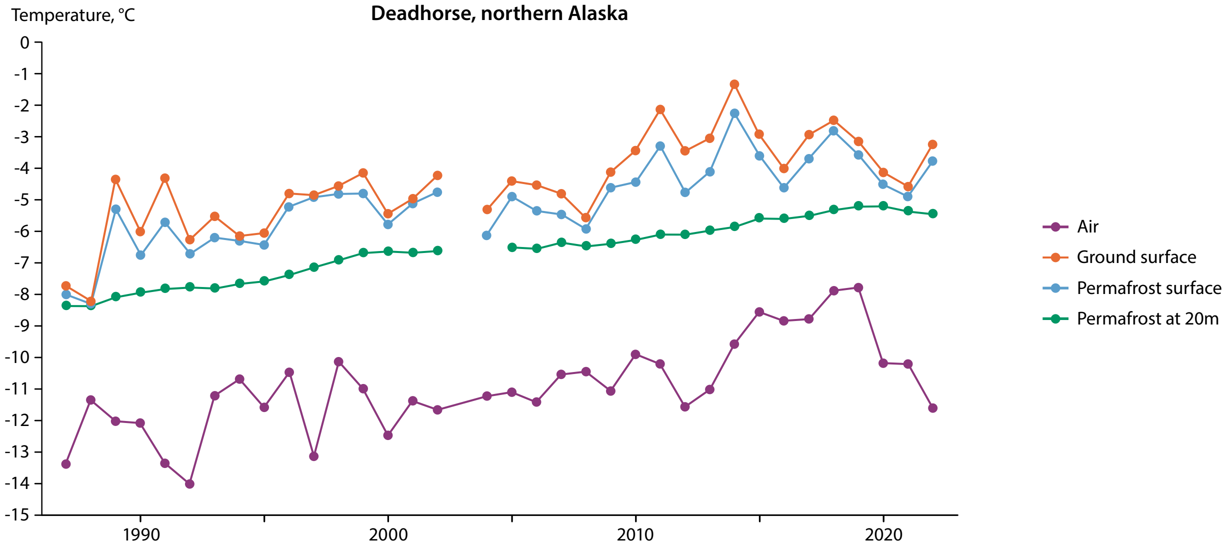


Figure 5.3 Air, surface, and ground temperatures (permafrost surface and 20 m depth) for a permafrost monitoring site at Deadhorse in northern Alaska, 1987–2022. Source: updated from Romanovsky et al. (2017).

2021). An acceleration in erosion over the past two decades has also been observed for sections of the Canadian Beaufort Sea coast (e.g., Whalen et al., 2022). The highest rates of coastline retreat in the 21st century are found along the Alaskan Beaufort Sea coast, ranging from 1.3 to 17.2 m/y (Jones et al., 2020), while rates along the Russian Arctic coast have reached up to 9.5 m/y, with the fastest retreat occurring along the Laptev Sea coast (Jones et al., 2020; Irrgang et al., 2022).

5.2.2 Impact of climate and other factors

Climate change is an important factor driving changes in permafrost thermal state and active layer thickness. However, the response of the ground thermal regime to climate change is modulated by the interrelated effects of vegetation, snow cover, organic layer thickness, and the thermal properties of the underlying earth materials (e.g., Romanovsky et al., 2017; Smith et al., 2022). The observed changes in permafrost temperature (Figure 5.1a) are generally consistent with increases in air temperature (e.g., Romanovsky et al., 2017; Biskaborn et al., 2019; Box et al., 2019, 2021; Etzelmüller et al., 2020; Smith et al., 2024). It has, however, been suggested that some of the increase in permafrost temperature may be the result of changing surface energy exchanges due to increases in snow cover, which insulates the ground particularly in the discontinuous zone (Biskaborn et al., 2019). Observed permafrost thaw and talik development in Iceland and Norway have been attributed to increases in both air temperature and snow depth (Etzelmüller et al., 2023; see also discussions in Chapter 6).

Shorter-term variations in both air temperature and snow cover have also been associated with changes in permafrost temperature. Periods of low snow cover at some sites in the Alaskan Interior in 2007–2014 have been linked to the colder ground conditions that occurred at that time (Romanovsky et al., 2017), as evidenced by the lack of variation in permafrost temperature (Figure 5.1a). More recently, lower air temperature in 2019–2022 in northern Alaska is associated with a decrease in ground temperature down to depths of 20 m (Figure 5.3). Similar recent decreases in permafrost temperature have been observed elsewhere in northwestern North America (Beaufort–Chukchi Sea region in Figure 5.1a, see also Chapter 2). Lower ground temperature and a decrease in ALT were also observed after 2020 at Svalbard (Figure 5.4), likely in response to lower air temperature (Smith et al., 2023). Lower ground temperatures in southern Scandinavia in 2011–2014 have been attributed to colder winters in 2010–2013 (Etzelmüller et al., 2020, 2023). A mild and snowy winter in 2017–2018 resulted in the active layer at many sites in the Alaskan Interior not completely freezing down to the permafrost table and initiation of talik formation (Romanovsky et al., 2019; Farquharson et al., 2022).

Periods of extreme warming can also have impacts on permafrost. Extreme warming in Norway in 2005 and 2006 and Svalbard in 2016 resulted in record high near-surface permafrost temperatures and a longer period for freeze-back of the active layer during the autumn/winter (Isaksen et al., 2022). ALT in Svalbard was also greater than in previous years (Figure 5.4); extreme warming in Svalbard

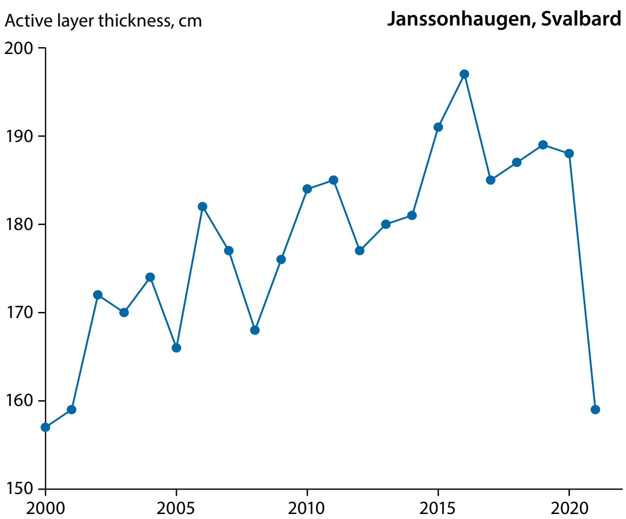


Figure 5.4 Active layer thickness for the Circumpolar Active Layer Monitoring (CALM) Network site at Janssonhaugen, Svalbard. Source: Data Ref. 5.1.

in 2016 resulted in ground temperatures down to 5–10 m being significantly higher than the maximum temperature observed in previous years (Isaksen et al., 2022). Lower air temperatures following 2016 led to ground cooling and a decrease in ALT (Christiansen et al., 2021). Similar impacts on shallow ground temperature were observed in central and northern Alaska in response to higher air temperatures in 2014–2019 (e.g., Figure 5.3), and widespread increases in thaw were also observed (Douglas et al., 2021; Swanson et al., 2021). The increase in ALT in 2020 in Siberia (Figure 5.2) has been attributed to a heatwave (Noetzli et al., 2021). Bernhard et al. (2022a) reported rapid initiation of retrogressive thaw slumps in the Taymyr Peninsula coinciding with the 2020 heatwave.

Fire, associated with warm and dry conditions, and the associated damage to vegetation and the organic layer can result in increases in ground temperature and ALT following the fire, with the magnitude of the increase depending on burn severity (Holloway et al., 2020; Li et al., 2021). These changes are generally greatest in the first five to ten years after the fire, followed by recovery in some ecosystems. However, progressive thaw and talik development can occur and last decades or more and, with the added effect of climate warming, permafrost may not recover, especially at the southern margins of the permafrost zone (Holloway et al., 2020). Fire has been identified as a major driver of permafrost thaw in boreal peatlands, accounting for 2200±1500 km^2 of thermokarst bog development in western Canadian permafrost peatlands over the past three decades, which is about 25% of all thermokarst bog expansion (Gibson et al., 2018). In northern Alaska, fire has been responsible for 10.5% of all thermokarst development (1950–2015), despite only affecting 3.4% of the tundra landscape (Chen et al., 2021). Over the four decades post-fire in the Alaskan tundra, thermokarst area was nine times greater within burn scars than in unburned tundra (Chen et al., 2021). Several other studies report observations in Alaska and western Canada of greater thaw depths and increases in thermokarst in burned areas compared to undisturbed terrain (Rey et al., 2020; Chen et al., 2021; Rettelbach et al., 2021; Daly et al., 2022; Foster et al., 2022; Jorgenson et al., 2022b). Similar results have been reported for the continuous permafrost zone in Siberia where increases in thaw depth of 30–50 cm occurred within the first 30 years after burning (Kirdyanov et al., 2020). Legacy effects of fires that occurred in the 1990s have contributed to increases in landslides triggered by permafrost thaw in northwest Canada during 2004–2020 (Young et al., 2022).

5.2.3 Permafrost processes and ecosystem impacts

Widespread landscape changes associated with permafrost thaw have been documented across the Arctic. These changes and the resulting changes in land cover, including declining extent of permafrost palsas and peatlands, ice-wedge degradation, talik formation, changes in surface water distribution and thaw slumping, also have implications for ecosystems (e.g., Gibson et al., 2021; Bernhard et al., 2022a,b; Jones et al., 2022; Jorgenson et al., 2022b; Webb et al., 2022).

Permafrost thaw is altering the quantity and composition of organic carbon transported from terrestrial to aquatic ecosystems, through both erosion and mass wasting associated with thermokarst processes (Shakil et al., 2020; Keskitalo et al., 2021; Bernhard et al., 2022a). Thaw-induced changes in the landscape are also altering vegetation and ecosystem function (Burd et al., 2020). Permafrost thaw can also mobilize heavy metals, such as mercury, into Arctic wetlands, freshwater, and coastal systems (AMAP, 2021b). Based on measurements in soils and sediments across the Arctic, the permafrost mercury pool is estimated to be two-fold higher than combined mercury stores in global soils, atmosphere, and the ocean (Schuster et al., 2018; AMAP, 2021b; Rutkowski et al., 2021). Upon thaw and mobilization to anoxic environments (i.e., wetlands, aquatic systems), mercury can be transformed into methylmercury, which can bioaccumulate in aquatic food webs. In a Fennoscandian permafrost peatland, methylmercury levels in soils were an order of magnitude higher in recently thawed areas than in frozen peat plateaus (Tarbier et al., 2021).

Permafrost thaw has been associated with changes in carbon cycling processes across the permafrost region. While the high-latitude permafrost region has been a carbon sink for millennia, it may become a net source of carbon to the atmosphere in the coming century (Schuur et al., 2022). At the pan-Arctic scale, estimates and uncertainty ranges for current tundra carbon dioxide (CO_2) exchange span from a net CO_2 sink to a source (Virkkala et al., 2021). However, in-situ observations and modeling studies suggest that thermokarst processes resulting from thawing of ice-rich permafrost may shift ecosystems to a net carbon source and accelerate carbon emission to the atmosphere (Turetsky et al., 2020; Knoblauch et al., 2021; Rodenhizer et al., 2022).

Long-term observations at a subarctic tundra site in Alaska have shown that thawing permafrost has already shifted this ecosystem to a net CO_2 source to the atmosphere (Schuur et al., 2021). At a long-term warming experiment at this site, permafrost thaw increased methane (CH_4) emissions, particularly in wet, graminoid-dominated microsites (Taylor et al., 2021). Recent studies have also highlighted the additional potential permafrost climate feedback resulting from nitrous oxide (N_2O) emissions, including from thawing yedoma (thick ice-rich silt deposits with organics) in the coldest regions of northeast Siberia and Alaska (Marushchak et al., 2021; Schuur et al., 2022).

Permafrost thaw-driven hydrological changes are a major driver of changes in carbon cycling, leading to decreased CH_4 emissions associated with drainage (Keuschnig et al., 2022) and increased CH_4 emissions from thermokarst ponds and thaw-induced wetland processes (Beckebanze et al., 2022; Holmes et al., 2022). Permafrost thaw has also been associated with increased CO_2 uptake, including due to earlier vegetation green-up across the permafrost region (Wang and Liu, 2022) and thaw-related changes in inundation and vegetation in a permafrost wetland complex in Sweden (Holmes et al., 2022). Permafrost thaw also affects the hydrological cycle, including surface water distribution and subsurface flow. See further discussions in Chapter 6.

5.2.4 Projections of future conditions

Observational evidence of permafrost warming and thawing in response to increases in air temperature over the past few decades indicates that further climate warming will continue to have impacts on permafrost conditions although there is much uncertainty regarding the magnitude and timing of the response (Meredith et al., 2019; Fisher and Koven, 2020; Fox-Kemper et al., 2021). Recent projections utilizing an equilibrium model suggest a committed loss of 30% and 40% of the area currently underlain by permafrost for global warming scenarios 1.5°C and 2°C above pre-industrial levels, respectively (Chadburn et al., 2017). Transient model projections generally focus on permafrost occurrence and loss in the upper 2–3 m. Depending on the climate scenario considered, thaw depth is projected to exceed 3 m over 24% (±16%) to 70% (±20%) of the current permafrost region by 2100 according to a recent IPCC report (Meredith et al., 2019). Other simulations indicate complete loss of permafrost in the upper 3 m under the most extreme warming scenario (RCP8.5) by 2100 (McSweeney and Kooperman, 2022). According to simulations by Burke et al. (2020; see also Fox-Kemper et al., 2021), reductions in northern hemisphere permafrost volume of 3.0–5.3 x 10^3 km^3 are anticipated for each 1°C increase in global mean surface air temperature, under SSP1-2.6 to SSP5-8.5 scenarios, but thaw below 2 m depth is not considered in projections. At a regional scale, simulations for subarctic Alaska project an increase in thaw depth of 1 m per 1°C increase in the site mean annual air temperature (Garnello et al., 2021); up to 5 m (RCP4.5) and more than 10 m (RCP8.5) of thaw are projected to occur by 2100.

There are limitations associated with many models utilized to simulate future conditions under a changing climate (Smith et al., 2022), including representation of subsurface material properties such as excess ice content, latent heat effects, and ground subsidence, which influence the thermal response of frozen ground to changes in air temperature. However, there have been recent efforts directed at improved representation of excess ice (Aas et al., 2019; Cai et al., 2020; Nitzbon et al., 2020). The role of landscape changes, including ground subsidence, is also being recognized as a critical factor for improving simulations of permafrost thaw and carbon release (Turetsky et al., 2020; Rodenhizer et al., 2020, 2022). Adequate representation of snow cover, including its spatial variation, is another key limitation, although improvements are being made in the simulation of snow redistribution and impacts on surface temperature (Nicolsky et al., 2017; Zweigel et al., 2021). There is some evidence that changes in rainfall may also be important, as infiltration of summer rainfall can influence the ground thermal regime (e.g., Neumann et al., 2019; Douglas et al., 2020; Clayton, et al., 2021; Mekonnen et al., 2021). Better understanding of the effect of infiltrating rainfall and incorporation into models could improve future projections of permafrost conditions.

Vegetation is also responding to changes in climate and these changes may mitigate or amplify permafrost thaw (Loranty et al., 2018; Heijmans et al., 2022). The expansion of shrubs into tundra and its effects on snow cover has been of particular interest. The trapping of snow by shrubs generally results in warmer ground conditions compared to tundra with shorter vegetation (Frost et al., 2018; Wilcox et al., 2019; Kropp et al., 2020; Way and Lapalme, 2021; Evans et al., 2022). The expansion of shrubs could result in permafrost warming and thaw; however, there is limited direct evidence of this and the impacts of shrub expansion on ground thermal dynamics are complex (e.g., Wilcox et al., 2019; Evans et al., 2022). Not incorporating vegetation-permafrost interactions into models is therefore a limitation of projections of permafrost conditions under a changing climate.

5.2.5 Knowledge gaps and recommendations

In contrast to other cryospheric variables, permafrost is a subsurface phenomenon and, as such, direct monitoring of permafrost conditions including thermal state relies on in-situ measurements rather than remote sensing techniques. This leads to spatial gaps in the understanding of changes in the permafrost thermal regime. Expansion of the permafrost monitoring network, including co-location with other observations, such as meteorological and cryospheric conditions (e.g., snow depth), would improve information for attribution of changes in permafrost conditions. Remote sensing techniques are becoming widely used for detecting landscape change that may be associated with warming and thawing of permafrost. While the utility of satellite data has been proven at local to regional scale, circumpolar implementation is still lacking (Bartsch et al., 2023). Greater integration between satellite and airborne observations with in-situ measurements would enhance permafrost monitoring over larger areas. Advancing development of applications to provide more direct measurement of permafrost characteristics would also be beneficial. This includes improved quantification of ground surface elevation and subsidence combined with thermal measurements to improve assessment of permafrost degradation as well as to reconcile subsidence measurements with displacement acquired from satellite imagery analyses (e.g., InSAR - Interferometric Synthetic Aperture Radar).

Greater understanding of the complex interactions between permafrost and atmospheric conditions (air temperature and precipitation), vegetation, and snow cover and incorporation of these interactions into models is required to reduce uncertainty in the assessment of the response of the ground thermal regime to climate change. Improved information on ground-ice conditions is required because adequate representation is currently lacking in simulations of future permafrost conditions, including their impact on the carbon cycle. Models could also be improved by better incorporation of landscape change that can exacerbate permafrost thaw.

5.3 Terrestrial snow-cover extent and mass

Most Arctic land areas accumulate snow during winter. The timing of the transition seasons in spring and autumn is sensitive to temperature, with higher air temperatures driving earlier spring melt and later autumn snow-onset. The amount of seasonal snow accumulation (expressed as the snow-water equivalent, SWE) is driven by total precipitation, temperature (via both melt and changes in the fraction of precipitation falling as snow), and surface processes such as wind redistribution and landscape or

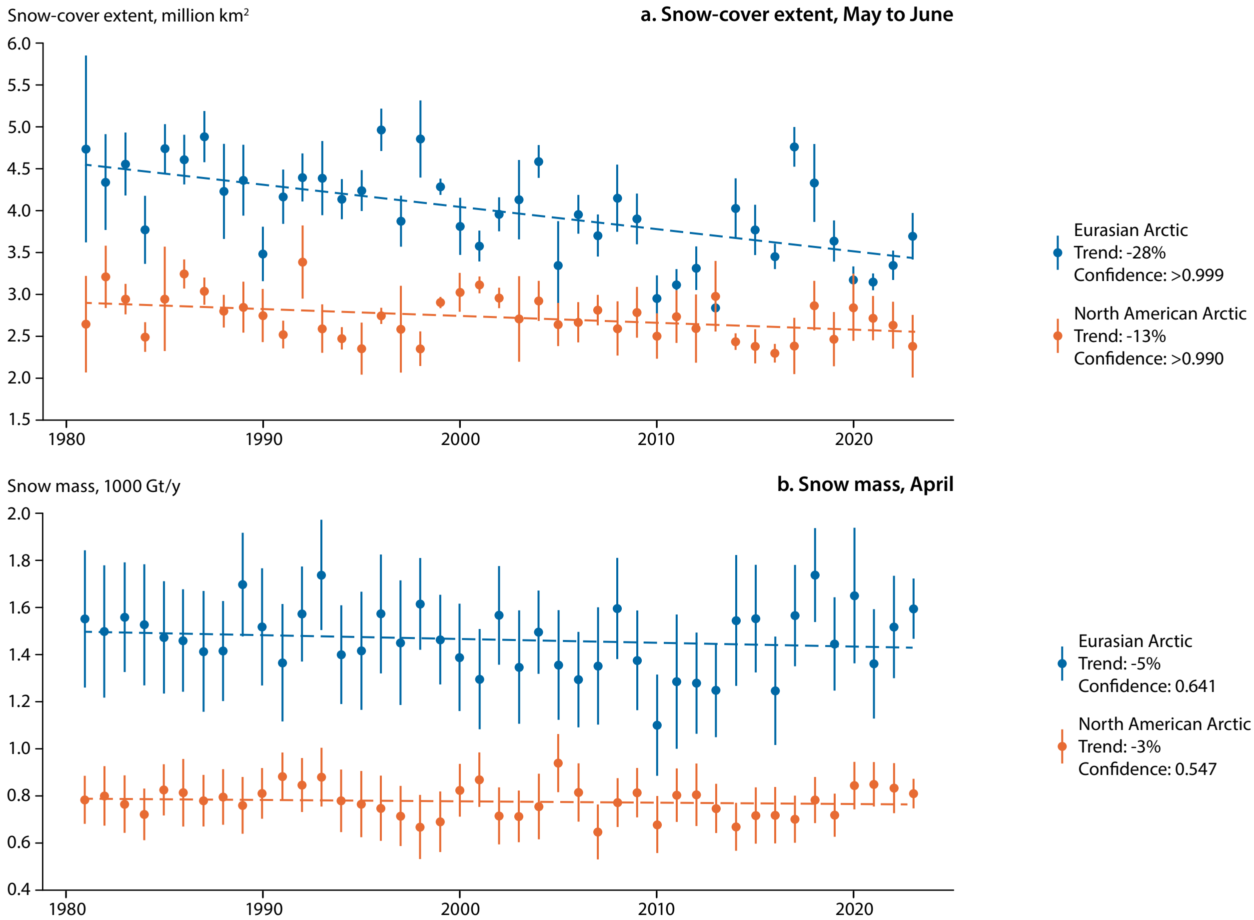


Figure 5.5 (a) Arctic spring (May through June) snow-cover extent on land for 1967–2023; all the linear trends passed the statistical test with higher than 99% confidence level, and (b) regional snow mass for 1981–2023 for April north of 60°N. Each dot indicates the average of the datasets listed in the text below and the whiskers indicate the 95% confidence range.

vegetation interception. Changes in the timing of snow cover and SWE affect the surface energy budget (Flanner et al., 2011; Euskirchen et al., 2016), the ground thermal regime and associated carbon fluxes (Natali et al., 2019), and the Arctic freshwater budget (Déry et al., 2016). Snow-cover changes also affect terrestrial and aquatic ecosystems, human community health and well-being, transportation, and infrastructure (Meredith et al., 2019).

As shown by Mortimer et al. (2020), combining multiple snow products produces better statistical agreement with reference snow-survey data. Here, to determine trends in snow-cover extent and SWE (1967–2023) across Arctic land areas, five independent snow analyses are averaged:

1. Output from the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) (Gelaro et al., 2017).
2. ERA5-land output (Copernicus Climate Change Service Climate Data Store (Muñoz-Sabater et al., 2021).
3. ERA5-driven Crocus snowpack model (Brun et al., 2013).
4. European Space Agency - Snow - Climate Change Initiative (CCI) v2 (Data Ref. 5.2).
5. NOAA snow chart Climate Data Record (1967–1980) (Estilow et al., 2015) combined with the Rutgers 24km (1981–2021) product derived primarily from optical satellite imagery (Data Ref. 5.3).

Using the snow cover data updated through 2023 shows that, consistent with earlier assessments, spring snow-cover extent has declined substantially across Arctic land areas (Callaghan et al., 2011; Brown et al., 2017; Meredith et al., 2019; IPCC, 2019; Pulliainen et al., 2020). The trend over the 1979–2023 period using the average of the products listed in the previous paragraph indicates a 26.7% reduction in pan-Arctic snow extent for May through June (Chapter 2; Figure 2.1c). The relative decrease is larger across the Eurasian Arctic at 28%, while North American Arctic snow-cover extent decreased by only 13% (Figure 5.5a). Negative snow-cover extent trends are also observed for the Arctic as a whole in October and November (Mudryk et al., 2020).

April snow-mass trends averaged from Datasets 1 through 4 are shown in Figure 5.5b. While Figure 5.5a indicated a robust signal of snow loss in Arctic spring snow extent, the trends in snow mass were weakly negative (over Eurasia) to statistically indistinguishable from zero (over North America) and show a comparatively high degree of interannual variability. April snow mass is analyzed as a reasonable proxy for the seasonal peak value, capturing the total snow accumulation since the preceding autumn, but excluding the influence of snow melt during May and June. For the Eurasian Arctic, a period of generally decreasing SWE between 1981 and 2010 was followed more recently by higher Arctic snow-mass values. Climate models project increasing peak SWE on average across Arctic land areas (see below), with statistically significant changes emerging by the end of the century (Brown et al., 2017). It is clear from the historical record, however, that increased snow accumulation will not provide a 'buffer' against earlier spring snowmelt driven by increasing temperatures. While variability in precipitation strongly influences the snow-mass time series from year to year (since outside the 'shoulder seasons', usually defined as October and November in the autumn and April and May in the spring, Arctic temperatures are and will remain sufficiently low for snow to accumulate), increased near-surface air temperature and downward longwave irradiance in spring result in earlier snow loss, consistent with earlier peak river discharge (Derksen and Mudryk, 2023).

Observed changes in Arctic snow vary by analysis variable, region, and season. For example, indicators in Chapter 2 show strong reductions in historical spring snow-cover extent while seasonal maximum Arctic snow mass shows weak or no significant trends over recent years. Arctic snow-cover extent also shows strong reductions during autumn in most datasets (Brown and Derksen, 2013; Peng et al., 2013; Hori et al., 2017; Mudryk et al., 2020), consistent with observed increases in Arctic air temperatures at this time of year. In contrast to the shoulder seasons, reductions in Arctic snow-cover extent are near-zero from December through March (Derksen and Mudryk, 2023) because the Arctic remains 100% snow-covered during these months.

Generally, these observed seasonal and regional differences between the two variables, snow cover and SWE, are consistent with corresponding influences from their respective drivers. Changes in snow-cover extent are primarily driven by temperature (Brutel-Vuilmet et al., 2013; Mudryk et al., 2017), with some additional variability related to large-scale teleconnections (Pederson et al., 2013; Henderson et al., 2018). SWE responds not only to temperature but also to precipitation (Sospedra-Alfonso and Merryfield, 2017), although the response simulated by climate models to the latter may be weak (Zhong et al., 2022). Drivers of observed changes in snow condition are further discussed in Chapter 6. The most recent three generations of climate models (Phases 3, 5, and 6 of the Coupled Model Intercomparison Project, CMIP3, CMIP5, CMIP6) have consistently projected increased precipitation across the Arctic (IPCC, 2007, 2013, 2021); however, this increased precipitation does not occur exclusively as increased snowfall due to concomitant changes in the partitioning of precipitation towards increased rainfall (Landrum and Holland, 2020; McCrystall et al., 2021). The combination of increasing precipitation, altered partitioning of rainfall and snowfall, and increasing near-surface air temperature is projected to lead to a geographically and seasonally varied response in SWE. Results from CMIP5 simulations demonstrated that seasonal maximum SWE decreases in most Arctic regions except for those with the coldest, most continental climates such as eastern Siberia and the Canadian Arctic Archipelago (AMAP, 2017).

Successive generations of climate model ensembles have improved in their ability to represent historical snow-cover extent (i.e., the skill of the multi-model ensemble mean has increased from CMIP3 through CMIP6); however, there remains a persistent amount of spread in skill among the individual models (Mudryk et al., 2020 and references therein). This spread in historical snow-cover extent continues to cause spread in assessments of simulated snow-albedo feedback (Thackeray et al., 2021). Assessment of climatological snow mass from CMIP6 climate models indicates that they are biased high on average (Mudryk et al., 2020), which is likely to be due to excessive snowfall (Kouki et al., 2022). However, the ability of climate models to reproduce the historical snow-mass climatology is less observationally constrained because estimates of historical snow mass from gridded products have relatively high uncertainty compared to snow-cover extent. This stems from the fact that snow observations are sampled at limited spatial and temporal frequency compared to their variability, although recent work has both narrowed the spread (Pulliainen et al., 2020) and better assessed the accuracy of gridded snow-mass products (Mortimer et al., 2020) across northern hemisphere non-alpine regions. The ability of climate models to simulate historical trends in snow-cover extent has also improved between CMIP3 and CMIP6. While not specific to the Arctic, integrated measures of observed snow change (northern hemisphere snow-cover extent and snow-mass trends) fall within the range of trends simulated by both the CMIP6 and previous CMIP5 generation of climate models (Mudryk et al., 2020).

To connect historical changes to projected changes in terrestrial snow, the simulated sensitivity of snow-cover extent and snow mass to increased global mean temperatures is further examined. Evaluating the sensitivity (changes in extent and mass per 1°C of warming) rather than the trends themselves helps account for differences in historical and simulated climate trajectories (which differ due to natural variability). Figure 5.6 compares the evolution of simulated Arctic spring snow-cover extent from 14 CMIP6 models relative to projected increases in global mean near-surface air temperatures (GSAT). Projected changes from the models scale near-linearly with GSAT and show minimal scenario dependence (the slopes are similar for different warming scenarios), consistent with results from

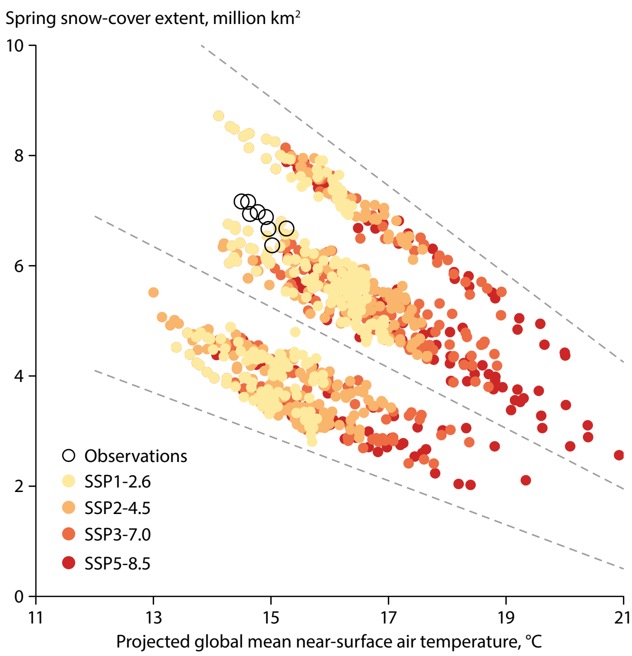


Figure 5.6 Simulated spring (April through June) snow-cover extent based on 14 CMIP6 models across four warming scenarios. Dashed lines illustrate linear decreases of -0.4, -0.55, and -0.8 million km²/°C. Source: Data Ref. 5.3.

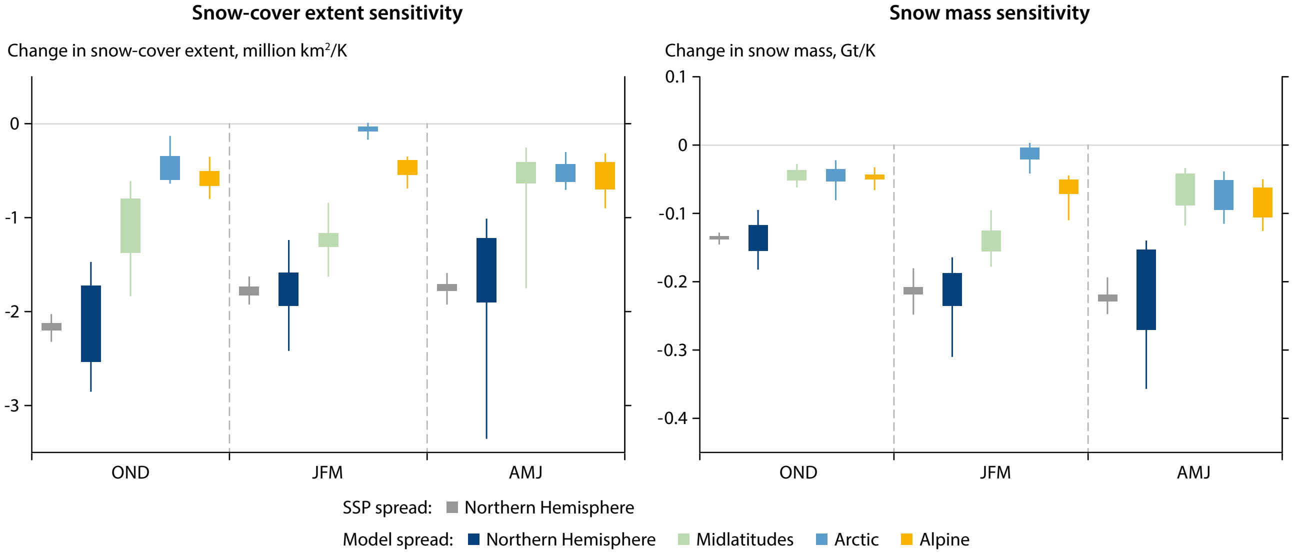


Figure 5.7 Seasonal sensitivities for snow-cover extent and snow mass based on 14 CMIP6 models across four emissions scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). Model spread in simulated sensitivities is shown with boxes (interquartile range) and whiskers (full extent) for the entire Northern Hemisphere and for three non-overlapping sub-regions: midlatitudes (0–60°N), Arctic (60–90°N), and alpine. SSP spread is shown for the Northern Hemisphere only. Source: Data Ref. 5.3 for observational data.

Mudryk et al. (2020). They *do* show strong model dependence, with differing slopes apparent for different model sub-groups. This is clearer in Figure 5.7, which illustrates the range in simulated snow-cover extent and snow mass sensitivities (the model- and scenario-specific slopes in snow-cover extent are from Figure 5.6) for several regions.

For the Northern Hemisphere as a whole, simulated snow-cover extent sensitivities have limited seasonal dependence. Regionally, the models simulate a stronger response in the midlatitudes relative to the Arctic and alpine regions. The response in the Arctic is the strongest in the shoulder seasons (OND and AMJ) because there is minimal snow-cover change projected during the winter (JFM), consistent with the historical trends as discussed above. Snow-mass sensitivities have more seasonal dependence (increasing magnitude of northern hemisphere snow-mass sensitivity from autumn through spring) and a strong spatial dependence apparent in the model median sensitivity (Figure 5.8).

The analysis presented here shows minimal dependence of snow-cover extent and snow-mass changes to the choice of CMIP6 scenario, only the amount of warming in a given scenario. This result is consistent with a previous snow-cover extent analysis by Mudryk et al. (2020) but is now extended to snow mass. The result indicates that it is not necessary to analyze different CMIP6 scenarios to obtain scenario-specific changes, rather that data can be pooled from the full range of models and scenarios for analysis. Additionally, the linear response of Arctic snow-cover extent (Figure 5.6) to global mean near-surface air temperature indicates that any reduction in the magnitude of global warming will also diminish subsequent snow-related responses. Across most of the Northern Hemisphere, this response consists of reduced snow cover and snow mass with

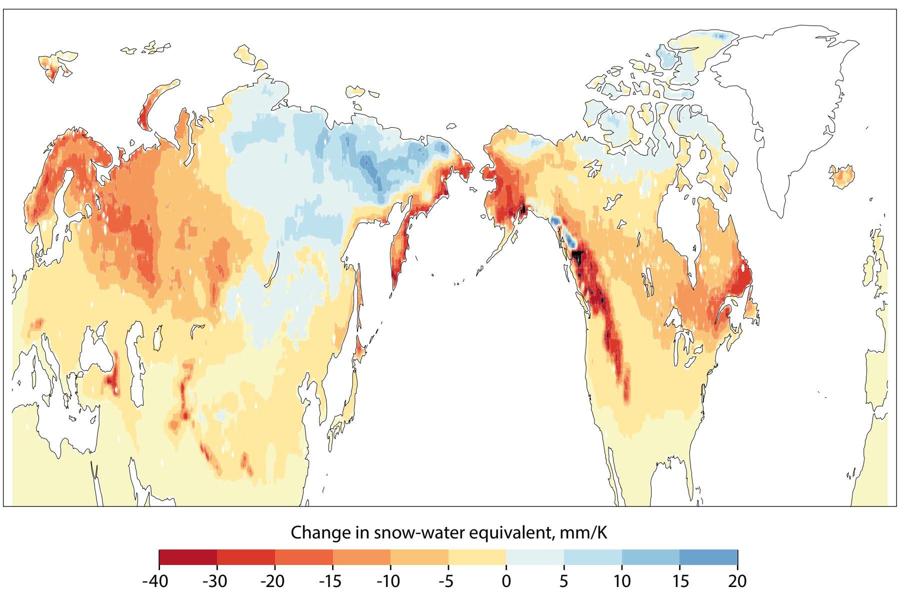


Figure 5.8 Geographical dependence of local snow-mass sensitivity (model median sensitivity based on 14 CMIP6 models under SSP5-8.5). Local sensitivity values are calculated as the change in snow-water equivalent per 1°C change in global mean near-surface air temperature.

greater warming. However, in eastern Siberia and the High Canadian Arctic the models project an increase in mid-to-late winter snow mass due to increased precipitation and surface temperatures which remain sufficiently cold.

The increased snow accumulation projected in some Arctic regions could result in complex ecosystem interactions (Meredith et al., 2019). Increased snow depth more effectively insulates and thus warms the underlying soil during winter, and results in a thicker active layer and exacerbated permafrost thaw. It can also locally increase spring soil-moisture conditions, which together with higher summer temperatures and longer growing seasons can alter the vegetation composition and phenology (Mekonnen et al., 2021). Together, these changes in vegetation composition, phenology, soil moisture, and temperature can alter the ecosystem carbon balance by affecting ecosystem net primary productivity and seasonally varying soil respiration (Natali et al., 2019). In more southern regions of the Arctic, decreased snow accumulation and earlier snowmelt can lead to drier soils and decreased water availability, with projected impacts on community water supplies and agricultural production and fire risk (Wieder et al., 2022).

Changing snow conditions (accumulation and seasonality) will impact wildlife and wildlife habitat in diverse and sometimes difficult to predict ways (Myers-Smith et al., 2011; Schmidt et al., 2012; Gagnon et al., 2020). Societally, changes in snow conditions disrupt traditional activities of northern and Indigenous Peoples, affecting overland travel, hunting, trapping, and harvesting. These changes can impact the mental health, food security, and even the entire livelihood of these groups (Meredith et al., 2019 and references therein). Winter recreation industries such as skiing and snowmobiling could also suffer from reduced snow accumulation and warmer temperatures.

5.4 Land ice

Changes in glacier ice mass arise from changes in mass inputs, mainly from snowfall, and changes in mass losses (ablation), predominantly in the form of meltwater runoff and solid ice discharge owing to iceberg calving. Other processes affecting mass accumulation are refreezing and wind-driven deposition; processes affecting mass loss are basal melting (Cuffey and Paterson, 2006; Karlsson et al., 2021) and underwater melting where glaciers are in contact with seawater (Rignot et al., 2010).

The annual mass balance for Arctic glaciers and ice caps since 1971 is derived from a scaling of the interannual variability of ground survey data from the World Glacier Monitoring Service (WGMS) (Data Ref. 5.4) satellite gravimetry after 2002 (Box et al., 2018). This 53-year record (1971–2023) also includes Greenland data from Mankoff et al. (2021). The rates of Arctic glacier ice loss have increased for all regions in each successive decade since the 1970s, indicating an acceleration of the ice loss contribution to sea-level rise (Figure 5.9).

Greenland provides the greatest contribution to sea-level rise from land ice, followed by Alaska and Arctic Canada (see Chapter 2, Figure 2.1g). For the period 2000–2019, approximately 15% of the ice loss from Greenland was from glaciers and ice caps peripheral to the ice sheet, from data after

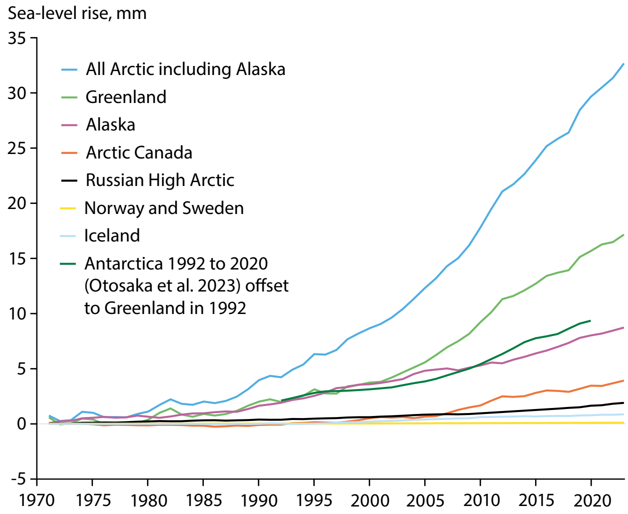


Figure 5.9 Contributions from losses of Arctic and Antarctic land ice to sea-level rise. Arctic data outside of Greenland are after Box et al. (2018) updated using the World Glacier Monitoring Service (WGMS) (Data Ref. 5.4). Greenland data are from Mankoff et al. (2021).

Hugonnet et al. (2021) and Hanna et al. (2024). In 2012 and 2019 there was a record mass loss from the Greenland Ice Sheet that caused the annual eustatic sea level to rise each year by 1.5 mm (Tedesco et al., 2013; Sasgen et al., 2020). It should be noted that Alaskan glaciers are concentrated south of 62°N. The rates of land-ice loss from Alaska and Arctic Canada accelerated after 2005, driven by surface melting (Sharp et al., 2011; O'Neel et al., 2019). Studies have also documented accelerated glacier mass loss across the Russian Arctic (Zheng et al., 2018; Tepes et al., 2021; Sommer et al., 2022) and across Svalbard (Morris et al., 2020; Noël et al., 2020; Schuler et al., 2020). Greenland ice, including the ice sheet and peripheral glaciers, exhibits a mass budget disequilibrium indicated by its average end of summer snowline position in the 2000–2019 period that commits at least 3.3% ice loss, equivalent to 274±68 mm global sea-level rise (Box et al., 2022).

Variations in the sea-level contribution of Arctic land ice are caused by year-to-year fluctuations in persistent weather patterns associated with the northern polar vortex (Sasgen et al., 2022). Such persistent atmospheric circulation extremes lead to high and low extremes in surface melting and the rate of mass loss from Greenland (Box et al., 2012; Hanna et al., 2015; McLeod and Mote, 2016; Bevis et al., 2019; Tedesco and Fettweis, 2020). Regression of annual Greenland mass balance with the June-August average North Atlantic Oscillation (NAO) index (Data Ref. 5.5) yields a correlation coefficient of 0.7, confirming the NAO association. However, the accelerated ice loss exceeds any trends in the NAO index. In addition to persistent extremes, recent analysis suggests that the amplified Arctic warming and increasing moist atmospheric rivers reaching Greenland (Mattingly et al., 2016) are additional drivers of increasing ice sheet melt.

The IPCC AR6 (IPCC, 2021) concluded that global mean sea-level rise since the late 1960s is mostly caused by increased loss of ice sheet mass, with the melting of the Greenland Ice Sheet (including peripheral glaciers) contributing approximately 1.7 times that of Antarctica for 2006–2018 (Fox-Kemper et al., 2021). Over this period, the global land-ice contribution was

51% of the total sea-level rise, while ocean thermal expansion accounted for 34% and land water extraction was 15%. From 1992 to the end of 2020, Greenland contributed 1.8 times that of Antarctica to global sea level, with the greater proportional contribution (1.9 times that from Antarctica) occurring between 2005 and 2020. From these data, there is still no sign of Antarctica taking over from Greenland despite Antarctica being roughly ten times larger in volume (Otosaka et al., 2023).

5.5 Sea ice

5.5.1 Observed trends: sea-ice extent

Sea-ice extent is defined as the total surface area covered by sea ice above a threshold concentration (typically 15%, as is used here). While both sea-ice area and sea-ice extent are used to describe the spatial coverage of sea ice, sea-ice extent has been used more broadly in both public reporting and climate model assessments. Sea-ice concentration has been consistently derived by spaceborne passive microwave instruments since late 1978, making it one of the longest satellite-derived climate records. Passive microwave instruments are particularly valuable because they provide near-complete daily coverage of the Arctic region (outside of a 'pole hole' region around the North Pole) in nearly all sky (including night-time and most cloud) conditions.

Several algorithms have been developed to derive sea-ice concentration, and then sea-ice extent, from the input passive microwave brightness temperature data. The present assessment uses the NASA Team algorithm (Cavalieri et al., 1984) developed at NASA Goddard. A consistent time-series of NASA Team concentrations, with adjustments for changing satellite sensors (Cavalieri et al., 1999), is archived at the NASA Snow and Ice Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC) (Data Refs. 5.6 and 5.7). Different algorithm products have been evaluated in numerous studies (e.g., Ivanova et al., 2015; Kern et al., 2020), which indicate differing performance, particularly during melt season and in the marginal ice zone, the part of the Arctic where sea-ice cover is closest to open water. However, while absolute values for extent and concentration can be quite different, for large-scale analysis of long-term trends and variability the different products show good agreement (e.g., Comiso et al., 2017; Meier and Stewart, 2019).

Sea-ice extent has been calculated from the concentration fields as part of the NSIDC Sea Ice Index (Data Ref. 5.8). Arctic (total northern hemisphere) sea-ice extent time-series show strong, statistically significant (with more than 95% confidence level) downward trends over the 1979–2024 record during all months of the year. However, within the overall downward trend, there is substantial seasonal variability, from year to year, and over multiple years. Two months of particular interest are September (month of the annual minimum extent) and March (month of the annual maximum extent).

In September, there was a moderate downward trend from 1979 through 1992 (Figure 5.10a). The 1993–2006 period shows a

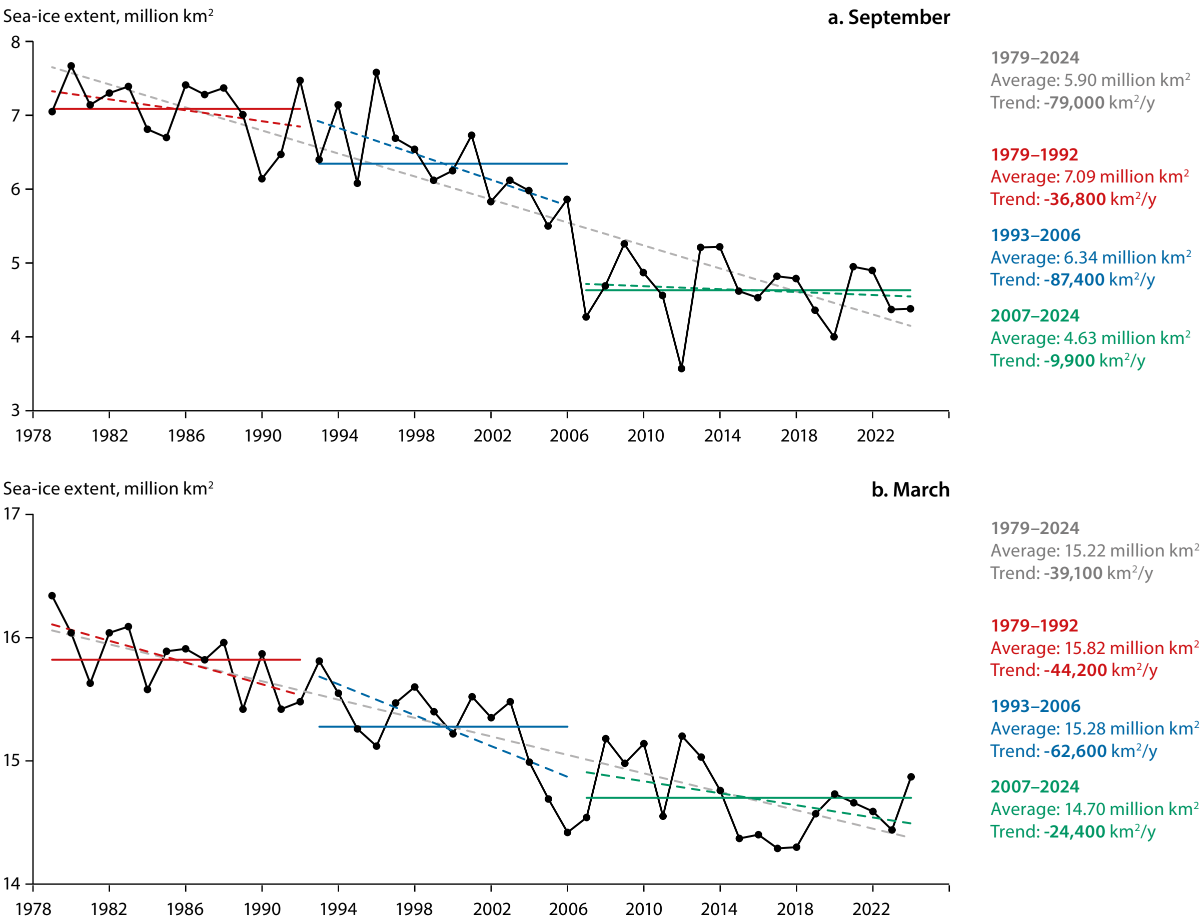


Figure 5.10 Arctic sea-ice extent time series and linear trend 1979–2024 for (a) September (seasonal minimum) and (b) March (seasonal maximum) (Data Ref 5.8). Dashed lines indicate linear trends for the indicated period and colored solid lines indicate the average for each sub-period.

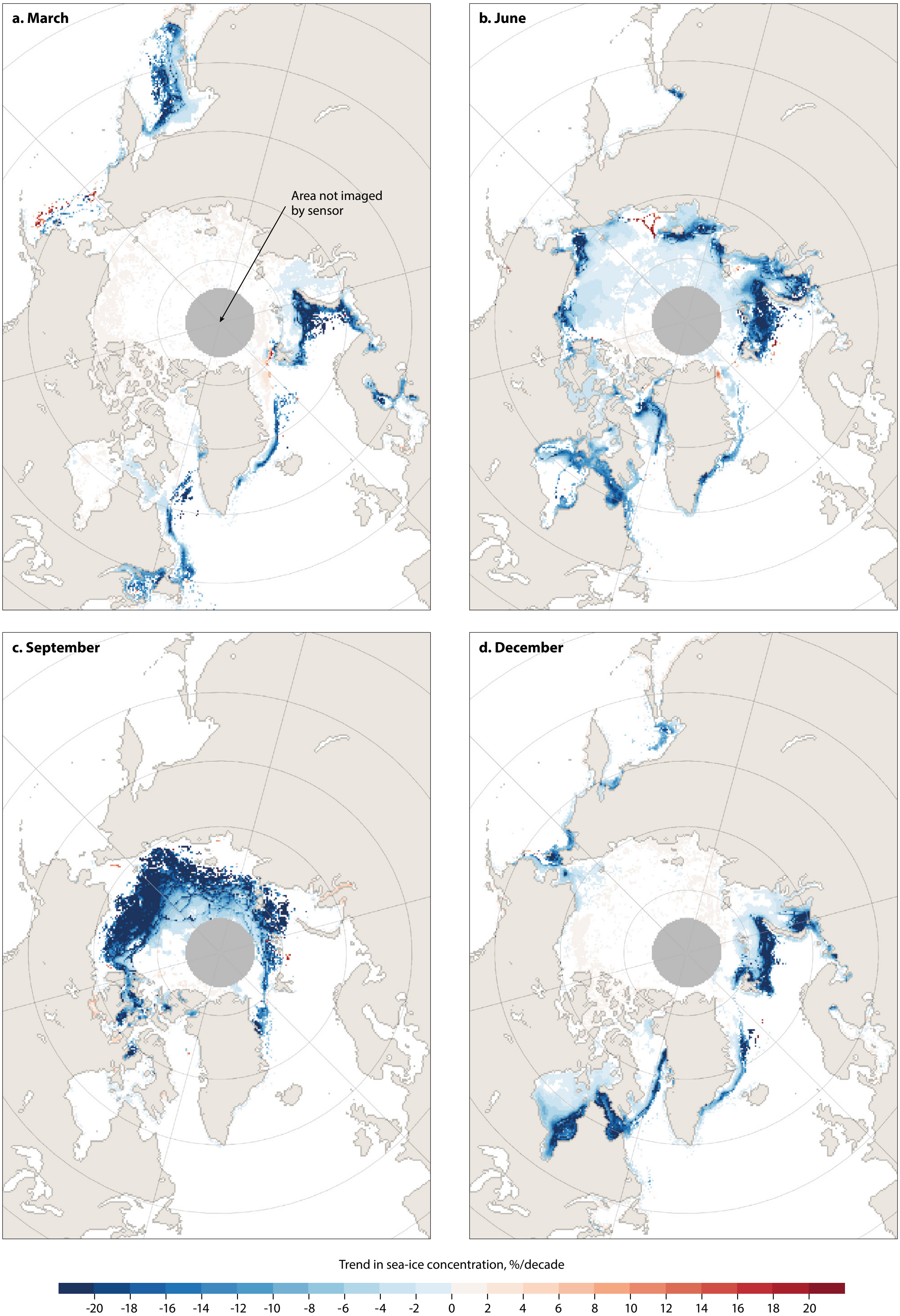


Figure 5.11 Arctic sea-ice concentration trends, 1979–2024 for March, June, September, and December. Trends shown are in % per decade and are statistically significant (p<0.05). The light gray circle around the pole indicates the region not covered by all satellites over the timeseries; trends are not calculated in that area. Images are adapted from the NSIDC Sea Ice Index (Data Ref. 5.8).

substantial decrease, followed by a sharp step change between 2006 and 2007 that resulted in a record low up to that time. Since 2007, extents have been at a much lower level than the previous 13-year period, with another record low in 2012. The 18 years from 2007 to 2024 comprise the lowest sea-ice extent in the 46-year satellite record. However, over this period, the trend has been flat. The ice remaining stays in the region north of Greenland and the Canadian Arctic Archipelago where it is continuously replenished via the Transpolar Drift Stream; that circulation also dynamically thickens the ice through convergence and ridging. In March, the downward trend is of lower magnitude, but is statistically significant ($p<0.05$) (Figure 5.10b). The linear trend of March sea-ice extent remains relatively consistent between the early and recent periods of the record, in contrast to September, which shows a fourfold change between these periods. The middle period (1993–2006) also exhibits statistically significant downward trends, nearly twice as steep as those of the early and recent intervals.

Sea-ice loss occurs in all Arctic regions and in all seasons (Figure 5.11). In nearly all locations where there is monthly variability, there are statistically significant ($p<0.05$) decreases in concentration. The only notable exception is in the Bering Sea in March. The summer (June, September) trends are stronger than those for winter and more widespread, covering a substantial part of the pack ice. Winter (December, March) trends are strong mostly near the ice edge.

Trends in regional sea-ice extent are calculated across the timeseries for March and September, based on regions as defined by Data Ref. 5.9. The extent also shows a negative trend over the record for all regions that have variability during the month (Figure 5.12). Of the regions that show variability during both months, all show a statistically significant ($p<0.05$) negative trend except for the Bering Sea during March. Some regions have no variability – they are either 100% ice-covered or 100% ice-free – in either March or September and thus have zero trend. Other months (not shown) have similar negative trends when there is variability in a given region.

5.5.2 Observed trends: sea-ice thickness

Accompanying the rapid declines in sea-ice cover, sea-ice thickness in the Arctic has also declined in recent decades. Sea-ice thickness is integral to its quality, directly influencing its strength, ecological role, climate importance, and usability for human activities. The thickness of Arctic sea ice continues to remain at levels well below those of earlier decades (1970s to 1990s), albeit with substantial regional and interannual variability (Meredith et al., 2019; Perovich et al., 2020). The ice has thinned concurrently with a shift to younger ice: since 1979, the areal proportion of thick ice at least 5 years old has declined by approximately 90% (Meredith et al., 2019). CryoSat-2, launched on 8 April 2010 by the European Space Agency, is dedicated to measuring polar sea-ice thickness and monitoring changes in ice sheets by means of radar altimetry. It can detect changes as small as 1.6 cm/y in sea-ice thickness. Another of ESA's missions, the Soil Moisture and Ocean Salinity (SMOS) satellite, was launched on 2 November 2009 and uses a radiometer to measure surface brightness temperatures, among others determining thin ice floating in the polar seas. Taking advantage of their complementary features, Ricker et al. (2017) were able to merge the CryoSat-2 and SMOS satellite data products to produce a weekly Arctic sea-ice thickness data record. Based on the merged CryoSat-2 and SMOS satellite ice-thickness data, it is clear that although sea-ice extent has shown a negative trend (Figure 5.12) in all regions, sea-ice thickness averaged over each region shows both negative and positive trends (Figure 5.13) for the period 2011–2022 when satellite-derived ice thickness data are available. One reason for such large variability is that the available data period is relatively short (12 years). This is consistent with the sea-ice extent trend shown in the previous section: when the entire satellite record was divided into three periods, linear trends are different for each period. For a time span further back in time, the thinning of Arctic sea ice since the 1980s has been reported by AMAP (2021a) and Gulev et al. (2021). More details on this thinning became clear from new research in which

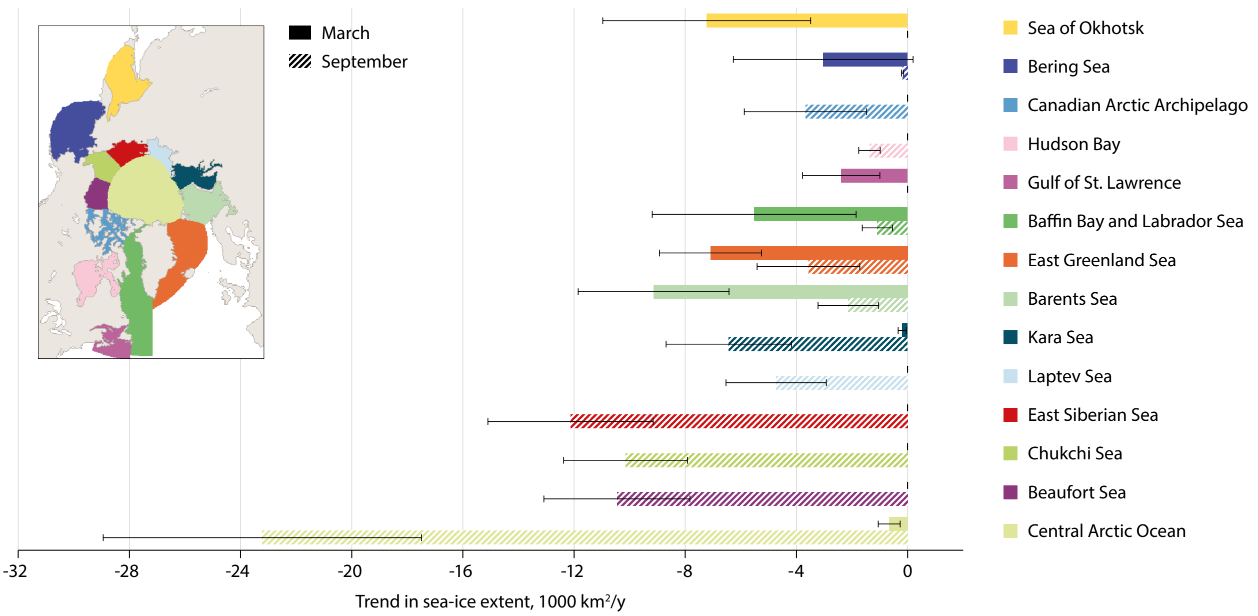
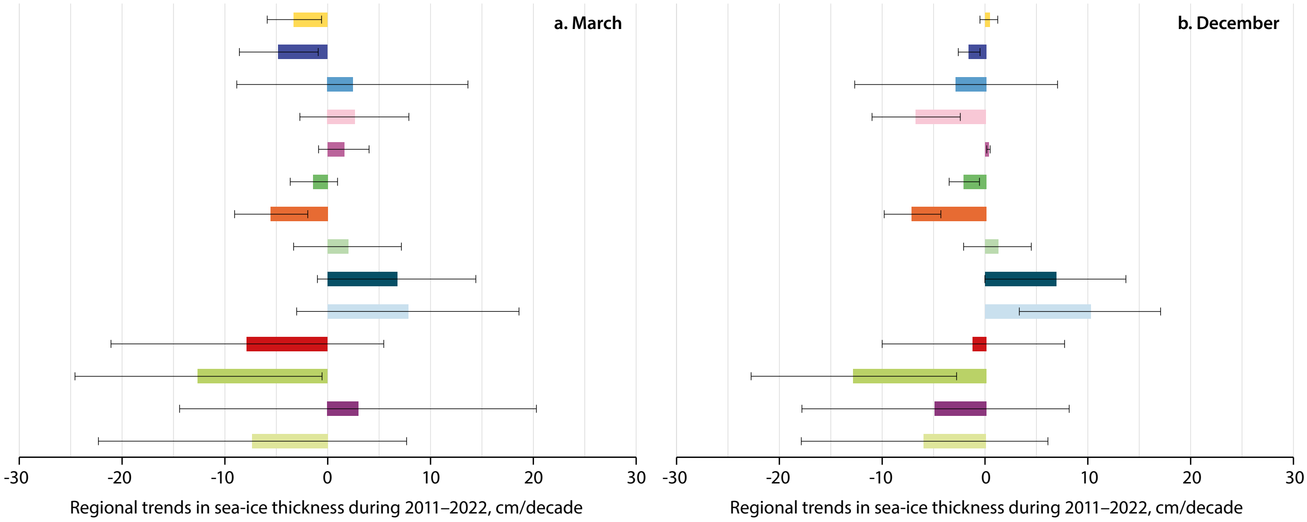


Figure 5.12 Regional sea-ice extent trend statistics for March and September for 1979 through 2022. Regions are denoted by the colors in the inset image, as defined by Data Ref 5.9. The whisker lines indicate the $p<0.05$ statistical significance level of each trend. If no bar is visible, it indicates zero trend for the month.



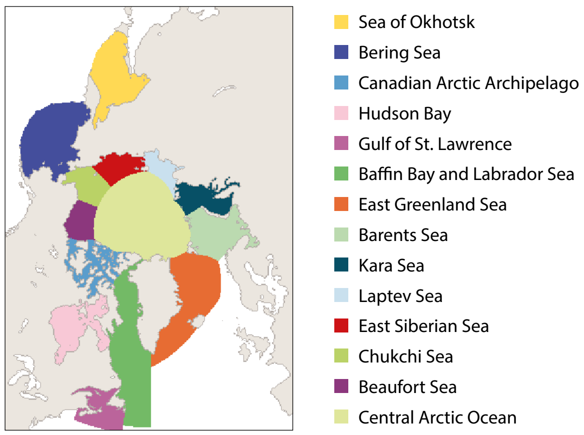


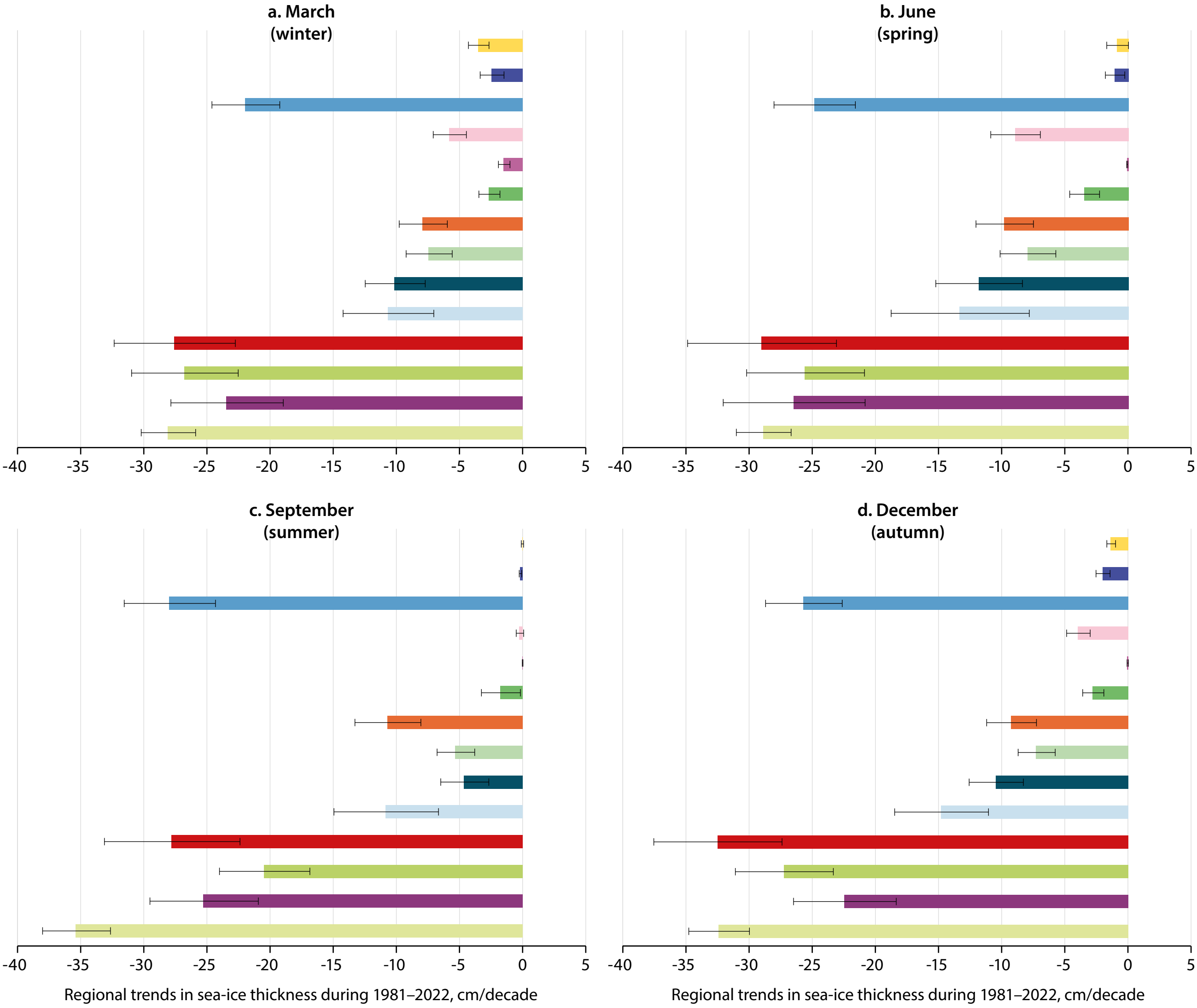
Figure 5.13 Regional trends in sea-ice thickness for March and December. The trends are calculated based on the merged CryoSat-2 and SMOS satellite sea-ice thickness data (Ricker et al., 2017) from Data Ref. 5.10.

data from upward-looking sonars installed since 1990 in Fram Strait, the main export gate for sea ice drifting out of the central Arctic Ocean, were analyzed (Sumata et al., 2023). This work revealed a regime shift for Arctic sea ice in 2007 from thicker and deformed ice to thinner and more uniform ice (change of modal thickness from 2.7 to 1.7 m), attributed to a two-step change of on-average shorter residence time of sea ice from 4.3 to 2.7 years in the central Arctic Ocean in 2005 and 2007. However, as indicated above, over shorter periods and on more regional scales, an increase in sea-ice thickness is also possible, as shown in a study by Hansen et al. (2023), analyzing upward-looking sonar data from 2014–2020 for the western Barents Sea. Sea-ice thickness data from the relatively new NASA ICESat-2 laser altimeter satellite (launched 15 September 2018) show promising results, and a reduction in Arctic sea-ice thickness, when comparing data from 2019 with thicknesses derived from observations with the first NASA ICESat satellite from 2008 (Petty et al., 2020).

As discussed in the previous section, sea-ice extent has shown strong, statistically significant declining trends at both the pan-Arctic and regional scale for 1979–2022, but with large multi-year variability. In contrast, the linear trend for sea-ice thickness computed for 2011–2022 shows considerable regional variability, which is partly due to the limited period of observational data (see Figures 5.12 and 5.13). Using climate models, it was possible to examine the trend in sea-ice thickness over a longer period. A regional breakdown of the linear trend in sea-ice thickness is shown in Figure 5.14, which covers both the historical period 1981–2014 and 2015–2022 under the SSP1-2.6 scenario. The SSP1-2.6 scenario was chosen to show the change for the most optimistic scenario. However, the choice of scenario makes little difference before 2025. Simulation results from CMIP6, the most recent generation of climate models, show a consistent negative linear trend for each region in each of the four seasons: winter (March), spring (June), summer (September), and autumn (December) for the period 1981–2022. The largest reductions in ice thickness occur in the Pacific sector of the Arctic Ocean: including the Beaufort Sea, Chukchi Sea, East Siberian Sea, and the Canadian Arctic Archipelago, as well as the central Arctic Ocean (Figure 5.14). There are some seasonal variations in the declining trend. For example: the Chukchi Sea shows the largest declining trend in winter and the smallest trend in summer; in the East Siberian Sea, the largest declining trend was observed in autumn.

5.5.3 Sea-ice projections

The CMIP6 models project negative linear trends in sea-ice thickness for the coming four decades, for all seasons and all regions under SSP1-2.6, one of the low emissions scenarios used in the IPCC AR6 assessment (Figure 5.15). The magnitude of the declining trend is projected to be about half that of the



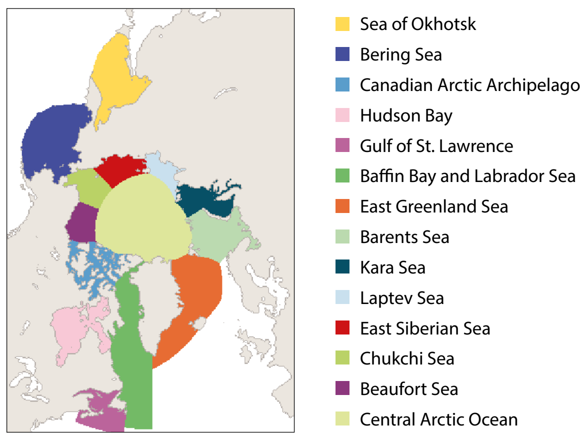


Figure 5.14 Regional trends in sea-ice thickness from four representative months: March (winter), June (spring), September (summer), and December (autumn). Data are based on the ensemble mean of CMIP6 model simulations, a combination of the historical period 1981–2014 and 2015–2022 under the SSP1-2.6 scenario.

past 40 years, ranging from 20% to 70% depending on region and season. The three largest declining trends in ice thickness are projected to occur in the Beaufort Sea, the Canadian Arctic Archipelago, and the central Arctic for all four seasons (Figure 5.15). Under the very high emissions scenario, SSP5-8.5 (not shown), the projected negative trend in sea-ice thickness is about twice that projected under the SSP1-2.6 scenario.

Another important scientific question is whether the Arctic could become ice-free in summer, which is defined as a sea-ice extent of less than 1 million km^2 (Wang and Overland, 2009). Based on a subgroup of CMIP3 and CMIP5 models, Wang and Overland (2009, 2012) projected that a sea ice-free Arctic in summer could be reached by 2035. Recent review studies found a distinct improvement in CMIP6 sea-ice simulations compared to previous generations of CMIPs (AMAP, 2021a; Jahn et al., 2024). According to the CMIP6 models, the Arctic is projected to be ice-free in summer under the high emissions scenario SSP5-8.5 as early as 2040 (AMAP, 2021a), and between 2060 and 2100 under the SSP2-4.5 and SSP3-7.0 scenarios. An ensemble mean of CMIP6 models under SSP1-2.6 (a low

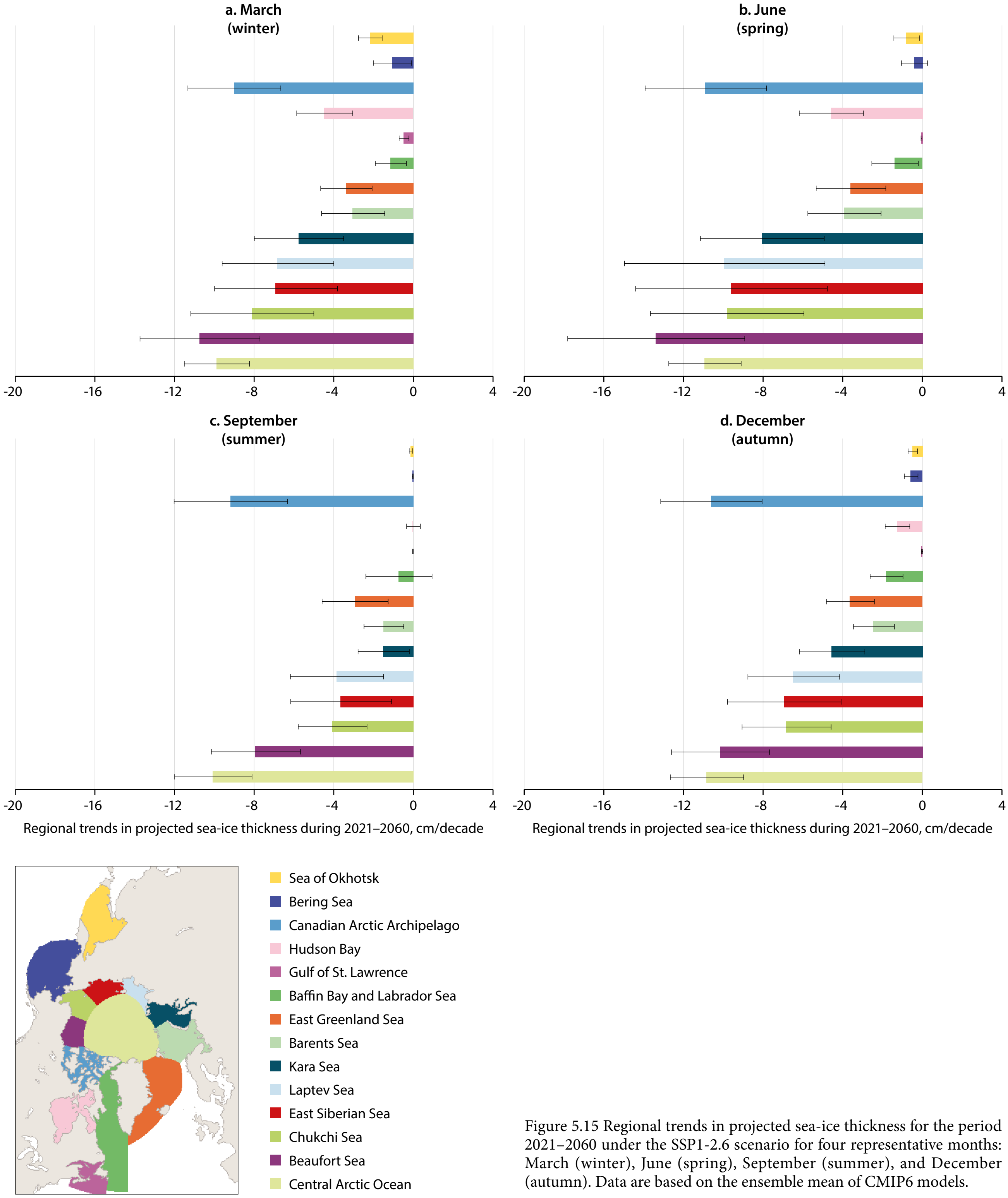


Figure 5.15 Regional trends in projected sea-ice thickness for the period 2021–2060 under the SSP1-2.6 scenario for four representative months: March (winter), June (spring), September (summer), and December (autumn). Data are based on the ensemble mean of CMIP6 models.

emissions scenario) projected no ice-free summers in the Arctic (AMAP, 2021a). This finding is consistent with the outcome of IPCC AR6, which concluded that under the very low (SSP1-1.9) and low (SSP1-2.6) emissions scenarios, a sea ice-free Arctic Ocean during summer could be avoided (IPCC, 2021).

Recent studies have attempted to improve sea-ice projections using observational constraints (Bonan et al., 2021; Kim et al., 2023). Bonan et al. (2021) constructed a simple model that projects future sea-ice area (SIA) based on present SIA and the sensitivity of SIA to changes in Arctic temperature. Sea-ice area is the total area covered by sea ice, accounting for the fraction of each grid box that is actually covered by ice. The correlation of SIA and sea-ice extent (SIE) is generally high, and they are closely aligned. Bonan et al. (2021) found that the constrained projections based on observations show a 10–35 year earlier ice-free Arctic than the unconstrained projections. Kim et al. (2023) used a formal attribution approach to show that the largest driver of recent Arctic sea-ice trends, forcing due to the increase in greenhouse gases in the atmosphere, is detectable in all months of the year, and that this impact is underestimated by models. A correction based on scaling the impact of greenhouse gases resulted in a projected ice-free Arctic by 2050 not only in the moderate and high emissions scenarios, but also in the low emissions scenarios. This result is consistent with a previous study (Notz and SIMIP Community, 2020). These results are also consistent with the observation that, on average, climate models underestimate the observed sea-ice loss, although interpretation of the results is complicated by the fact that observed sea-ice loss is the result of climate forcing and internal variability, and the amplitude of internal variability is unknown. Overall, these studies suggest that future sea ice may decline faster than unconstrained CMIP6 model simulations project. A review by Jahn et al. (2024) based on CMIP5 and CMIP6 model simulations also suggested that an ice-free Arctic in summer could be reached as early as 2040, consistent with the findings of Wang and Overland (2009, 2012) using CMIP3 and CMIP5 simulation results. The timing of an ice-free Arctic summer is influenced by the magnitude of global warming. Jahn et al. (2024) also found that the probability of at least one ice-free September occurring before 2050 is extremely unlikely if global warming remains below 1.5°C, consistent with the previous findings that the probability of an ice-free Arctic summer is an order of magnitude smaller under a 1.5°C global warming scenario compared with a 2.0°C global warming scenario (AMAP, 2021a).

Two other recent studies report substantial increases in open-water season lengths based on CMIP6 model results. Crawford et al. (2021) and Jahn et al. (2024) both found that, averaged over the Arctic Ocean as a whole, the open-water period could increase by more than two months under 2°C global warming (compared to the 1850–1900 average), and that most of the Arctic Ocean could be ice-free for three months under 3.5°C and for six months under 5°C of global warming.

5.5.4 Impacts of sea-ice change

Changes in seasonal sea-ice extent and thickness are altering marine primary production, with impacts on ecosystems, and shipping routes through the Arctic. Thicker sea ice is stronger and more resistant to external forces like wind, waves, and ocean currents. This stability is essential for supporting structures such as polar research stations and for providing habitat for marine species like polar bears and seals, as well as a stable platform for Indigenous people hunting. Thinning of sea ice also influences heat and moisture exchange between the ocean and atmosphere, which amplifies changes in polar environments, weather patterns, and ecosystems. Shorter transit times allow more access for shipping, which to some extent already has increased (e.g., Stocker et al., 2020) and will further increase Arctic ship-based transportation and tourism. This will have socioeconomic and political implications for global trade, northern nations, and economies linked to traditional shipping corridors as sea ice declines or diminishes. Mudryk et al. (2021) focused on the Canadian Arctic and quantified the impact of declining sea ice on navigability, based on the operational Polar Code regulations. They found the largest shift in ship-accessible season length to be in the Beaufort Sea region, and 100% navigability probability for part of the year above 2°C for the Northwest Passage and Arctic Bridge trade routes. These results highlight the dramatic impact of future climate change on global trade routes, even under low to moderate emissions scenarios.

Sea ice provides crucial habitat for many Arctic species, including polar bears, walruses, seals, and various types of marine life. A reduction in sea ice and its snow cover can disrupt these ecosystems by altering habitat availability, food-web dynamics, and predator-prey relationships (e.g., Steiner et al., 2021; Kovacs et al., 2024). Sea ice influences atmosphere-ocean heat exchange, as well as atmospheric circulation patterns, which in turn affect weather patterns both locally and globally. Disruption of the atmospheric circulation patterns can lead to changes in precipitation, temperature, and extreme weather events. Other effects associated with reduced sea ice include an increase in coastal erosion and increased storm surges (Nielsen et al., 2022).

5.6 Snow on sea ice

Snow on sea ice plays a critical role in the evolution of the sea ice, through its effect on surface albedo, its insulating effect, and its role in melt pond formation (AMAP, 2021a). Snow on sea ice is also relevant for the lower atmosphere over sea ice and for the marine ecosystem, and snow thickness information is important for calibration of satellite remote sensing products (Stroeve et al., 2020; AMAP, 2021a), and calculation of climate reanalysis datasets (e.g., Herrmannsdörfer et al., 2023).

New findings since AMAP's previous climate change assessment (AMAP, 2021a) are being generated through various means:

1. Ongoing research that includes awareness of the role of snow on Arctic sea ice, such as for melt pond formation (see recent work by Anhaus et al., 2021; Webster et al., 2022; Thielke et al., 2023).

2. Recent field activities, especially MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate), an international research expedition to study the physical, chemical, and biological processes that couple the Arctic atmosphere, sea ice, ocean, and ecosystems. This one-year campaign in drifting sea ice followed the Transpolar Drift route and enabled the collection of rare winter data for the central Arctic Ocean (Nicolaus et al., 2022; Wagner et al., 2022; Itkin et al., 2023).

3. Analysis of older sea ice data, including those collected from Russian drifting stations (Mallett et al., 2022) and during the International Polar Year 2007–2008, the latter including snow depth and sea-ice thickness observed at the drifting ice station Tara (Cheng et al., 2021).

Methods to quantify the snow cover, or where snow is needed as input data, have been further developed and improved (e.g., Song et al., 2020; Jutila et al., 2021; Mallett et al., 2021), as have models (e.g., Rösel et al., 2021; Webster et al., 2021) and sensors (e.g., Cabaj et al., 2020).

Snow thickness on sea ice was observed during MOSAiC to be relatively low compared to historical data (Itkin et al., 2023), with cumulative snowfall of 98–114 mm, and a precipitation mass loss of snow cover due to erosion and sublimation of between 47% and 58%, for the period 31 October 2019 to 26 April 2020. Snow-thickness distributions from the MOSAiC expedition from transect loops at its central observatory show modal snow thicknesses clearly below 10 cm for some dates in both January and July 2020 (Nicolaus et al., 2022). The presence of only little snow on Arctic sea ice is generally in line with the negative trends seen for the Arctic as a whole (except for the Atlantic sector north of Svalbard), as previously discussed and summarized by AMAP (2021a).

Understanding the effect of snow on sea ice is continuously improving. Using data from north of Svalbard combined with a 1-D snow and ice thermodynamic model, Merkouriadi et al. (2020) showed that warm events with winter storms result in additional amounts of snow on the sea ice, reducing thermodynamic sea-ice growth rates to negligible levels. New research on melt pond formation has shown that the preconditioning in winter is very important for how melt ponds form in summer and that both snow and sea-ice thickness are relevant (Thielke et al., 2023). Flooding of the ice surface of snow-covered sea ice and connected wicking (water in between snow grains being pushed upwards by capillary forces) and saturation of basal snow layers can affect the physical properties of the snow, and can bias measurements of snow thickness by snow radars (e.g., Jutila et al., 2021), leading to underestimation of snow thickness (Rösel et al., 2021). Rain-on-snow events affect snow cover and ultimately surface albedo, and new research indicates that the timing of such events has shifted in recent decades to occur earlier in the season, by up to 4–6 days per decade in some Arctic regions (Dou et al., 2021). The changing average age of sea ice since the 1980s (Meier et al., 2022) is due to less snow contributing to the sea-ice mass, since older ice used to accumulate more meltwater into its mass each melt season (Lange et al., 2021); the same research team also found that flooding events on first-year sea ice may be more prevalent throughout the Arctic Ocean than previously assumed.

References

Text references

Aas, K.S., L. Martin, J. Nitzbon, M. Langer, J. Boike, H. Lee, T.K. Bernsten and S. Westermann, 2019. Thaw processes in ice-rich permafrost landscapes represented with laterally coupled tiles in a land surface model. The Cryosphere, 13:591-609. doi:10.5194/tc-13-591-2019

Abramov, A., S. Davydov, A. Ivashchenko, D. Karelin, A. Kholodov, G. Kraev, A. Lupachev, A. Maslakov, V. Ostroumov, E. Rivkina, D. Shmelev, V. Sorokovikov, O. Tregubov, A. Veremeeva, D. Zamolodchikov and S. Sergey Zimov, 2021. Two decades of active layer thickness monitoring in northeastern Asia. Polar Geography, 44:186-202. doi:10.1080/1088937X.2019.1648581

AMAP, 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 269pp.

AMAP, 2021a. AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. viii + 148pp.

AMAP, 2021b. AMAP Assessment 2021: Mercury in the Arctic. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, 324pp.

Anhaus, P., C. Katlein, M. Nicolaus, M. Hoppmann and C. Haas, 2021. From bright windows to dark spots: Snow cover controls melt pond optical properties during refreezing. Geophysical Research Letters, 48:e2021GL095369. doi:10.1029/2021GL095369

Bartsch, A., T. Strozzi and I. Nitze, 2023. Permafrost monitoring from space. Surveys in Geophysics, 44:1579-1613. doi:10.1007/s10712-023-09770-3

Beckebanze, L., Z. Rehder, D. Holl, C. Wille, C. Mirbach and L. Kutzbach, 2022. Ignoring carbon emissions from thermokarst ponds results in overestimation of tundra net carbon uptake. Biogeosciences, 19:1225-1244. doi:10.5194/bg-19-1225-2022

Bernhard, P., S. Zwieback, S. Leinss and I. Hajnsek, 2020. Mapping retrogressive thaw slumps using single-pass TanDEMX observations. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 13:3263-3280. doi:10.1109/JSTARS.2020.3000648

Bernhard, P., S. Zwieback and I. Hajnsek, 2022a. Accelerated mobilization of organic carbon from retrogressive thaw slumps on the northern Taymyr Peninsula. The Cryosphere, 16:2819-2835. doi:10.5194/tc-16-2819-2022

Bernhard, P., S. Zwieback, N. Berngner and I. Hajnsek, 2022b. Assessing volumetric change distributions and scaling relations of retrogressive thaw slumps across the Arctic. The Cryosphere, 16:1-15. doi:10.5194/tc-16-1-2022

Bevis, M., C. Harig, S.A. Khan, A. Brown, F.J. Simons, M. Willis, X. Fettweis, M.R. van den Broeke, F.B. Madsen, E. Kendrick, D.J. Caccamise, T. van Dam, P. Knudsen and T. Nylen, 2019. Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing. Proceedings of the National Academy of Sciences, 116:1934-1939. doi:10.1073/pnas.1806562116

Biskaborn, B.K., S.L. Smith, J. Noetzli, H. Matthes, G. Vieira, D.A. Streletskiy and 43 others, 2019. Permafrost is warming at a global scale. Nature Communications, 10:264. doi:10.1038/s41467-018-08240-4

Bonan, D.B., T. Schneider, I. Eisenman and R.C.J. Wills, 2021. Constraining the date of a seasonally ice-free Arctic using a simple model. Geophysical Research Letters, 48:e2021GL094309. doi:10.1029/2021GL094309

Box, J.E., X. Fettweis, J.C. Stroeve, M. Tedesco, D.K. Hall and K. Steffen, 2012. Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. The Cryosphere, 6:821-839. doi:10.5194/tc-6-821-2012

Box, J.E., W.T. Colgan, B. Wouters, D.O. Burgess, S. O'Neel, L.I. Thomson, and S.H. Mernild, 2018. Global sea-level contribution from Arctic land ice: 1971–2017. Environmental Research Letters, 13:125012. doi:10.1088/1748-9326/aaf2ed

Box, J.E., W.T. Colgan, T.R. Christensen, N.M. Schmidt, M. Lund, F.-W. Parmentier, R. Brown, U.S. Bhatt, E.S. Euskirchen, V.E. Romanovsky, J.E. Walsh, J.E. Overland, M. Wang, R.W. Corell, W.N. Meier, B. Wouters, S. Mernild, J. Mård, J. Pawlak and M.S. Olsen, 2019. Key indicators of Arctic climate change: 1971–2017. Environmental Research Letters, 14:045010. doi:10.1088/1748-9326/aafc1b

Box, J.E., U.S. Bhatt, T.R. Christensen, C. Derksen, S. Gerland, M. Granskog, K. Isaken, J. Kohler, J. Mård, W.N. Meier, L. Mudryk, V.E. Romanovsky, A. Shiklomanov, S. Smith, I. Vanha-Majamaa, B. Wouters and D. Yang, 2021. Recent developments in Arctic climate observational indicators. In: AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, pp. 7-29.

Box, J.E., A. Hubbard, D.B. Bahr, W.T. Colgan, X. Fettweis, K.D. Mankoff, A. Wehrlé, B. Noël, M.R. van den Broeke, B. Wouters, A.A. Bjørk and R.S. Fausto, 2022. Greenland ice sheet climate disequilibrium and committed sea-level rise. Nature Climate Change, 12:808-813. doi:10.1038/s41558-022-01441-2

Bronen, R., D. Pollock, J. Overbeck, A. Stevens, S. Natali and C. Maio, 2020. Usteq: integrating Indigenous knowledge and social and physical sciences to coproduce knowledge and support community-based adaptation. Polar Geography, 43:188-205. doi:10.1080/1088937X.2019.1679271

Brown, R.D. and C. Derksen, 2013. Is Eurasian October snow cover extent increasing? Environmental Research Letters, 8:024006. doi:10.1088/1748-9326/8/2/024006

Brown, R.D., D.V. Schuler, O. Bulygina, C. Derksen, K. Loujus, L. Mudryk, L. Wang and D. Yang, 2017. Arctic terrestrial snow cover. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, pp. 25-64.

Brun, E., V. Vionnet, A. Boone, B. Decharme, Y. Peings, R. Valette, F. Karbou and S. Morin, 2013. Simulation of northern Eurasian local snow depth, mass, and density using a detailed snowpack model and meteorological reanalyses. Journal of Hydrometeorology, 14:203-219. doi:10.1175/jhm-d-12-012.1

Brutel-Vuilmet, C., M. Ménégoz and G. Krinner, 2013. An analysis of present and future seasonal Northern Hemisphere land snow cover simulated by CMIP5 coupled climate models. The Cryosphere, 7:67-80. doi:10.5194/tc-7-67-2013

Burd, K., C. Estop-Aragones, S.E. Tank and D. Olefeldt, 2020. Lability of dissolved organic carbon from boreal peatlands: interactions between permafrost thaw, wildfire, and season. Canadian Journal of Soil Science, 100:503-515. doi:10.1139/cjss-2019-0154

Burke, E.J., Y. Zhang and G. Krinner, 2020. Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change. The Cryosphere, 14:3155-3174. doi:10.5194/tc-14-3155-2020

Burn, C.R., A.G. Lewkowicz and M.A. Wilson, 2021. Long-term field measurements of climate-induced thaw subsidence above ice wedges on hillslopes, western Arctic Canada. Permafrost and Periglacial Processes, 32:261-276. doi:10.1002/ppp.2113

Cabaj, A., P.J. Kushner, C.G. Fletcher, S. Howell and A.A. Petty, 2020. Constraining reanalysis snowfall over the Arctic Ocean using CloudSat observations. Geophysical Research Letters, 47:e2019GL086426. doi:10.1029/2019GL086426

Cai, L., H. Lee, K.S. Aas and S. Westermann, 2020. Projecting circum-Arctic excess-ground-ice melt with a sub-grid representation in the Community Land Model. The Cryosphere, 14:4611-4626. doi:10.5194/tc-14-4611-2020

Callaghan, T.V., M. Johansson, R.D. Brown, P.Y. Groisman, N. Labba, V. Radionov, R.G. Barry, O.N. Bulygina, R.L.H. Essery, D.M. Frolov, V.N. Golubev, T.C. Grenfell, M.N. Petrushina, V.N. Razuvaev, D.A. Robinson, P. Romanov, D. Shindell, A.B. Shmakin, S.A. Sokratov, S. Warren and D. Yang, 2011. The changing face of Arctic snow cover: a synthesis of observed and projected changes. Ambio, 40:17-31. doi:10.1007/s13280-011-0212-y

Cavalieri, D.J., P. Gloersen and W.J. Campbell, 1984. Determination of sea ice parameters with the NIMBUS-7 SMMR. Journal of Geophysical Research: Atmospheres, 89:5355-5369. doi:10.1029/JD089iD04p05355

Cavalieri, D.J., C.l. Parkinson, P. Gloersen, J.C. Comiso and H.J. Zwally, 1999. Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets. Journal of Geophysical Research: Oceans, 104:15803-15814. doi:10.1029/1999JC900081

Chadburn, S.E., E.J. Burke, P.M. Cox, P. Friedlingstein, G. Hugelius and S. Westermann, 2017. An observation-based constraint on permafrost loss as a function of global warming. Nature Climate Change, 7:340-344. doi:10.1038/nclimate3262

Chen, Y., M.J. Lara, B.M. Jones, G.V. Frost and F.S. Hu, 2021. Thermokarst acceleration in Arctic tundra driven by climate change and fire disturbance. One Earth, 4:1718-1729. doi:10.1016/j.oneear.2021.11.011

Chen, Y., A. Liu and X. Cheng, 2022. Detection of thermokarst lake drainage events in the northern Alaska permafrost region. Science of the Total Environment, 807:150828. doi:10.1016/j.scitotenv.2021.150828

Cheng, B., T. Vihma, T. Palo, M. Nicolaus, S. Gerland, L. Rontu, J. Haapala and D. Perovich, 2021. Observation and modelling of snow and sea ice mass balance and its sensitivity to atmospheric forcing during spring and summer 2007 in the Central Arctic. Advances in Polar Science, 32:312-326. doi:10.13679/j.advps.2021.0047

Christiansen, H.H., G.L. Gilbert, U. Neumann, N. Demidov, M. Guglielmin, K. Isaksen, M. Osuch and J. Boike, 2021. Ground ice content, drilling methods and equipment and permafrost dynamics in Svalbard 2016–2019 (PermaSval). In: Moreno-Ibáñez, M., J.O. Hagen, C. Hübner, H. Lihavainen and A. Zaborska (Eds.), State of Environmental Science in Svalbard (SESS) report 2020. Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 258-275. doi:10.5281/zenodo.4294095

Clayton, L.K., K. Schaefer, M.J. Battaglia, L. Bourgeau-Chavez, J. Chen, R.H. Chen, A. Chen, K. Bakian-Dogaheh, S. Grelik, E. Jafarov, L. Liu, R.J. Michaelides, M. Moghaddam, A.D. Parsekian, S.R. Schaefer, T. Sullivan, A. Tabatabaeenejad, K. Wang, C.J. Wilson, H.A. Zebker, T. Zhang and Y. Zhao, 2021. Active layer thickness as a function of soil water content. Environmental Research Letters, 16:055028. doi:10.1088/1748-9326/abfa4c

Comiso, J.C., W.N. Meier and R. Gersten, 2017.Variability and trends in the Arctic Sea ice cover: Results from different techniques. Journal of Geophysical Research: Oceans, 122:6883-6900. doi:10.1002/2017JC012768

Crawford, A., J. Stroeve, A. Smith and A. Jahn, 2021. Arctic open-water periods are projected to lengthen dramatically by 2100. Communications Earth & Environment, 2:109. doi:10.1038/s43247-021-00183-x

Cuffey, K.M. and W.S.B. Paterson, 2006. The Physics of Glaciers. Butterworth-Heinemann/Elsevier.

Daly, S.V., P.P. Bonnaventure and W. Kochtitzky, 2022. Influence of ecosystem and disturbance on near-surface permafrost distribution, Whatì, Northwest Territories, Canada. Permafrost and Periglacial Processes, 33:339-352. doi:10.1002/ppp.2160

de la Barreda-Bautista, B., D.S. Boyd, M. Ledger, M.B. Siewert, C. Chandler, A.V. Bradley, D. Gee, D.J. Large, J. Olofsson, A. Sowter and S. Sjogersten, 2022. Towards a monitoring approach for understanding permafrost degradation and linked subsidence in Arctic peatlands. Remote Sensing, 14:444. doi:10.3390/rs14030444

Derksen, C. and L. Mudryk, 2023. Assessment of Arctic seasonal snow cover rates of change. The Cryosphere, 17:1431-1442. doi:10.5194/tc-17-1431-2023

Déry, S.J., T.A. Stadnyk, M.K. MacDonald and B. Gauli-Sharma, 2016. Recent trends and variability in river discharge across northern Canada. Hydrology and Earth System Sciences, 20:4801–4818. doi:10.5194/hess-20-4801-2016

Dou, T., C. Xiao, J. Liu, Q. Wang, S. Pan, J. Su, X. Yuan, M. Ding, F. Zhang, K. Xue, P.A. Bieniek and H. Eicken, 2021. Trends and spatial variation in rain-on-snow events over the Arctic Ocean during the early melt season. The Cryosphere, 15:883-895. doi:10.5194/tc-15-883-2021

Douglas, T.A., M.R. Turetsky and C.D. Koven, 2020. Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. npj Climate and Atmospheric Science, 3:28. doi:10.1038/s41612-020-0130-4

Douglas, T.A., C.A. Hiemstra, J.E. Anderson, R.A. Barbato, K.L. Bjella, E.J. Deeb, A.B. Gelvin, P.E. Nelsen, S.D. Newman, S.P. Saari and A.M. Wagner, 2021. Recent degradation of interior Alaska permafrost mapped with ground surveys, geophysics, deep drilling, and repeat airborne lidar. The Cryosphere, 15:3555-3575. https://doi.org/10.5194/tc-15-3555-2021

Estilow, T.W., A.H. Young and D.A. Robinson, 2015. A long-term Northern Hemisphere snow cover extent data record for climate studies and monitoring. Earth System Science Data, 7:137-142. doi:10.5194/essd-7-137-2015

Etzelmüller, B., M. Guglielmin, C. Hauck, C. Hilbich, M. Hoelzle, K. Isaken, J. Noetzli, M. Oliva and M. Ramos, 2020. Twenty years of European mountain permafrost dynamics - the PACE legacy. Environmental Research Letters, 15:104070. doi:10.1088/1748-9326/abae9d

Etzelmüller, B., K. Isaken, J. Czerkirda, S. Westermann, C. Hilbich and C. Hauck, 2023. Rapid warming and degradation of mountain permafrost in Norway and Iceland. The Cryosphere, 17:5477-5497. doi: 10.5194/tc-17-5477-2023

Euskirchen, E.S., A.P. Bennett, A.L. Breen, H. Genet, M.A. Lindgren, T.A. Kurkowski, A.D. McGuire and T.S. Rupp, 2016. Consequences of changes in vegetation and snow cover for climate feedbacks in Alaska and northwest Canada. Environmental Research Letters, 11:105003. doi:10.1088/1748-9326/11/10/105003

Evans, S.G., J.H. Raberg, S.E. Crump, M.K. Raynolds, M.M. Sugg, A.R. Brodie and G.H. Miller, 2022. Control of short-stature vegetation type on shallow ground temperatures in permafrost across the eastern Canadian Arctic. Journal of Geophysical Research: Biogeosciences, 127:e2022JG006941. doi:10.1029/2022JG006941

Farquharson, L.M., V.E. Romanovsky, W.L. Cable, D.A. Walker, S.V. Kokelj and D. Nicolsky, 2019. Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian High Arctic. Geophysical Research Letters, 46:6681-6689. doi:10.1029/2019GL082187

Farquharson, L.M., V.E. Romanovsky, A. Kholodov and D. Nicolsky, 2022. Sub-aerial talik formation observed across the discontinuous permafrost zone of Alaska. Nature Geoscience, 15:475-481. doi:10.1038/s41561-022-00952-z

Fisher, R.A. and C.D. Koven, 2020. Perspectives on the future of land surface models and the challenges of representing complex terrestrial systems. Journal of Advances in Modeling Earth Systems, 12:e2018MS001453. doi:10.1029/2018MS001453

Flanner, M.G., K.M. Shell, M. Barlage, D.K. Perovich and M.A. Tschudi, 2011. Radiative forcing and albedo feedback from the Northern Hemisphere cryosphere between 1979 and 2008. Nature Geoscience, 4:151-155. doi:10.1038/ngeo1062

Foster, A.C., J.A. Wang, G.V. Frost, S.J. Davidson, K.W. Turner, O. Sonnentag and 17 others, 2022. Disturbances in North American boreal forest and Arctic tundra: impacts, interactions, and responses. Environmental Research Letters, 17:113001. doi:10.1088/1748-9326/ac98d7

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi: 10.1017/9781009157896.011.

Fraser, R.H., S.V. Kokelj, T.C. Lantz, M. McFarlane-Winchester, I. Olthof and D. Lacelle, 2018. Climate sensitivity of High Arctic permafrost terrain demonstrated by widespread ice-wedge thermokarst on Banks Island. Remote Sensing, 10:954. doi:10.3390/rs10060954

Frost, G.V., H.E. Epstein, D.A. Walker, G. Matyshak and K. Ermokhina, 2018. Seasonal and long-term changes to active-layer temperatures after tall shrubland expansion and succession in Arctic tundra. Ecosystems, 21:507-520. doi:10.1007/s10021-017-0165-5

Gagnon, S. and M. Allard, 2020. Changes in ice-wedge activity over 25 years of climate change near Salluit, Nunavik (northern Québec, Canada). Permafrost and Periglacial Processes, 31:69-84. doi:10.1002/ppp.2030

Gagnon, C.A., S. Hamel, D.E. Russell, T. Powell, J. Andre, M.Y. Svoboda and D. Berteaux, 2020. Merging indigenous and scientific knowledge links climate with the growth of a large migratory caribou population. Journal of Applied Ecology, 57:1644-1655. doi:10.1111/1365-2664.13558

Garnello, A., S. Marchenko, D. Nicolsky, V. Romanovsky, J. Ledman, G. Celis, C. Schädel, Y. Luo and E.A.G. Schuur, 2021. Projecting permafrost thaw of sub-Arctic tundra with a thermodynamic model calibrated to site measurements. Journal of Geophysical Research: Biogeosciences, 126:e2020JG006218. doi:10.1029/2020JG006218

Gelaro, R., W. McCarty, M.J. Suárez, R. Todling, A. Molod and 25 others, 2017. The modern-era retrospective analysis for research and applications, Version 2 (MERRA-2). Journal of Climate, 30:5419-5454. doi:10.1175/JCLI-D-16-0758.1

Gibbs, A.E., L.H. Erikson, B.M. Jones, B.M. Richmond and A.C. Engelstad, 2021. Seven decades of coastal change at Barter Island, Alaska: Exploring the importance of waves and temperature on erosion of coastal permafrost bluffs. Remote Sensing, 13:4420. doi:10.3390/rs13214420

Gibson, C.M., L.E. Chasmer, D.K. Thompson, W.L. Quinton, M.D. Flannigan and D. Olefeldt, 2018. Wildfire as a major driver of recent permafrost thaw in boreal peatlands. Nature Communications, 9:3041. doi:10.1038/s41467-018-05457-1

Gibson, C., K. Cottenie, T. Gingras-Hill, S.V. Kokelj, J.L. Baltzer, L. Chasmer and M.R. Turetsky, 2021. Mapping and understanding the vulnerability of northern peatlands to permafrost thaw at scales relevant to community adaptation planning. Environmental Research Letters, 16:055022. doi:10.1088/1748-9326/abe74b

Gulev, S.K., P.W. Thorne, J. Ahn, F.J. Dentener, C.M. Domingues, S. Gerland, D. Gong, D.S. Kaufman, H.C. Nnamchi, J. Quaas, A. Rivera, S. Sathyendranath, S.L. Smith, B. Trewin, K. von Schuckmann and R.S. Vose, 2021. Changing state of the climate system. In: [Masson-Delmotte, V., P. Zhai, A. Pirani et al. (eds.)]. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, pp. 287-422. doi:10.1017/9781009157896.004

Hancock, B., W. Andersen, F. Calmels, J. Collier, A. Cunsolo and 20 others, 2022. Northern Canada. In: Warren, F.J., N. Lulham, D.I. Dupuis and D.S. Lemmen (Eds.), Canada in a Changing Climate: Regional Perspectives Report. Government of Canada, Ottawa, Chapter 6. https://changingclimate.ca/regional-perspectives/chapter/6-0/

Hanna, E., T.E. Cropper, P.D. Jones, A.A. Scaife and R. Allan, 2015. Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland Blocking Index. International Journal of Climatology, 35:2540-2554. doi:10.1002/joc.4157

Hanna, E., D. Topál, J.E. Box, S. Buzzard, F.D.W. Christie, C. Hvidberg, M. Morlighem and 22 others, 2024. Short- and long-term variability of the Antarctic and Greenland ice sheets. Nature Reviews Earth & Environment, 5:193-210. doi:10.1038/s43017-023-00509-7

Hansen, E., Å. Ervik, K. Eik, A. Olsson and S.H. Teigen, 2023. Long-term observations (2014–2020) of level ice draft, keel depth and ridge frequency in the Barents Sea. Cold Regions Science and Technology, 216:103988. doi:10.1016/j.coldregions.2023.103988

Hausner, V.E., S. Trainor, D. Cook, P. Fauchald, J. Ford, K. Klokov, V. Sokolenko and W. Wayner, 2021. Impacts of climate change and climate extremes on Arctic livelihoods and communities. In: AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway, pp. 107-144.

Heijmans, M.P.D., R.I. Magnusson, M.J. Lara, G.V. Frost, I.H. Myers-Smith, J. van Huissteden, M.T. Jorgenson, A.N. Federov, H.E. Epstein, D.M. Lawrence and J. Limpens, 2022. Tundra vegetation change and impacts on permafrost. Nature Reviews Earth & Environment, 3:68-84. doi:10.1038/s43017-021-00233-0

Henderson, G.R., Y. Peings, J.C. Furtado and P.J. Kushner, 2018. Snow–atmosphere coupling in the Northern Hemisphere. Nature Climate Change, 8:954-963. doi:10.1038/s41558-018-0295-6

Herrmannsdörfer, L., M. Müller, M.D. Shupe and P. Rostosky, 2023. Surface temperature comparison of the Arctic winter MOSAiC observations, ERA5 reanalysis, and MODIS satellite retrieval. Elementa: Science of the Anthropocene, 11:00085. doi:10.1525/elementa.2022.00085

Hjort, J., D. Streletskiy, G. Doré, Q. Wu, K. Bjella and M. Luoto, 2022. Impacts of permafrost degradation on infrastructure. Nature Reviews Earth & Environment, 3:24-38. doi:10.1038/s43017-021-00247-8

Holloway, J.E., A.G. Lewkowicz, T.A. Douglas, X. Li, M.R. Turetsky, J.L. Baltzer and H. Jin, 2020. Impact of wildfire on permafrost landscapes: A review of recent advances and future prospects. Permafrost and Periglacial Processes, 31:371-382. doi:10.1002/ppp.2048

Holmes, M.E., P.M. Crill, W.C. Burnett, C.K. McCalley, R.M. Wilson, S. Frolking, K.-Y. Chang, W.J. Riley, R.K. Varner, S.B. Hodgkins, A.P. McNichol, S.R. Saleska, V.I. Rich and J.P. Chanton, 2022. Carbon accumulation, flux, and fate in Stordalen Mire, a permafrost peatland in transition. Global Biogeochemical Cycles, 36:e2021GB007113. doi:10.1029/2021GB007113

Hori, M., K. Sugiura, K. Kobayashi, T. Aoki, T. Tanikawa, K. Kuchiki, M. Niwano and H. Enomoto, 2017. A 38-year (1978–2015) Northern Hemisphere daily snow cover extent product derived using consistent objective criteria from satellite-borne optical sensors. Remote Sensing of the Environment, 191:402-418, doi:10.1016/j.rse.2017.01.023

Hugonnet, R., R. McNabb, E. Berthier, B. Menounos, C. Nuth, L. Girod, D. Farinotti, M. Huss, I. Dussaillant, F. Brun and A. Kääb, 2021. Accelerated global glacier mass loss in the early twenty-first century. Nature, 592:726-731. doi:10.1038/s41586-021-03436-z

IPA, 1998. Multi-language Glossary of Permafrost and Related Ground Ice Terms, version 2.0. Van Everdingen, R.O. (Ed.) International Permafrost Association (IPA). University of Calgary, Canada.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (Eds.). Cambridge University Press.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.). Cambridge University Press. 1535 pp.

IPCC, 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. [Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N.M. Weyer (eds.)]. Cambridge University Press, 755 pp. https://doi.org/10.1017/9781009157964

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. doi:10.1017/9781009157896

Irrgang, A.M., M. Bendixen, L.M. Farquharson, A.V. Baranskaya, L.H. Eriksen, A.E. Gibbs, S.A. Ogorodov, P.P. Overduin, H. Lantuit, M.N. Grigoriev and B.M. Jones, 2022. Drivers, dynamics and impacts of changing Arctic coasts. Nature Reviews Earth & Environment, 3:39-54. doi:10.1038/s43017-021-00232-1

Isaksen, K., J. Lutz, A.M. Sorensen, O. Godoy, L. Ferrighi, S. Eastwood and S. Aaboe, 2022. Advances in operational permafrost monitoring on Svalbard and in Norway. Environmental Research Letters, 17:095012. doi:10.1088/1748-9326/ac8e1c

Itkin, P., S. Hendricks, M. Webster, L. von Albedyll, S. Arndt, D. Divine, M. Jaggi, M. Oggier, I. Raphael, R. Ricker, J. Rohde, M. Schneebeli, and G.E. Liston, 2023. Sea ice and snow characteristics from year-long transects at the MOSAiC Central Observatory. Elementa: Science of the Anthropocene, 11:00048. doi:10.1525/elementa.2022.00048

Ivanova, N., L.T. Pedersen, R.T. Tonboe, S. Kern, G. Heygster, T. Lavergne, A. Sørensen, R. Saldo, G. Dybkjær, L. Brucker and M. Shokr, 2015. Inter-comparison and evaluation of sea ice algorithms: towards further identification of challenges and optimal approach using passive microwave observations. The Cryosphere, 9:1797-1817. doi:10.5194/tc-9-1797-2015

Jahn, A., M.M. Holland and J.E. Kay, 2024. Projections of an ice-free Arctic Ocean. Nature Reviews Earth & Environment, 5:164-176. doi:10.1038/s43017-023-00515-9

Jones, B.M., L.M. Farquharson, C.A. Baughman, R.M. Buzard, C.D. Arp and 21 others, 2018. A decade of remotely sensed observations highlight complex processes linked to coastal permafrost bluff erosion in the Arctic. Environmental Research Letters, 13:115001. doi:10.1088/1748-9326/aae471

Jones, B.M., A.M. Irrgang, L.M. Farquharson, H. Lantuit, D. Whalen, S.A. Ogorodov and 18 others, 2020. Arctic Report Card 2020: Coastal Permafrost Erosion. National Oceanic and Atmospheric Administration. doi:10.25923/e47w-dw52

Jones, B.M., G. Grosse, L.M. Farquharson, P. Roy-Léveillée, A. Veremeeva, M.Z. Kanevskiy, B.V. Gaglioti, A.L. Breen, A.D. Parsekian, M. Ulrich and K.M. Hinkel, 2022. Lake and drained lake basin systems in lowland permafrost regions. Nature Reviews Earth & Environment, 3:85-98. doi:10.1038/s43017-021-00238-9

Jorgenson, M.T., M.Z. Kanevskiy, J.C. Jorgenson, A. Liljedahl, Y. Shur, E. Epstein, K. Kent, C.G. Griffin, R. Daanen, M. Boldenow, K. Orndahl, C. Witharana and B.M. Jones, 2022a. Rapid transformation of tundra ecosystems from ice-wedge degradation. Global and Planetary Change, 216:103921. doi:10.1016/j.gloplacha.2022.103921

Jorgenson, M.T., M. Kanevskiy, C. Roland, K. Hill, D. Schirokauer, S. Stehn, B. Schroeder and Y. Shur, 2022b. Repeated permafrost formation and degradation in Boreal peatland ecosystems in relation to climate extremes, fire, ecological shifts, and a geomorphic legacy. Atmosphere, 13:1170. doi:10.3390/atmos13081170

Jutila, A., J. King, J. Paden, R. Ricker, S. Hendricks, C. Polashenski, V. Helm, T. Binder and C. Haas, 2021. High-resolution snow depth on Arctic sea ice from low-altitude airborne microwave radar data. IEEE Transactions on Geoscience and Remote Sensing, 60:4300716. doi:10.1109/TGRS.2021.3063756

Karlsson, N.B., A.M. Solgaard, K.D. Mankoff, F. Gillet-Chaulet, J.A. MacGregor, J.E. Box, M. Citterio, W.T. Colgan, S.H. Larsen, K.K. Kjeldsen, N.J. Korsgaard, D.I. Benn, I.J. Hewitt and R.S. Fausto, 2021. A first constraint on basal melt-water production of the Greenland ice sheet. Nature Communications, 12:3461. doi:10.1038/s41467-021-23739-z

Kaverin, D., G. Malkova, D. Zamolodchikov, N. Shiklomanov, A. Pastukhov, A. Novakovskiy, M. Sadurtdinov, A. Skvortsov, A. Tsarev, A. Pochikalov, S. Malitsky and G. Kraev, 2021. Long-term active layer monitoring at CALM sites in the Russian European North. Polar Geography, 44:203-216. doi:10.1080/1088937X.2021.1981476

Kern, S., T. Lavergne, D. Notz, L.T. Pedersen and R. Tonboe, 2020. Satellite passive microwave sea-ice concentration data set inter-comparison for Arctic summer conditions. The Cryosphere, 14:2469-2493. doi:10.5194/tc-14-2469-2020

Keskitalo, K.H., L. Broder, S. Shakil, S. Zolkos, S.E. Tank, B.E. van Dongen, T. Tesi, N. Haghipour, T.I. Eglinton, S.V. Kokelj and J.E. Vonk, 2021. Downstream evolution of particulate organic matter composition from permafrost thaw slumps. Frontiers in Earth Science, 9:642675. doi:10.3389/feart.2021.642675

Keuschnig, C., C. Larose, M. Rudner, A. Pesqueda, S. Doleac, B. Elberling, R.G. Björk, L. Klemedtsson and M.P. Björkman, 2022. Reduced methane emissions in former permafrost soils driven by vegetation and microbial changes following drainage. Global Change Biology, 28:3411-3425. doi:10.1111/gcb.16137

Kim, Y.-H., S.-K. Min, N.P. Gillett, D. Notz and E. Malinina, 2023. Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. Nature Communications, 14:3139. doi:10.1038/s41467-023-38511-8

Kirdyanov, A.V., M. Saurer, R. Siegwolf, A.A. Knorre, A.S. Prokushkin, O.V. Churakova, M.V. Fonti and U. Buntgen, 2020. Long-term ecological consequences of forest fires in the continuous permafrost zone of Siberia. Environmental Research Letters, 15:034061. doi:10.1088/1748-9326/ab7469

Knoblauch, C., C. Beer, A. Schuett, L. Sauerland, S. Liebner, A. Steinhof, J. Rethemeyer, M.N. Grigoriev, A. Faguet and E.M. Pfeiffer, 2021. Carbon dioxide and methane release following abrupt thaw of Pleistocene permafrost deposits in Arctic Siberia. Journal of Geophysical Research: Biogeosciences, 126:e2021JG006543. doi:10.1029/2021JG006543

Kokelj, S.V., J. Kokoszka, J. van der Sluijs, A.C.A. Rudy, J. Tunnicliffe, S. Shakil, S.E. Tank and S. Zolkos, 2021. Thaw-driven mass wasting couples slopes with downstream systems, and effects propagate through Arctic drainage networks. The Cryosphere, 15:3059-3081. doi:10.5194/tc-15-3059-2021

Kouki, K., P. Räisänen, K. Luojus, A. Luomaranta and A. Riihelä, 2022. Evaluation of Northern Hemisphere snow water equivalent in CMIP6 models during 1982–2014. The Cryosphere, 16:1007-1030. doi:10.5194/tc-16-1007-2022

Kovacs, K.M., G.E. Liston, A.K. Reinking, S. Gerland and C. Lydersen, 2024. Climate warming impacts on ringed seal breeding habitat in Svalbard. Ecological Modelling, 495:110790. doi:10.1016/j.ecolmodel.2024.110790

Kropp, H., M.M. Loranty, S.M. Natali, A.L. Kholodov, A.V. Rocha, I. Myers-Smith, B.W. Abbot and 44 others, 2020. Shallow soils are warmer under trees and tall shrubs across Arctic and Boreal ecosystems. Environmental Research Letters, 16:015001. doi:10.1088/1748-9326/abc994

Landrum, L. and M.M. Holland, 2020. Extremes become routine in an emerging new Arctic. Nature Climate Change, 10:1108-1115. doi:10.1038/s41558-020-0892-z

Lange, B.A., C. Haas, A. Mucci, J.F. Beckers, J.A. Casey, S. Duerksen, M.A. Granskog, I. Hatam, A. Niemi, A. Reppchen and C. Michel, 2021. Contribution of snow to Arctic first-year and multi-year sea ice mass balance within the Last Ice Area. Journal of Geophysical Research: Oceans, 126:e2020JC016971. doi:10.1029/2020JC016971

Lewkowicz, A.G. and R.G. Way, 2019. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. Nature Communications, 10:1329. doi:10.1038/s41467-019-09314-7

Li, X.-Y., H.-J. Jin, H.-W. Wang, S.S. Marchenko, W. Shan, D.-L. Luo, R.-X. He, V. Spektor, Y.-D. Huang, X.-Y. Li and N. Jia, 2021. Influences of forest fires on the permafrost environment: A review. Advances in Climate Change Research, 12:48-65. doi:10.1016/j.accre.2021.01.001

Lindgren, P.R., L.M. Farquharson, V.E. Romanovsky and G. Grosse, 2021. Landsat-based lake distribution and changes in western Alaska permafrost regions between the 1970s and 2010s. Environmental Research Letters, 16:025006. doi:10.1088/1748-9326/abd270

Loranty, M.M., B.W. Abbott, D. Blok, T.A. Douglas, H.E. Epstein, B.C. Forbes, B.M. Jones, A.L. Kholodov, H. Kropp, A. Malhotra, S.D. Mamet, I.H. Myers-Smith, S.M. Natali, J.A. O'Donnell, G.K. Phoenix, A.V. Rocha, O. Sonnentag, K.D. Tape and D.A. Walker, 2018. Reviews and syntheses: Changing ecosystem influences on soil thermal regimes in northern high-latitude permafrost regions. Biogeosciences, 15:5287-5313. doi:10.5194/bg-15-5287-2018

Malkova, G., D. Drozdov, A. Vasiliev, A. Gravis, G. Kraev, Y. Korostelev, K. Nikitin, P. Orekhov, O. Ponomareva, V. Romanovsky, M. Sadurtdinov, A. Shein, A. Skvortsov, M. Sudakova and A. Tsarev, 2022. Spatial and temporal variability of permafrost in the western part of the Russian Arctic. Energies, 15:2311. doi:10.3390/en15072311

Mallett, R.D.C., J.C. Stroeve, M. Tsamados, J.C. Landy, R. Willatt, V. Nandan and G.E. Liston, 2021. Faster decline and higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover. The Cryosphere, 15:2429-2450. doi:10.5194/tc-15-2429-2021

Mallett, R.D.C., J.C. Stroeve, M. Tsamados, R. Willatt, T. Newman, V. Nandan, J.C. Landy, P. Itkin, M. Oggier, M. Jaggi and D. Perovich, 2022. Sub-kilometre scale distribution of snow depth on Arctic sea ice from Soviet drifting stations. Journal of Glaciology, 68:1014-1026. doi:10.1017/jog.2022.18

Mankoff, K.D., X. Fettweis, P.L. Langen, M. Stendel, K.K. Kjeldsen, N.B. Karlsson, B. Noël, M.R. van den Broeke, A. Solgaard, W. Colgan, J.E. Box, S.B. Simonsen, M.D. King, A.P. Ahlstrøm, S.B. Andersen and R.S. Fausto, 2021. Greenland ice sheet mass balance from 1840 through next week. Earth System Science Data, 13:5001-5025. doi:10.5194/essd-13-5001-2021

Marushchak, M.E., J. Kerttula, K. Diakova, A. Faguet, J. Gil, G. Grosse, C. Knoblauch, N. Lashchinskiy, P.J. Martikainen, A. Morgenstern, M. Nykamb, J.G. Ronkainen, H.M.P. Siljanen, L. van Delden, C. Voigt, N. Zimov, S. Zimov and C. Biasi, 2021. Thawing Yedoma permafrost is a neglected nitrous oxide source. Nature Communications, 12:7107. doi:10.1038/s41467-021-27386-2

Mattingly, K.S., C.A. Ramseyer, J.J. Rosen, T.L. Mote and R. Muthyala, 2016. Increasing water vapor transport to the Greenland Ice Sheet revealed using self-organizing maps: increasing Greenland moisture transport. Geophysical Research Letters, 43:9250-9258. doi:10.1002/2016gl070424

McCrystall, M.R., J. Stroeve, M. Serreze, B.C. Forbes and J.A. Screen, 2021. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nature Communications, 12:6765, doi:10.1038/s41467-021-27031-y

McLeod, J.T. and T.L. Mote, 2016. Linking interannual variability in extreme Greenland blocking episodes to the recent increase in summer melting across the Greenland ice sheet. International Journal of Climatology, 36:1484-1499. doi:10.1002/joc.4440

McSweeney, K. and G.J. Kooperman, 2022. Consistent timing of Arctic permafrost loss across the CESM1 large ensemble. Geophysical Research Letters, 49:e2022GL100864. doi:/10.1029/2022GL100864

Meier, W.N. and J.S. Stewart, 2019. Assessing uncertainties in sea ice extent climate indicators. Environmental Research Letters, 14:035005. doi:10.1088/1748-9326/aaf52c

Meier, W.N., A. Petty, S. Hendricks, D. Perovich, S. Farrell, M. Webster, D. Divine, S. Gerland, L. Kaleschke, R. Ricker and X. Tian-Kunze, 2022. Sea ice. In: Arctic Report Card 2022. doi:10.25923/xyp2-vz45. https://arctic.noaa.gov/Report-Card/Report-Card-2022/ArtMID/8054/ArticleID/989/Sea-Ice

Mekonnen, Z.A., W.J. Rileyk, R.F. Grant and V.E. Romanovsky, 2021. Changes in precipitation and air temperature contribute comparably to permafrost degradation in a warmer climate. Environmental Research Letters, 16:024008. doi:10.1088/1748-9326/abc444

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard and E.A.G. Schuur, 2019. Polar regions. In: Pörtner, H.-O., D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N.M. Weyer, (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press. pp. 203-320. doi:10.1017/9781009157964.005

Merkouriadi, I., B. Cheng, S.R. Hudson and M.A. Granskog, 2020. Effect of frequent winter warming events (storms) and snow on sea-ice growth – a case from the Atlantic sector of the Arctic Ocean during the N-ICE2015 campaign. Annals of Glaciology, 61:164-170. doi:10.1017/aog.2020.25

Miner, K.R., M.R. Turetsky, E. Malina, A. Bartsch, J. Tamminen, A.D. McGuire, A. Fix, C. Sweeney, C.D. Elder and C.E. Miller, 2022. Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth & Environment 3:55-67. doi:10.1038/s43017-021-00230-3

Morgenstern, A., P.P. Overduin, F. Gunther, S. Stettner, J. Ramage, L. Schirrmeister, M.N. Grigoriev and G. Grosse, 2021. Thermo-erosional valleys in Siberian ice-rich permafrost. Permafrost and Periglacial Processes, 32:59-75. doi:10.1002/ppp.2087

Morris, A., G. Moholdt and L. Gray, 2020. Spread of Svalbard glacier mass loss to Barents Sea margins revealed by CryoSat-2. Journal of Geophysical Research: Earth Surface, 125:e2019JF005357. doi:10.1029/2019jf005357

Mortimer, C., L. Mudryk, C. Derksen, K. Luojus, R. Brown, R. Kelly and M. Tedesco, 2020. Evaluation of long-term Northern Hemisphere snow water equivalent products. The Cryosphere, 14:1579-1594. doi:10.5194/ tc-14-1579-2020

Mudryk, L.R., P.J. Kushner, C. Derksen and C. Thackeray, 2017. Snow cover response to temperature in observational and climate model ensembles. Geophysical Research Letters, 44:919-926. doi:10.1002/2016GL071789

Mudryk, L., M. Santolaria-Otín, G. Krinner, M. Ménégoz, C. Derksen, C. Brutel-Vuilmet, M. Brady and R. Essery, 2020. Historical Northern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble. The Cryosphere, 14:2495-2514. doi:10.5194/tc-14-2495-2020

Mudryk, L.R., J. Dawson, S.E.L. Howell, C. Derksen, T.A. Zagon and M. Brady, 2021. Impact of 1, 2 and 4°C of global warming on ship navigation in the Canadian Arctic. Nature Climate Change, 11:673-679. doi:10.1038/s41558-021-01087-6

Muñoz-Sabater, J., E. Dutra, A. Agustí-Panareda, C. Albergel, G. Arduini, G. Balsamo, S. Boussetta, M. Choulga, S. Harrigan, H. Hersbach and B. Martens, 2021. ERA5-Land: A state-of-the-art global reanalysis dataset for land applications. Earth System Science Data, 13:4349-4383. doi:10.5194/essd-13-4349-2021

Myers-Smith, I.H., B.C. Forbes, M. Wilmking, M. Hallinger, T. Lantz, D. Blok, K.D. Tape, M. Macias-Fauria, U. Sass-Klaassen and E. Lévesque, 2011. Shrub expansion in tundra ecosystems: dynamics, impacts and research priorities. Environmental Research Letters, 6:045509. doi:10.1088/1748-9326/6/4/045509

Natali, S.M., J.D. Watts, B.M. Rogers, S. Potter, S.M. Ludwig and 70 others, 2019. Large loss of CO_2 in winter observed across the northern permafrost region. Nature Climate Change, 9:852-857. doi:10.1038/s41558-019-0592-8

Nelson, F.E., N.I. Shiklomanov and K.E. Nyland, 2021. Cool, CALM, collected: the Circumpolar Active Layer Monitoring program and network. Polar Geography, 44:155-166. doi:10.1080/1088937X.2021.1988001

Neumann, R.B., C.J. Moorberg, J.D. Lundquist, J.C. Turner, M.P. Waldrop, J.W. McFarland, E.S. Euskirchen, C.W. Edgar and M.R. Turetsky, 2019. Warming effects of spring rainfall increase methane emissions from thawing permafrost. Geophysical Research Letters, 46:1393-1401. doi:10.1029/2018GL081274

Nicolaus, M., D.K. Perovich, G. Spreen, M.A. Granskog, L. von Albedyll and 99 others, 2022. Overview of the MOSAiC expedition – snow and sea ice. Elementa: Science of the Anthropocene, 10:000046. doi:10.1525/elementa.2021.000046

Nicolsky, D.J., V.E. Romanovsky, S.K. Panda, S.S. Marchenko and R.R. Muskett, 2017. Applicability of the ecosystem type approach to model permafrost dynamics across the Alaska North Slope. Journal of Geophysical Research: Earth Surface, 122:50-75. doi:10.1002/2016JF003852

Nielsen, D.M., P. Pieper, A. Barkhordarian, P. Overduin, T. Ilyina, V. Brovkin, J. Baehr and M. Dobrynin, 2022. Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. Nature Climate Change, 12:263-270. doi:10.1038/s41558-022-01281-0

Nitzbon, J., S. Westermann, M. Langer, L.C.P. Martin, J. Strauss, S. Laboor and J. Boike, 2020. Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate. Nature Communications, 11:2201. doi:10.1038/s41467-020-15725-8

Nitze, I., G. Grosse, B.M. Jones, V.E. Romanovsky and J. Boike, 2018. Remote sensing quantifies widespread abundance of permafrost region disturbances across the Arctic and Subarctic. Nature Communications, 9:5423. doi:10.1038/s41467-018-07663-3

Nitze, I., K. Heidler, S. Barth and G. Grosse, 2021. Developing and testing a deep learning approach for mapping retrogressive thaw slumps. Remote Sensing, 13:4294. doi:10.3390/rs13214294

Noël, B., C.L. Jakobs, W.J.J. van Pelt, S. Lhermitte, B. Wouters, J. Kohler, J.O. Hagen, B. Luks, C.H. Reijmer, W.J. van de Berg and M.R. van den Broeke, 2020. Low elevation of Svalbard glaciers drives high mass loss variability. Nature Communications, 11:4597. doi:10.1038/s41467-020-18356-1

Noetzli, J., H.H. Christiansen, F. Hrbáček, K. Isaksen, S.L. Smith, L. Zhao and D.A. Streletskiy, 2021. [Global Climate] Permafrost thermal state. In: State of the Climate in 2020. Bulletin of the American Meteorological Society, 102:S42-S44. doi:10.1175/BAMS-D-21-0098.1

Notz, D. and SIMIP Community, 2020. Arctic Sea Ice in CMIP6. Geophysical Research Letters, 47:e2019GL086749. doi:10.1029/2019GL086749

Nyland, K.E., N.I. Shiklomanov, D.A. Streletskiy, F.E. Nelson, A.E. Klene and A.L. Kholodov, 2021. Long-term Circumpolar Active Layer Monitoring (CALM) program observations in Northern Alaskan tundra. Polar Geography, 44:176-185. doi:10.1080/1088937X.2021.1988000

Olvmo, M., B. Holmer, S. Thorsson, H. Reese and F. Lindberg, 2020. Sub-arctic palsa degradation and the role of climatic drivers in the largest coherent palsa mire complex in Sweden (Vissátvuopmi), 1955–2016. Scientific Reports, 10:8937. doi:10.1038/s41598-020-65719-1

O'Neel, S., C. McNeil, L.C. Sass, C. Florentine, E.H. Baker, E. Peitzsch, D. McGrath, A.G. Fountain and D. Fagre, 2019. Reanalysis of the US Geological Survey Benchmark Glaciers: long-term insight into climate forcing of glacier mass balance. Journal of Glaciology, 65:850-866. doi:10.1017/jog.2019.66

O'Neill, H.B., S.L. Smith, C.R. Burn, C. Duchesne and Y. Zhang, 2023. Widespread permafrost degradation and thaw subsidence in northwest Canada. Journal of Geophysical Research: Earth Surface, 128:e2023JF007262. doi:10.1029/2023JF007262

Otosaka, I.N., A. Shepherd, E.R. Ivins, N.-J. Schlegel, C. Amory and 63 others, 2023. Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. Earth System Science Data, 15:1597-1616. doi:10.5194/essd-15-1597-2023

Pederson, G.T., J.L. Betancourt and G.J. McCabe, 2013. Regional patterns and proximal causes of the recent snowpack decline in the Rocky Mountains, U.S. Geophysical Research Letters, 40:1811-1816. doi:10.1002/grl.50424

Peng, S., S. Piao, P. Ciais, P. Friedlingstein, L. Zhou and TY. Wang, 2013. Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades. Environmental Research Letters, 8:014008. doi:10.1088/1748-9326/8/1/014008

Perovich, D., W. Meier, M. Tschudi, S. Hendricks, A.A. Petty, D. Divine, S. Farrell, S. Gerland, C. Haas, L. Kaleschke and O. Pavlova, R. Ricker, X. Tian-Kunze, M. Webster and K. Wood, 2020. Arctic Report Card 2020: Sea Ice. doi:10.25923/n170-9h57

Petty, A.A., N.T. Kurtz, R. Kwok, T. Markus and TY.A. Neumann, 2020. Winter Arctic sea ice thickness from ICESat-2 freeboards. Journal of Geophysical Research: Oceans, 125:e2019JC015764. doi:10.1029/2019JC015764

Pulliainen, J., K. Luojus, C. Derksen, L. Mudryk, J. Lemmetyinen, M. Salminen, J. Ikonen, M. Takala, J. Cohen, T. Smolander and J. Norberg, 2020. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature, 581:294-298. doi:10.1038/ s41586-020-2258-0

Rantanen, M., A.Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma and A. Laaksonen, 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, 3:168. doi:10.1038/s43247-022-00498-3

Rettelbach, T., M. Langer, I. Nitze, B. Jones, V. Helm, J.-C. Freytag and G.A. Grosse, 2021. Quantitative graph-based approach to monitoring ice-wedge trough dynamics in polygonal permafrost landscapes. Remote Sensing, 13:3098. doi:10.3390/rs13163098

Rey, D.M., M.A. Walvoord, B.J. Minsley, B.A. Ebel, C.I. Voss and K. Singha, 2020. Wildfire-initiated talik development exceeds current thaw projections: Observations and models from Alaska's continuous permafrost zone. Geophysical Research Letters, 47:e2020GL087565. doi:10.1029/2020GL087565

Ricker, R., S. Hendricks, L. Kaleschke, X. Tian-Kunze, J. King and C. Haas, 2017. A weekly Arctic sea-ice thickness data record from merged CryoSat-2 and SMOS satellite data. The Cryosphere, 11:1607-1623. doi:10.5194/tc-11-1607-2017

Rignot, E., M. Koppes and I. Velicogna, 2010. Rapid submarine melting of the calving faces of west Greenland glaciers. Nature Geoscience, 3:187-191. doi:10.1038/NGEO765

Rodenhizer, H., J. Ledman, M. Mauritz, S.M. Natali, E. Pegoraro, C. Plaza, E. Romano, C. Schadel, M. Taylor and E. Schuur, 2020. Carbon thaw rate doubles when accounting for subsidence in a permafrost warming experiment. Journal of Geophysical Research: Biogeosciences, 125:e2019JG005528. doi:10.1029/2019JG005528

Rodenhizer, H., J. Ledman, F. Belshe, G. Celis, M. Mauritz, S. Goetz, T. Sankey and E.A.G. Schuur, 2022. Abrupt permafrost thaw accelerates carbon dioxide and methane release at a tussock tundra site. Arctic, Antarctic, and Alpine Research, 54:443-464. doi:10.1080/15230430.2022.2118639

Romanovsky, V., K. Isaksen, D. Drozdov, O. Anisimov, A. Instanes, M. Leibman, A.D. McGuire, N. Shiklomanov, S.L. Smith and D. Walker, 2017. Changing permafrost and its impacts. In: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, pp. 65-102.

Romanovsky, V.E., S.L. Smith, K. Isaksen, N.I. Shiklomanov, D.A. Streletskiy, A.L. Kholodov, H.H. Christiansen, D.S. Drozdov, G.V. Malkova and S.S. Marchenko, 2019. Terrestrial Permafrost. In: State of the Climate in 2018. Bulletin of the American Meteorological Society, 100:S153-S156. doi:10.1175/2019BAMSStateoftheClimate.1

Rösel, A., S.L. Farrell, V. Nandan, J. Richter-Menge, G. Spreen, D.V. Divine, A. Steer, J.-C. Gallet and S. Gerland, 2021. Implications of surface flooding on airborne estimates of snow depth on sea ice. The Cryosphere, 15:2819-2833. doi:10.5194/tc-15-2819-2021

Runge, A., I. Nitze and G. Grosse, 2022. Remote sensing annual dynamics of rapid permafrost thaw disturbances with LandTrendr. Remote Sensing of Environment, 268:112752. doi:10.1016/j.rse.2021.112752

Rutkowski, C., J. Lenz, A.D. Lang, J. Wolter, S. Mothes, T. Reemtsma, G. Grosse, M. Ulrich, M. Fuchs, L. Schirrmeister, A. Fedorov, M. Grigoriev, H. Lantuit and J. Strauss, 2021. Mercury in sediment core samples from deep Siberian ice-rich permafrost. Frontiers in Earth Science, 9. doi:10.3389/feart.2021.718153

Sasgen, I., B. Wouters, A.S. Gardner, M.D. King, M. Tedesco, F.W. Landerer, C. Dahle, H. Save and X. Fettweis, 2020. Return to rapid ice loss in Greenland and record loss in 2019 detected by the GRACE-FO satellites. Communications Earth & Environment, 1:8. doi:10.1038/ s43247-020-0010-1

Sasgen, I., A. Salles, M. Wegmann, B. Wouters, X. Fettweis, B.P.Y. Noël and C. Beck, 2022. Arctic glaciers record wavier circumpolar winds. Nature Climate Change, 12:249-255. doi:10.1038/s41558-021-01275-4

Schmidt, N.M., R.A. Ims, T.T. Høye, O. Gilg, L.H. Hansen, J. Hansen, M. Lund, E. Fuglei, M.C. Forchhammer and B. Sittler, 2012. Response of an arctic predator guild to collapsing lemming cycles. Proceedings of the Royal Society B, 279:4417-4422. doi:10.1098/rspb.2012.1490

Schuler, T.V., J. Kohler, N. Elagina, J.O.M. Hagen, A.J. Hodson, J.A. Jania, A.M. Kääb, B. Luks, J. Małecki, G. Moholdt, V.A. Pohjola, I. Sobota and W.J.J. Van Pelt, 2020. Reconciling Svalbard glacier mass balance. Frontiers in Earth Science, 8:156. doi:10.3389/feart.2020.00156

Schuster, P.F., K.M. Schaefer, G.R. Aiken, R.C. Antweiler, J.F. Dewild, J.D. Gryziec, A. Gusmeroli, G. Hugelius, E. Jafarov, D.P. Krabbenhoft, L. Liu, N. Herman-Mercer, C. Mu, D.A. Roth, T. Schaefer, R.G. Striegl, K.P. Wickland and T. Zhang, 2018. Permafrost stores a globally significant amount of mercury. Geophysical Research Letters, 45:1463-1471. doi:10.1002/2017GL075571

Schuur, E.A.G. and M.C. Mack, 2018. Ecological response to permafrost thaw and consequences for local and global ecosystem services. Annual Review of Ecology, Evolution, and Systematics, 49:279-301. doi:10.1146/annurev-ecolsys-121415-032349

Schuur, E.A.G., R. Bracho, G. Celis, E.F. Belshe, C. Ebert, J. Ledman, M.M. Mauritz, E.F. Pegoraro, C. Plaza, H. Rodenhizer, V. Romanovsky, C. Schadel, D. Schirokauer, M. Taylor, J.G. Vogel and E.E. Webb, 2021. Tundra underlain by thawing permafrost persistently emits carbon to the atmosphere over 15 years of measurements. Journal of Geophysical Research: Biogeosciences, 126:e2020JG006044. doi:10.1029/2020JG006044

Schuur, E.A.G., B.W. Abbott, R. Commane, J. Ernakovich, E. Euskirchen, G. Hugelius, G. Grosse, M. Jones, C. Koven, V. Leshyk, D. Lawrence, M.M. Loranty, M. Mauritz, D. Olefeldt, S. Natali, H. Rodenhizer, S. Salmon, C. Schadel, J. Strauss, C. Treat and M. Turetsky, 2022. Permafrost and climate change: carbon cycle feedbacks from the warming Arctic. Annual Review of Environment and Resources, 47:343-371. doi:10.1146/annurev-environ-012220-011847

Shakil, S., S.E. Tank, S.V. Kokelj, J.E. Vonk and S. Zolkos, 2020. Particulate dominance of organic carbon mobilization from thaw slumps on the Peel Plateau, NT: Quantification and implications for stream systems and permafrost carbon release. Environmental Research Letters, 15:114019. doi:10.1088/1748-9326/abac36

Sharp, M., D.O. Burgess, J. Graham Cogley, M. Ecclestone, C. Labine and G.J. Wolken, 2011. Extreme melt on Canada's Arctic ice caps in the 21st century. Geophysical Research Letters, 38:L11501. doi:10.1029/2011gl047381

Smith, S.L., C. Duchesne and A.G. Lewkowicz, 2019. Tracking changes in permafrost thermal state in Northern Canada. In: Bilodeau, J.-P., D.F. Nadeau, D. Fortier and D. Conciatori (Eds.), Cold Regions Engineering 2019. American Society of Civil Engineers, Quebec, Canada, pp. 670-677. https://ascelibrary.org/doi/10.1061/9780784482599.077

Smith, S.L., H.B. O'Neill, K. Isaksen, J. Noetzli and V.E. Romanovsky, 2022. The changing thermal state of permafrost. Nature Reviews Earth & Environment, 3:10-23. doi: 10.1038/s43017-021-00240-1

Smith, S.L., V.E. Romanovsky, K. Isaken, K. Nyland, N.I. Shiklomanov, D.A. Streletskiy and H.H. Christiansen, 2023. Permafrost. In: State of the Climate in 2022. Bulletin of the American Meteorological Society, 104:S301-S305. doi:10.1175/BAMS-D-23-0079.1

Smith, S.L., C. Duchesne and H.B. O'Neill, 2024. Long-term permafrost monitoring in northern Canada – What have we learned? In: Beddoe, R. and K. Karunaratne (Eds.), 12th International Conference on Permafrost. International Permafrost Association, Whitehorse Yukon, pp. 398-404. doi:10.52381/ICOP2024.84.1

Sommer, C., T. Seehaus, A. Glazovsky and M.H. Braun, 2022. Brief communication: Increased glacier mass loss in the Russian High Arctic (2010-2017). The Cryosphere, 16:35-42, doi:10.5194/tc-16-35-2022

Song, Y., A. Behrangi and E. Blanchard-Wrigglesworth, 2020. Assessment of satellite and reanalysis cold season snowfall estimates over Arctic sea ice. Geophysical Research Letters, 47:e2020GL088970. doi:10.1029/2020GL088970

Sospedra-Alfonso, R. and W.J. Merryfield, 2017. Influences of temperature and precipitation on historical and future snowpack variability over the northern hemisphere in the second generation Canadian earth system model. Journal of Climate, 30:4633-4656. doi:10.1175/JCLI-D-16-0612.1

Steiner, N.S., J. Bowman, K. Campbell, M. Chierici, E. Eronen-Rasimus, M. Falardeau and 19 others, 2021. Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene, 9:00007. doi:10.1525/elementa.2021.00007

Stocker, A.N., A.H. Renner and M. Knol-Kauffman, 2020. Sea ice variability and maritime activity around Svalbard in the period 2012–2019. Scientific Reports, 10:17043. doi:10.1038/s41598-020-74064-2

Strand, S.M., H.H. Christiansen, M. Johansson, J. Akerman and O. Humlum, 2021. Active layer thickening and controls on interannual variability in the Nordic Arctic compared to the circum-Arctic. Permafrost and Periglacial Processes, 32:47-58. doi:10.1002/ppp.2088

Strand, S.M., H.H. Christiansen and G.L. Gilbert, 2022. Permafrost thermal dynamics and cryostratigraphy at Villum Research Station, Station Nord, eastern North Greenland (81°N). Journal of Geophysical Research: Earth Surface, 127:e2021JF006502. doi:10.1029/2021JF006502

Streletskiy, D.A., N.I. Shiklomanov, J.D. Little, J.E. Nelson, J. Brown, K.E. Nyland and A.E. Klene, 2017. Thaw subsidence in undisturbed tundra landscapes, Barrow, Alaska, 1962–2015. Permafrost and Periglacial Processes, 28:566-572. doi:10.1002/ppp.1918

Stroeve, J., G.E. Liston, S. Buzzard, L. Zhou, R. Mallett, A. Barrett, M. Tschudi, M. Tsamados, P. Itkin and S. Stewart, 2020. A Lagrangian snow evolution system for sea ice applications (SnowModel-LG): Part II - Analyses. Journal of Geophysical Research: Oceans, 125:e2019JC015900. doi:10.1029/2019JC015900

Sumata, H., L. de Steur, D.V. Divine, M.A. Granskog and S. Gerland, 2023. Regime shift in Arctic Ocean sea ice thickness. Nature, 615:443-449. doi:10.1038/s41586-022-05686-x

Swanson, D.K., 2019. Thermokarst and precipitation drive changes in the area of lakes and ponds in the National Parks of northwestern Alaska, 1984–2018. Arctic, Antarctic, and Alpine Research, 51:265-279. doi: 10.1080/15230430.2019.1629222

Swanson, D.K., P.J. Sousanes and K. Hill, 2021. Increased mean annual temperatures in 2014–2019 indicate permafrost thaw in Alaskan national parks. Arctic, Antarctic, and Alpine Research, 53:1-19. doi: 10.1080/15230430.2020.1859435

Tarbier, B., G. Hugelius, A.B.K. Sannel, C. Baptista-Salazar and S. Jonsson, 2021. Permafrost thaw increases methylmercury formation in subarctic Fennoscandia. Environmental Science and Technology, 55:6710-6717. doi:10.1021/acs.est.0c04108

Taylor, M., G. Celis, J.D. Ledman, M. Mauritz, S.M. Natali, E.F. Pegoraro, C. Schadel and E.A.G. Schuur, 2021. Experimental soil warming and permafrost thaw increase CH_4 emissions in an upland tundra ecosystem. Journal of Geophysical Research: Biogeosciences, 126:e2021JG006376. doi:10.1029/2021JG006376

Tedesco, M. and X. Fettweis, 2020. Unprecedented atmospheric conditions (1948–2019) drive the 2019 exceptional melting season over the Greenland ice sheet. The Cryosphere, 14:1209-1223. doi:10.5194/tc-14-1209-2020

Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J.E. Box and B. Wouters, 2013. Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. The Cryosphere, 7:615-630. doi:10.5194/tc-7-615-2013

Tepes, P., P. Nienow and N. Gourmelen, 2021. Accelerating ice mass loss across arctic Russia in response to atmospheric warming, sea ice decline, and atlantification of the Eurasian arctic shelf seas. Journal of Geophysical Research: Earth Surface, 126:e2021JF006068. doi:10.1029/2021jf006068

Thackeray, C.W., A. Hall, M.D. Zelinka and C.G. Fletcher, 2021. Assessing prior emergent constraints on surface albedo feedback in CMIP6. Journal of Climate, 34:3889-3905. doi:10.1175/JCLI-D-20-0703.1

Thielke, L., N. Fuchs, G. Spreen, B. Tremblay, G. Birnbaum, M. Huntemann, N. Hutter, P. Itkin, A. Jutila and M.A. Webster, 2023. Preconditioning of summer melt ponds from winter sea ice surface temperature. Geophysical Research Letters, 50:e2022GL101493. doi:10.1029/2022GL101493

Turetsky, M.R., B.W. Abbott, M.C. Jones, K.W. Anthony, D. Olefeldt, E.A.G. Schuur, G. Grosse, P. Kuhry, G. Hugelius, C. Koven, D.M. Lawrence, C. Gibson, A.B.K. Sannel and A.D. McGuire, 2020. Carbon release through abrupt permafrost thaw. Nature Geoscience, 13:138-143. doi:10.1038/s41561-019-0526-0

Vasiliev, A.A., D.S. Drozdov, A.G. Gravis, G.V. Malkova, K.E. Nyland and D.A. Streletskiy, 2020. Permafrost degradation in the Western Russian Arctic. Environmental Research Letters, 15:045001. doi:10.1088/1748-9326/ab6f12

Veremeeva, A., N. Nitze, F. Gunther, G. Grosse and E. Rivkina, 2021. Geomorphological and climatic drivers of thermokarst lake area increase trend (1999–2018) in the Kolyma Lowland Yedoma Region, North-Eastern Siberia. Remote Sensing, 13:178. doi:10.3390/rs13020178

Virkkala, A.M., J. Aalto, B.M. Rogers, T. Tagesson, C.C. Treat and 44 others, 2021. Statistical upscaling of ecosystem CO_2 fluxes across the terrestrial tundra and boreal domain: Regional patterns and uncertainties. Global Change Biology, 27:4040-4059. doi:10.1111/gcb.15659

Wagner, D.N., M.D. Shupe, C. Cox, O.G. Persson, T. Uttal and 18 others, 2022. Snowfall and snow accumulation during the MOSAiC winter and spring seasons. The Cryosphere, 16:2373-2402. doi:10.5194/tc-16-2373-2022

Wang, J. and D.S. Liu, 2022. Vegetation green-up date is more sensitive to permafrost degradation than climate change in spring across the northern permafrost region. Global Change Biology, 28:1569-1582. doi:0.1111/gcb.16011

Wang, M. and J.E. Overland, 2009. A sea ice free summer Arctic within 30 years? Geophysical Research Letters, 36:L07502. doi:10.1029/2009GL037820

Wang, M. and J.E. Overland, 2012. A sea ice free summer Arctic within 30 years: An update from CMIP5 models. Geophysical Research Letters, 39:L18501. doi:10.1029/2012GL052868

Ward Jones, M.K., W.H. Pollard and B.M. Jones, 2019. Rapid initialization of retrogressive thaw slumps in the Canadian high Arctic and their response to climate and terrain factors. Environmental Research Letters, 14:055006. doi:10.1088/1748-9326/ab12fd

Way, R.G. and C.M. Lapalme, 2021. Does tall vegetation warm or cool the ground surface? Constraining the ground thermal impacts of upright vegetation in northern environments. Environmental Research Letters, 16:054077. doi:10.1088/1748-9326/abef31

Webb, E.E., A.K. Liljedahl, J.A. Cordeiro, M. Loranty, C. Witharana and J.W. Lichstein, 2022. Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. Nature Climate Change, 12:841-846. doi:10.1038/s41558-022-01455-w

Webster, M.A., A.K. DuVivier, M.M. Holland and D.A. Bailey, 2021. Snow on arctic sea ice in a warming climate as simulated in CESM. Journal of Geophysical Research: Oceans, 125:e2020JC016308. doi:10.1029/2020JC016308

Webster, M.A., M. Holland, N.C. Wright, S. Hendricks, N. Hutter, P. Itkin, B. Light, F. Lindhardt, D.K. Perovich, I.A. Raphael, M.M. Smith, L. von Albedyll and J. Zhang, 2022. Spatiotemporal evolution of melt ponds on Arctic sea ice: MOSAiC observations and model results. Elementa: Science of the Anthropocene, 10:000072. doi:10.1525/elementa.2021.000072

Whalen, D., D.L. Forbes, V. Kostylev, L. Lim, P. Fraser, M.R. Nedimović and S. Stuckey, 2022. Mechanisms, volumetric assessment, and prognosis for rapid coastal erosion of Tuktoyaktuk Island, an important natural barrier for the harbour and community. Canadian Journal of Earth Sciences, 59:945-960. doi:10.1139/cjes-2021-0101

Wieder, W., D. Kennedy, F. Lehner, K. Musselman, K. Rodgers, N. Rosenbloom, I.R. Simpson and R. Yamaguchi, 2022. Pervasive alterations to snow-dominated ecosystem functions under climate change. Proceedings of the National Academy of Sciences, 119:e2202393119. doi:10.1073/pnas.220239311

Wilcox, E.J., D. Keim, T. de Jong, B. Walker, O. Sonnentag, A.E. Sniderhan, P. Mann and P. Marsh, 2019. Tundra shrub expansion may amplify permafrost thaw by advancing snowmelt timing. Arctic Science, 5:202-217. doi:10.1139/as-2018-0028

Witharana, C., M.R. Udawalpola, A.K. Liljedahl, M.K.W. Jones, B.M. Jones, A. Hasan, D. Joshi and E. Manos, 2022. Automated detection of retrogressive thaw slumps in the High Arctic using high-resolution satellite imagery. Remote Sensing, 14:4132. doi:10.3390/rs14174132

Yang, Y., B.M. Rogers, G. Fiske, J. Watts, S. Potter, T. Windholz, A. Mullen, I. Nitze and S.M. Natali, 2023. Mapping retrogressive thaw slumps using deep neural networks. Remote Sensing of Environment, 288:113495. doi: 10.1016/j.rse.2023.113495

Young, J.M., A. Alvarez, J. van der Sluijs, S.V. Kokelj, A. Rudy, A. McPhee, B.J. Stoker, M. Margold and D. Froese, 2022. Recent intensification (2004–2020) of permafrost mass-wasting in the central Mackenzie Valley foothills is a legacy of past forest fire disturbances. Geophysical Research Letters, 49:e2022GL100559. doi:10.1029/2022GL100559

Zheng, W., M.E. Pritchard, M.J. Willis, P. Tepes, N. Gourmelen, T.J. Benham and J.A. Dowdeswell, 2018. Accelerating glacier mass loss on Franz Josef Land, Russian Arctic. Remote Sensing of Environment, 211:357-375. doi:10.1016/j.rse.2018.04.004

Zhong, X., T. Zhang, S. Kang and J. Wang, 2022. Snow depth trends from CMIP6 Models conflict with observational evidence. Journal of Climate, 35:1293-1307. doi:10.1175/JCLI-D-21-0177.1

Zweigel, R.B., S. Westermann, J. Nitzbon, M. Langer, J. Boike, B. Etzelmüller and T. Vikhamar-Schuler, 2021. Simulating snow redistribution and its effect on ground surface temperature at a high-Arctic site on Svalbard. Journal of Geophysical Research: Earth Surface, 126:e2020JF005673. doi:10.1029/2020JF005673

Data references

Data Ref. 5.1 Long-Term Observations of the Climate-Active Layer-Permafrost System. Circumpolar Active Layer Monitoring Network-CALM. www2.gwu.edu/~calm

Data Ref. 5.2 Snow Climate Change Initiative (CCI). European Space Agency (ESA). https://climate.esa.int/en/projects/snow

Data Ref. 5.3 Rutgers Northern Hemisphere 24 km Weekly Snow Cover Extent, September 1980 Onward, Version 1. https://nsidc.org/data/g10035/versions/1

Data Ref. 5.4 Fluctuations of Glaciers Database. World Glacier Monitoring Service (WGMS). doi:10.5904/wgms-fog-2024-01

Data Ref. 5.5 North Atlantic Oscillation (NAO). National Weather Service, Climate Prediction Centre www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml

Data Ref. 5.6 Meier, W.N., J.S. Stewart, H. Wilcox, M.A. Hardman and D.J. Scott, 2021. Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations, Version 2 [Data Set]. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi:10.5067/YTTHO2FJQ97K Date Accessed 01-31-2023.

Data Ref. 5.7 DiGirolamo, N., C.L. Parkinson, D.J. Cavalieri, P. Gloersen and H.J. Zwally, 2022. Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data (NSIDC-0051, Version 2). [Data Set]. Boulder, Colorado, USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi:10.5067/MPYG15WAA4WX. Date Accessed 01-31-2023

Data Ref. 5.8 Fetterer, F., K. Knowles, W.N. Meier, M. Savoie and A.K. Windnagel, 2017. Sea Ice Index, Version 3 [Data Set]. National Snow and Ice Data Center. doi:10.7265/N5K072F8. Date Accessed 01-31-2023.

Data Ref. 5.9 Meier, W.N. and J.S. Stewart, 2023. Arctic and Antarctic Regional Masks for Sea Ice and Related Data Products, Version 1 [Data Set]. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi:10.5067/CYW3O8ZUNIWC

Data Ref. 5.10 The Sea Ice Portal – Chronical of a Disappearing Land. www.meereisportal.de

Mård, J., J.E. Box, J., Culpepper, S. Sharma, A. Shiklomanov, Y. Sjöberg, T. Vihma and E. Webb, 2024. Terrestrial hydrology. In: AMAP Arctic Climate Change Update 2024: Key Trends and Impacts, pp. 57-93. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://doi.org/10.21352/q1rn-0246

6. Terrestrial hydrology

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Key findings

- *Precipitation has increased over recent decades, especially in cold seasons, and is associated with an increase in rainfall in all seasons and a decrease in snowfall in summer, with spatially varying trends in winter. This century, precipitation events presently regarded as extremes are expected to become routine. Snow mass has decreased across northern North America, but in Eurasia the trend has been negligible and snow depth has increased in parts of Eurasia.*
- *Permafrost thaw is likely to drive changes in the water balance in Arctic areas, but the relevant subsurface processes are difficult to observe directly at the catchment scale. However, observed changes in streamflow dynamics and water chemistry indicate that permafrost thaw is influencing hydrological connectivity by creating deeper and longer waterflow pathways through catchments across the Arctic.*
- *Increasing trends in annual river discharge to the Arctic Ocean from both continents have continued, providing compelling evidence of intensification of the Arctic water cycle. A significant increase in base streamflow during the cold season is observed across most regions of the pan-Arctic drainage basin. The magnitude of maximum river discharge has not changed significantly; however, the timing of snowmelt freshet has become earlier almost everywhere across the pan-Arctic.*
- *Lake area is declining across the discontinuous permafrost zone. In the continuous permafrost zone, however, the number of sites with decreasing lake area is similar to the number with increasing lake area. Stronger lake area declines in the discontinuous permafrost zone is consistent with permafrost thaw being further advanced there than in the continuous permafrost zone.*
- *Ice-cover duration on rivers has declined significantly in cold regions over the past several decades due to later freeze-up and earlier breakup. The observed decline in river ice is likely to continue in the future due to the projected increase in air temperature. Maximum river-ice thickness has decreased significantly on most pan-Arctic rivers over the last 50 to 60 years, with the greatest decrease observed before 2000.*
- *Lakes are rapidly losing ice across the Northern Hemisphere, with later ice-on dates, earlier ice-off dates, and in some years, some lakes not freezing at all.*
- *Freshwater delivery from Arctic land ice is roughly equivalent to that from North American rivers. Eurasian river discharge is roughly three times higher. However, the increase in Arctic river discharge was 1.6 times smaller than the increase in freshwater flux from Arctic land ice. Most of the increased land-ice freshwater discharge originated from Greenland and Arctic Canada. A further increase in freshwater flux from land ice reduction is likely to continue with the projected future increase in Arctic warming.*
- *Changes in the terrestrial hydrological system have important impacts on ecosystems and Arctic livelihoods. Declining snow cover, permafrost, lake area, and lake ice have implications for ecosystems, as well as for hunting, fishing, reindeer herding, transportation, and drinking water availability. Impacts also include feedbacks to the climate and ocean circulation through increased freshwater fluxes to the Arctic Ocean and changes in lake area and ice cover.*

6.1 Introduction

Climate warming has triggered rapid and substantial changes in the Arctic freshwater system by transforming frozen water into its liquid form. Melting glaciers, increased precipitation, changes in snow cover, thawing permafrost (see Chapter 5 for changes in the cryosphere), and changes in river and lake ice are altering the entire water cycle, including river regimes, groundwater recharge, and patterns of lakes and wetlands in Arctic landscapes. Changes in the freshwater system are in turn having a wide range of impacts on climate, ecosystems, landscapes, Indigenous Peoples, and other Arctic inhabitants.

The geographical domain of the terrestrial freshwater system is the pan-Arctic drainage basin (PADB) as defined by Shiklomanov et al. (2000, 2021) and used in the Arctic Freshwater Synthesis (Prowse, 2015a; see also Figure 6.1). This definition differs from the AMAP definition of the Arctic, and encompasses all land areas contributing runoff to the Arctic Ocean, including both rivers that extend equatorward of 45°N in some cases, and glaciers and ice sheets that supply freshwater directly to the marine system. Thus, the PADB comprises diverse hydrophysiographic regions, as defined by Bring et al. (2016), including Arctic tundra, boreal plains, grasslands, wetlands, mountains, shield regions, and glaciers/ice caps (Figure 6.2). These widely differing environments all exhibit local variations in hydrology and hydrological processes that together contribute to the Arctic freshwater circulation.

The Arctic freshwater system (including its sources, fluxes, storage, and effects) has been a revisited topic in initiatives and assessments over recent decades. For example, the Freshwater Budget of the Arctic Ocean (FWBAO; Lewis et al., 2000);

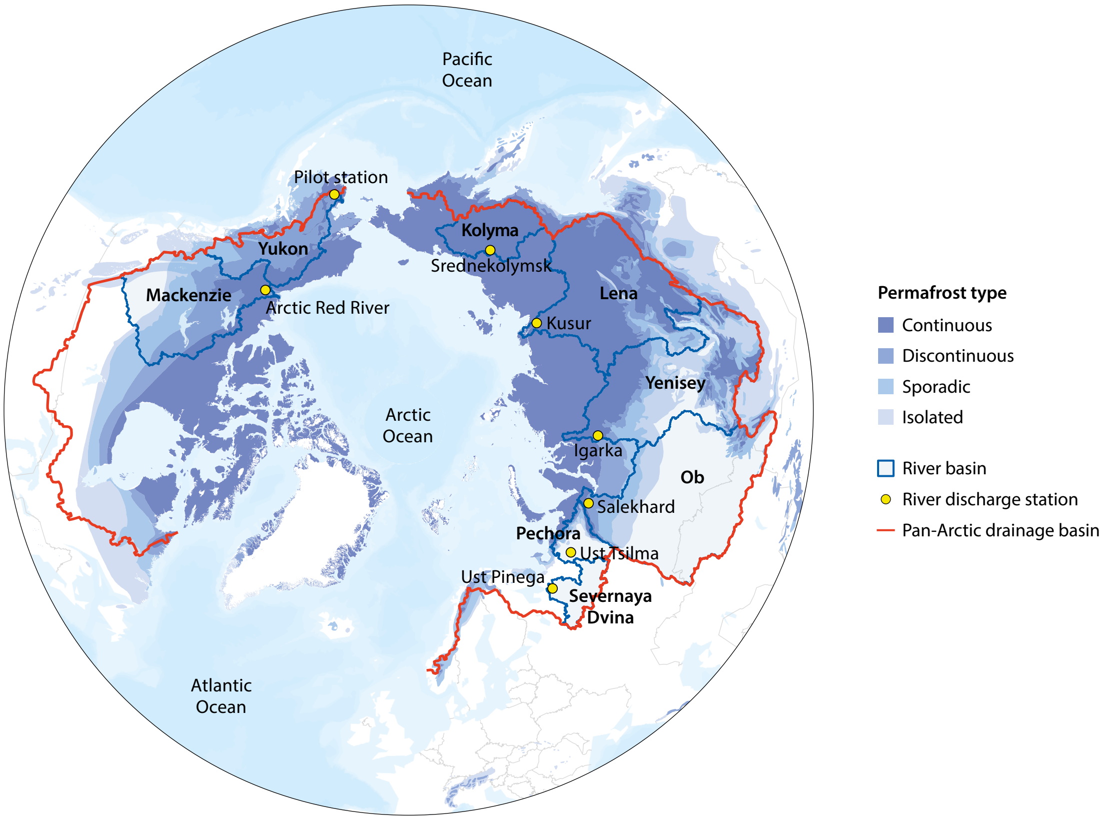

Figure 6.1 The geographical domain of the terrestrial freshwater system defined as the pan-Arctic drainage basin, including its eight largest rivers (Yenisey, Lena, Ob, Pechora, Severnaya Dvina, Kolyma, Mackenzie, Yukon). The map also shows permafrost distribution. Source: based on data from the Global Runoff Data Centre (discharge stations), HydroBASINS (river basins), and permafrost extent from Brown et al. (1997).

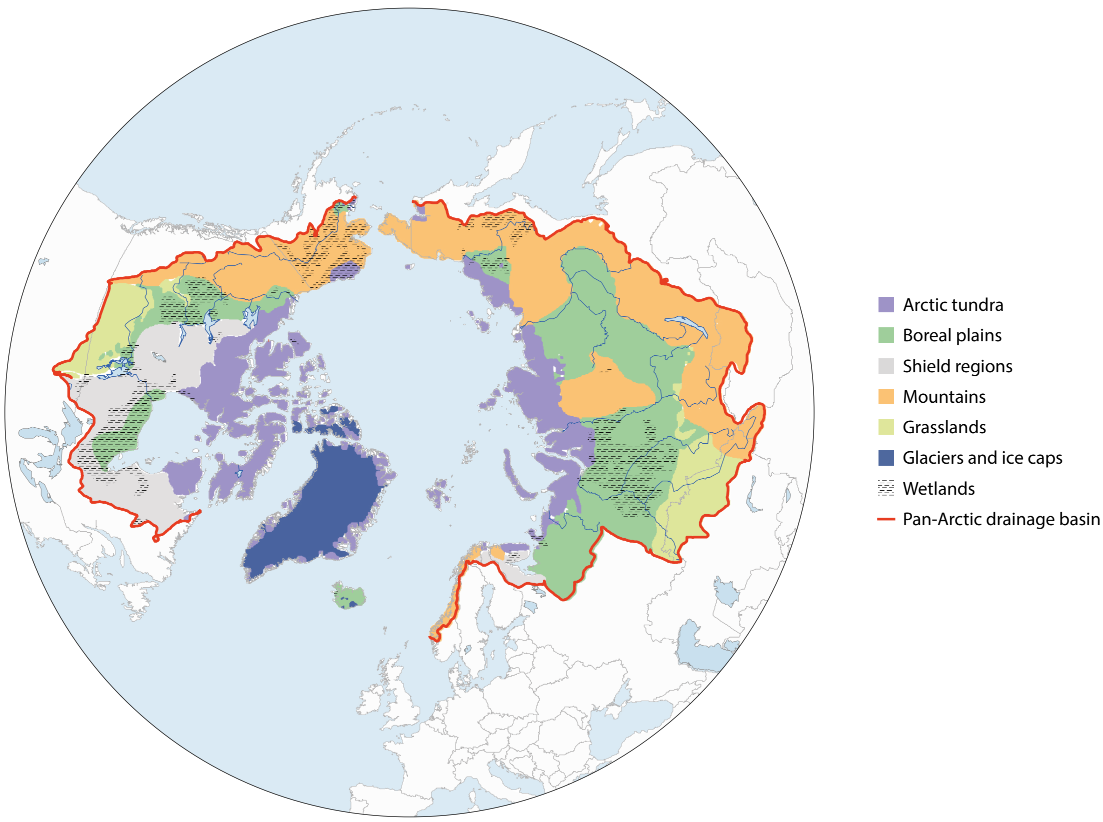

Figure 6.2 Major hydrophysiographical regions within the pan-Arctic drainage basin. Source: Bring et al. (2016).

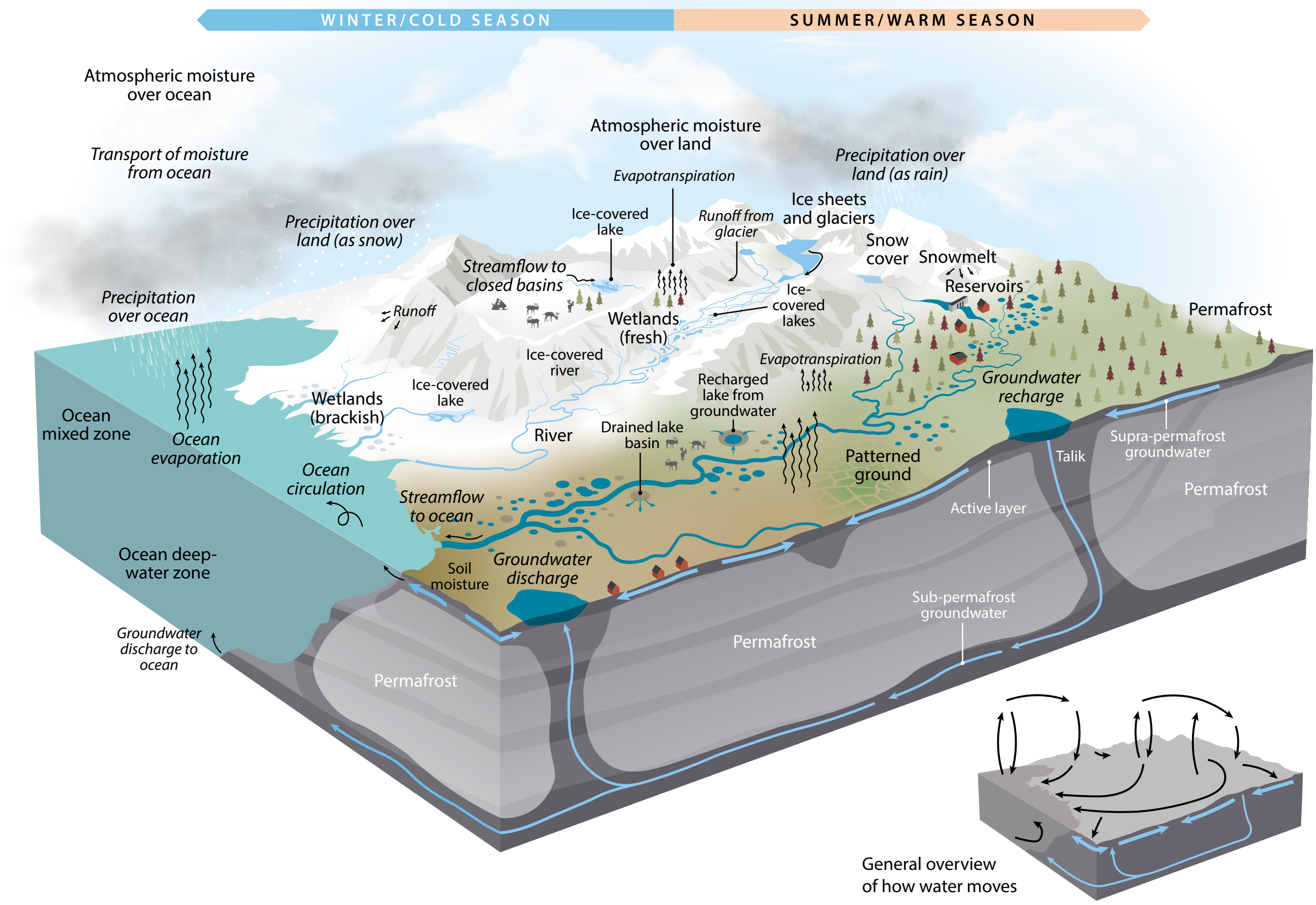

Figure 6.3 Conceptual illustration of the climate-water interactions and key processes within the terrestrial hydrological domain addressed in this chapter, including water stored in the atmosphere, oceans, and on or below the Earth's surface, and fluxes between storage sites (shown in *italics*). Source: Modified from Corson-Dosch et al. (2023).

the Arctic Community-wide Hydrological Analysis and Monitoring Program (Arctic-CHAMP), also known as the Freshwater Integration Study, that resulted in several summary publications (e.g., Serreze et al., 2006; Holland et al., 2007; White et al., 2007; Francis et al., 2009; Rawlins et al., 2010); the Arctic Hydrological Cycle Monitoring, Modelling and Assessment Program (Arctic-HYDRA), from 2006 to 2010 (Arctic-HYDRA, 2010); the Arctic Freshwater Synthesis (AFS) during the period 2013–2015 that resulted in eight publications (Prowse et al., 2015a,b; Bring et al., 2016; Carmack et al., 2016; Instanes et al., 2016; Lique et al., 2016; Vihma et al., 2016; Wrona et al., 2016) and a summary report (CliC/AMAP/IASC, 2016); previous Arctic Report Cards (e.g., Moon et al., 2021; Walsh et al., 2023a,b); and AMAP's Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017 assessment (AMAP, 2017).

This chapter reports developments regarding the Arctic freshwater system that have taken place since the SWIPA 2017 Assessment (AMAP, 2017), with a focus on climate-water interactions and key processes within the terrestrial hydrological domain, including precipitation and snow cover (Section 6.2), impacts of permafrost thaw on hydrology (Section 6.3), river discharge (Section 6.4), surface water (lakes) (Section 6.5), river ice (Section 6.6), lake ice (Section 6.7), and freshwater contributions from land ice (Section 6.8), all with an emphasis on observed changes and key drivers, as well as projected changes. The chapter concludes with a summary of how these changes are affecting ecosystems and Arctic livelihoods (Section 6.9). The outcome of the chapter will also serve as input to the AMAP/CAFF assessment on Climate Change Impacts on Arctic Ecosystems and Associated Climate Feedbacks, and the AMAP assessment on Societal Implications of Climate Change in the Arctic (SICCA) (both to be produced in the period 2024–2027). Figure 6.3 provides a conceptual illustration of the components of the terrestrial freshwater system addressed in this chapter.

6.2 Precipitation and snow cover

- Precipitation has increased over recent decades, especially in cold seasons, and is associated with an increase in rainfall in all seasons and a decrease in snowfall in summer, with spatially varying trends in winter.
- This century, precipitation events presently regarded as extremes are expected to become routine.
- Snow mass has decreased across northern North America, but in Eurasia the trend has been negligible and snow depth has increased in parts of Eurasia.

Precipitation accounts for the major influx of freshwater to the terrestrial hydrological system. Across the Arctic, snowfall is for most areas the dominant form of precipitation, and most of the terrestrial surfaces are covered by snow for the majority of the year (Mohammadzadeh Khani et al., 2022). The freshwater retained in the snow cover is later released to the river network during spring snowmelt. The snow pack has a major role in the climate system, acting as a strong reflector and insulator, and is thus associated with climate feedback mechanisms, as well as affecting hydrology, ecosystems, and human activities. Precipitation is a rapidly changing component of the Arctic climate and hydrological system, and exhibits a lot of small-scale spatial variability, which in turn creates challenges for the measurement and prediction of snow conditions (Bokhorst et al., 2016).

6.2.1 Observed changes and key drivers

6.2.1.1 Precipitation

Consistent with the warming climate, an increase in pan-Arctic (north of 60°N) mean precipitation is apparent over the period 1950–2023, as indicated by both the ERA5 reanalysis and the station-based dataset of the Global Precipitation Climatology Center (GPCC, land-based data only) (Walsh et al., 2023a). For a more recent period of 1979–2022, the trends are larger and statistically significant ($p<0.05$) for the entire year and for all seasons except spring (April through May) (Walsh et al., 2023b).

When comparing different studies, however, it should be noted that the Arctic precipitation trends vary depending on the study period, region, season, and data source. Yu and Zhong (2021) detected a significant positive trend in ERA-Interim total precipitation for 1989–2016 over large parts of the marine Arctic, particularly in autumn and winter. The strongest trends, up to 0.5 mm/y, occurred in autumn over the east coast of Greenland. Negative trends occurred over limited areas of northern Eurasia and North America. Utilizing the NCEP-NCAR reanalysis, Box et al. (2019) detected an increase of 6.8% in the cold-season (October through May) total precipitation in the area north of 50°N during 1971–2017. The increase during June through September was only 4.7%. A detected overall increase of 1.5% to 2.0% per decade for annual precipitation is consistent with the estimated sensitivity of Arctic precipitation to increased air temperature (Box et al., 2019).

Overall, among the most evident trends in precipitation in the circumpolar Arctic are the increases in rain and decreases in snowfall (Boisvert et al., 2018; Box et al., 2019; Räisänen, 2023). These precipitation changes are generally seen as smaller amounts of snowfall and more frequent rain events during winter, and as higher rain rates during summer. Dates when snowfall dominated in the past are increasingly experiencing precipitation as rain (Moon et al., 2021). More frequent winter rains have also been observed and documented by Indigenous Peoples (Markkula et al., 2019). However, in the High Arctic, an increase in snowfall has been reported over the period 1930–2010 (Mohammadzadeh Khani et al., 2022), and Zhong et al. (2018) found that snowfall in northern Eurasia showed a positive trend from 1966 through 2009. Further, in northern Finland, snowfall increased over 1961–2014 (Luomaranta et al., 2019). On the basis of the ERA5 reanalysis results for

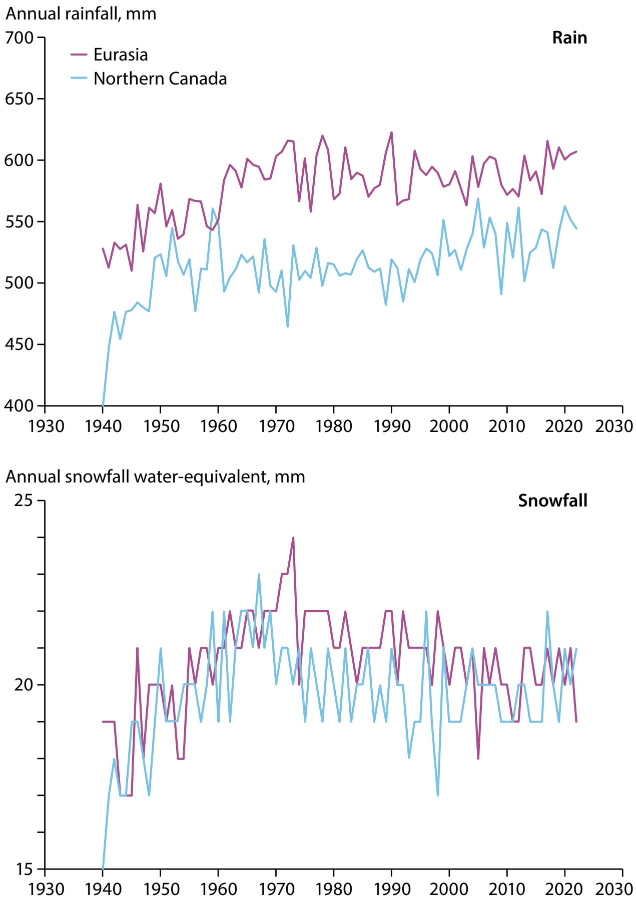

Figure 6.4 Annual mean rain and snowfall water-equivalent averaged over northern Canada (50–75°N, 60–125°W) and Eurasia (50–75°N, 40–190°E) for 1940–2022 on the basis of ERA5 reanalysis results. Source: Data ref. 6.1.

1940–2022, annual rain has significant ($p<0.01$) trends of 0.64 mm/y for Eurasia (50–75°N, 40–190°E) and 0.63 mm/y for northern Canada (50–75°N, 60–125°W) (Figure 6.4). For this period over the same regions, the trends in snowfall are insignificant.

Uncertainty in the precipitation trends arises from the high degree of variability in precipitation over small spatial scales, a sparse observational network biased to low elevations, gauge undercatch in windy conditions, particularly for snowfall (Walsh et al., 2020; Ye et al., 2021), as well as errors and uncertainties in atmospheric reanalyses (Boisvert et al., 2018). Koyama and Stroeve (2019) found that the Arctic System Reanalysis version 1 (ASRv1) monthly precipitation generally agrees with corrected gauge-based precipitation measured at coastal or near-coastal stations in Greenland, but not in every location. Over the high-altitude station Summit on the Greenland Ice Sheet, the ASRv1 precipitation was overestimated compared to precipitation retrieved from the Precipitation Occurrence Sensor System (POSS). Loeb et al. (2022) concluded that the most recent reanalyses (ERA5, MERRA-2 and NCEP/CFSR) represent aggregated extreme precipitation reasonably well, but struggle to match the timing and location of the events consistently.

Large and statistically significant increases in the yearly maximum one-day and five-day precipitation as well as in the annual maximum number of consecutive wet days (CWD) have occurred in the Atlantic sector of the Arctic and northeastern Greenland (Walsh et al., 2023b). The CWD trend is positive from Svalbard eastward to the Chukchi Sea, approximately collocated with areas of reduced sea-ice coverage (Walsh et al., 2023b). Events of heavy precipitation have become less common in scattered regions, including parts of western Canada, Alaska, central Siberia, the Beaufort Sea, and the southern Barents Sea (Walsh et al., 2020, 2023b). ERA-Interim reanalysis suggests that during 1979–2016 the predominantly positive trends in the seasonal total precipitation were typically associated with consistent trends in the occurrence of seasonal extreme precipitation (Yu and Zhong, 2021). Evaluation of trends in extreme precipitation in the Arctic and subarctic is challenging due to the use of several different metrics to quantify precipitation extremes. Freezing rain and rain-on-snow events may also be considered as extreme precipitation events, at least from the perspective of their impacts on Indigenous Peoples and northern communities, namely, on transportation, reindeer herding (e.g., Rosqvist et al., 2022), risk of avalanches, and wildlife (Groisman et al., 2016). The frequency of occurrence of freezing rain increased by one day per year in the 2005–2014 decade compared to the three previous decades (Groisman et al., 2016). Substantial increases have also been found over northern Norway and Svalbard. Peeters et al. (2019) found that in Ny Ålesund (data since 1969) and at Svalbard Airport (data since 1957), every third to fourth winter during the earlier decades was essentially rain-free, but since 1998 some rain had occurred almost every winter.

Several periods or events of extreme precipitation have been observed during recent years. In winter and spring 2017, there was abundant snowfall in Eurasia due to atmospheric circulation patterns favoring lower air temperatures and enhanced precipitation (Richter-Menge et al., 2017). In July 2018, record-high precipitation was observed on Svalbard, while mainland Norway had a 40% negative anomaly, which was followed by extensive forest fires in both Norway and Sweden (Osborne et al., 2018). In winter 2019–2020, snowfall was above average in Scandinavia, and in the following summer, the precipitation aggregated over the Mackenzie and Yukon watersheds was the highest since 1985 (Thoman et al., 2020). A year later, in August 2021, a warm moist-air intrusion over the Greenland Ice Sheet brought the first rainfall ever observed at the high-elevation Summit station (Box et al., 2022; Xu et al., 2022).

A prerequisite for an increase in precipitation is an increase in the moisture content of the atmosphere. The increasing Arctic precipitation has mainly been linked to strengthening moisture transport into the Arctic (Gimeno-Sotelo et al., 2018), in combination with an intensification of local surface evaporation / evapotranspiration (Singh et al., 2017). However, the relationships between these variables are not simple (Gimeno-Sotelo et al., 2018). Nygård et al. (2020), for example, demonstrated that the regional moistening patterns during 1979–2018 were predominantly shaped by strong trends in horizontal moisture transport, largely driven by changes in atmospheric circulation. Trends in evaporation, mostly driven by local sea-ice decline, had a lesser role in shaping the atmospheric moisture content on a circumpolar scale.

In terms of Arctic precipitation, a key circulation change has been the increase in the Greenland Blocking Index, favoring increasing precipitation in southeast Greenland (Auger et al., 2017). In northern Greenland, precipitation is moderately correlated with the North Atlantic Oscillation (Koyama and Stroeve, 2019). Considering changes during the past 50 years in extreme seasonal precipitation in Arctic Fennoscandia, the key circulation drivers have been the Scandinavian pattern in spring, the East Atlantic / Western Russia pattern in summer and autumn, and the North Atlantic Oscillation as well as the Polar/Eurasia and East Atlantic patterns in winter (Marshall et al., 2020). In Canada, the most widespread events of freezing rain during 1964–2005 were driven by two circulation patterns: strong synoptic-scale warm advection and chinooks east of the Rocky Mountains (Kochtubajda et al., 2017).

For terrestrial hydrology, net precipitation (precipitation minus evapotranspiration) is more important than precipitation alone. However, direct observations of evapotranspiration are sparse, and not sufficient for reliable evaluation of regional trends. Hence, estimates have been made using satellite data, land surface models, reanalysis products, atmospheric water budget calculations, and empirical upscaling of point observations (Zhan et al., 2019). In general, both positive and negative trends in evapotranspiration have been found for the terrestrial Arctic (Li S. et al., 2022), and the results are sensitive to the method and data set, as well as to the study period and region. For example, on the basis of ERA5 meteorological data and use of the Penman–Monteith–Leuning model, Shi et al. (2022) estimated that from 2000 to 2020, the annual evapotranspiration in Siberia increased by 0.54±1.38 mm/y. The major driver of the increase was vegetation greening, with a contribution of 0.79±0.76 mm/y. However, a decrease in evapotranspiration during 1960–2016 was detected in the Northwest Territories of Canada (Krogh and Pomeroy, 2018). See Section 6.3.1 for more information.

6.2.1.2 Snow cover

The changes observed in the Arctic terrestrial snow cover have been dominated by a rapid decrease in snow-cover extent (SCE), particularly in spring (Overland et al., 2019). Until recently, reliable quantitative knowledge concerning potential trends in seasonal snow mass have been lacking (Bormann et al., 2018; Pulliainen et al., 2020). However, new satellite remote sensing methods have demonstrated a snow mass decrease of 46 Gt/decade over 1980–2018 across North America, but a negligible trend across Eurasia (Pulliainen et al., 2020). Moreover, for a longer study period, applying in-situ observations from 1814 stations across the Eurasian continent, Zhong et al. (2018) observed snow depth increases of 0.2 cm/decade for the annual mean and 0.6 cm/decade for the annual maximum from 1966 through 2012. The observed regional increase in snow depth was significant ($p \leq 0.05$) in areas north of 50°N. However, the monthly mean snow depth decreased in autumn and increased in winter and spring over 1966 through 2012 (Zhong et al., 2018). Focusing on the High Arctic, Mohammadzadeh Khani et al. (2022) observed that during the period 1930–2010 the snow depth, and in some regions snow mass (water equivalent), mostly increased. In addition, negative trends have been observed in snow-cover duration (Mohammadzadeh Khani et al., 2022). Focusing on Europe, Fontrodona Bach et al. (2018) found predominantly negative trends in snow depth, but positive trends at a few stations mainly located in northern and inland Scandinavia as well as in Russia. Some of the positive trends were up to

+10%/decade, but most were small. Common among studies on observed changes are the conclusions on the importance of spatial variation in trends; even in a region as small as Finland the variations have been large (Luomaranta et al., 2019).

Historical changes in snow condition have also been addressed by modeling studies. Santolaria-Otín and Zolina (2020) found that most historical CMIP5 experiments show negative pan-Arctic trends in snow-cover extent (SCE) and snow-water equivalent (SWE), but that the modelled trends are weaker than observed trends. In general, the CMIP5 models yielded better results for trends in SCE than SWE. In addition to challenges in reproducing trends, most CMIP5 models have biases in SCE, particularly for spring, and the annual cycle of SWE is biased, especially across northern North America (Santolaria-Otín and Zolina, 2020).

Drivers of observed changes in snow condition can be roughly divided into three groups: (1) changes in air temperature and precipitation, which may either enhance or compensate for each other; (2) changes in Earth surface properties, above all in vegetation; and (3) changes in atmospheric circulation. In terms of snow condition at any given location, Groups 1 and 2 represent local drivers and Group 3 a remote driver.

Considering Group 1, latitude has a major impact on the changes (Shi and Liu, 2021). Increased air temperatures at high latitudes and altitudes have strongly enhanced snowmelt during winter (Musselman et al., 2021). Increased air temperatures also allow more precipitation, which increases snowfall in the coldest regions, such as northern Alaska (Littell et al., 2018) and Siberia (Mohammadzadeh Khani et al., 2022), but in warmer regions, such as western Svalbard, increased air temperatures often result in the replacement of snowfall by rain (Peeters et al., 2019), which decreases the snowpack on the ground. Zhong et al. (2018) concluded that snowfall had a greater influence than air temperature on snow depth during November through March in large parts of northern Eurasia. In another study, Luomaranta et al. (2019) concluded that the decrease in snow depth in the southern, western and central parts of Finland in late winter and early spring was driven by the combined effects of increasing temperature and rain/sleet. However, in northern Finland, no trend in snow depth was found in winter, due to the compensating trends in snowfall, rain, and air temperature (Luomaranta et al., 2019). See Section 6.2.1.1 on changes in snowfall.

As to Group 2, Thackeray et al. (2019) demonstrated that changes in vegetation, light-absorbing impurities, and sea ice also contribute to Arctic snow loss and variability (Ala-Aho et al., 2021a). Sea-ice decline allows higher local evaporation and, hence, favors an increase in precipitation. Thackeray et al. (2019) highlighted the long-term impact of changes in vegetation: after snow has accumulated at the height of the prevailing ground vegetation, it is redistributed by wind to topographic depressions and drifts (Bokhorst et al., 2016). A large inaccuracy in estimates of sublimation during blowing-snow events generates uncertainty in the snow mass budget (Lundquist et al., 2024). Hence, changes in vegetation cover may generate trends in the occurrence of blowing snow and further in the snow mass budget (Thackeray et al., 2019). Changes in vegetation also influence albedo, and thus influence snowmelt in spring and summer (Gleason et al., 2019).

Group 3 has been addressed by Irannezhad et al. (2016). On the basis of daily climatological time series covering about 100 years from three sites in Finland, they concluded that in southern Finland, wintertime air temperature, snow hydrological processes, and continuous snow-cover duration were all affected by the Arctic Oscillation. However, in central and northern Finland, winter precipitation, snow hydrological processes and continuous snow-cover duration were influenced by the East Atlantic Pattern, East Atlantic / West Russia Pattern, and the Arctic Oscillation. At short timescales, isotope analyses allow attribution of snow pack properties in Alaskan tundra to atmospheric circulation patterns, such as synoptic-scale cyclones (Ala-aho et al., 2021b).

There is a strong need for interdisciplinary studies to better measure and model snow characteristics on a broad range of spatial scales (Bokhorst et al., 2016). New satellite instruments have a high potential for better detecting snow pack properties (An et al., 2020; Pulliainen et al., 2020). Recent advances in satellite remote sensing of snow include analyses on the impact of rainfall on snow depth estimation (An et al., 2020). Further, snow isotope analyses have a high potential to increase understanding of the role of snow in the Arctic water cycle (Ala-aho et al., 2021b).

6.2.2 Projected changes and key drivers

6.2.2.1 Precipitation

Several recent studies on precipitation in the future Arctic based on climate model projections address the increase in rain and decrease in snowfall. Based on the CMIP5 Multi-Model Large Ensemble (37 models) following the RCP8.5 scenario, statistically significant increasing signals on these changes are expected to emerge in the mid-to-late 21st century (Landrum and Holland, 2020). Using the same CMIP5 results, Bintanja and Andry (2017) concluded that, under the RCP8.5 scenario, annual means for both rainfall and total precipitation will strongly increase in the circumpolar area north of 70°N, while snowfall will decrease. Further, rain will become the predominant form of precipitation by the end of the century. Under the RCP4.5 scenario, snowfall will remain almost unchanged but rainfall will increase. The increase in rain in the Arctic is expected to be greatest in summer and autumn but will also occur in winter, yielding a higher occurrence of rain-on-snow events (Bintanja and Andry, 2017), among others in large parts of Alaska (Bieniek et al., 2018; Pan et al., 2018). The transition from snow to rain may shorten the snow season so that seasons previously considered extremely short will become common in the future (Walsh et al., 2020). In the coldest regions in winter, however, precipitation will fall predominantly as snow throughout the 21st century (Bintanja and Andry, 2017) and snowfall is expected to increase in these coldest areas (McCrystall et al., 2021; Bigalke and Walsh, 2022).

Compared to CMIP5, the results of CMIP6 (sixth phase of the coupled model intercomparison project) suggest more rapid Arctic warming and larger and faster changes in precipitation (McCrystall et al., 2021). The CMIP6 results show stronger Arctic amplification and sea-ice loss as well as increased sensitivity of precipitation to Arctic warming. Hence, both total precipitation and rain increase more rapidly in CMIP6 than in CMIP5, resulting in an earlier (by decades) transition from a snow- to a rain-dominated Arctic in summer and autumn (McCrystall et al., 2021). The transition will potentially occur under 1.5°C global warming.

Regarding projected changes in extreme events, most climate models suggest more events of heavy precipitation, either in terms of increased precipitation intensity or increased frequency of the events (Walsh et al., 2020; McCrystall et al., 2021). A significant positive correlation between the amplified Arctic warming and extreme precipitation has been documented for the past (1901–2018) and is projected for the rest of the century (Liu et al., 2021). One factor suggested by Liu et al. (2021) as favoring an increase in extreme accumulated precipitation is increased and further increasing persistency of weather patterns. Overall, events presently regarded as extremes are expected to become routine in an emerging new Arctic (Landrum and Holland, 2020).

Considering drivers of projected changes in Arctic precipitation, Bintanja and Andry (2017) attributed the strong increase in Arctic precipitation to enhanced surface evaporation associated with sea-ice retreat. Analyzing the output of 37 global climate models, Bintanja (2018) concluded that increases in moisture transport and regional evaporation will both contribute to an increase of 50–60% in Arctic precipitation by the end of the century. Hence, compared to the conditions over recent decades (see Section 6.2.1), the relative importance of regional evaporation is expected to increase. In the terrestrial Arctic, evapotranspiration is expected to increase more in peatlands than in boreal forests (Helbig et al., 2020). By allowing a higher atmospheric moisture content, Arctic warming will be a key precondition for precipitation changes. According to Oh et al. (2020), in 2070–2099 in northern Canada and Eurasia, precipitation related to synoptic-scale cyclones will increase, but there will be an even stronger increase in precipitation generated by mesoscale weather systems. On the basis of experiments using the Community Earth System Model, Pan et al. (2020) concluded that during 2016–2080 the Arctic precipitation phase is three times more sensitive to aerosol forcing (due to global aerosol reduction) than to greenhouse gas forcing. Both favor a transition from solid to liquid precipitation in the Arctic.

In addition to trends, changes in interannual variability in precipitation are important but highly uncertain. Bintanja et al. (2020) analyzed climate model output on interannual variability of Arctic precipitation and concluded that the variability is likely to increase by up to 40%. This will be mostly driven by the greater magnitude and variability of poleward atmospheric moisture transport.

6.2.2.2 Snow cover

Concerning the projected changes in snow cover with a focus on this century, large-scale snow losses are expected to continue in all but the coldest climates (Thackeray et al., 2019). In general, regional variations will be large, with the biggest changes projected for the Canadian Arctic (Mohammadzadeh Khani et al., 2022). The period with seasonal snow cover is expected to decrease by 10–20% in most of the Arctic but by more than 30% in western Alaska and the European Arctic. The shorter snow-cover duration is largely due to an earlier start to the melt season (Overland et al., 2019), although the onset of the snow season will also be delayed (Thackeray et al., 2019). Spring snow-cover extent is projected to decrease by 10–35% by the end of the century, but projected trends in the annual maximum snow depth may be either positive or negative, depending on the region (Mohammadzadeh Khani et al., 2022). However, model projections suggest that reductions in greenhouse gas emissions could enable a stabilization of Arctic snow-cover loss by the end of the 21st century (Overland et al., 2019).

A widespread decrease in SWE is projected for Fennoscandia (Räisänen, 2021). This is due to the combined effects of changes in total precipitation, the snowfall fraction of precipitation, and the fraction of accumulated snowfall that remains on the ground. In southern parts of Fennoscandia, SWE will decrease due to a decrease in the latter two terms. In the northern parts, the interannual SWE variability is dominated by variations in total precipitation, but its projected increase over decadal time scales is not enough to compensate for the lower snowfall and snow-on-ground fractions (Räisänen, 2021).

The impacts of changes in Arctic snow conditions can be subdivided in terms of impacts on other variables in the physical climate system, impacts on ecosystems, and impacts on Indigenous Peoples, and other Arctic inhabitants. Considering impacts on physical variables, changes in snow accumulation and melt strongly affect runoff characteristics (Thackeray et al., 2019), which further affect impacts on ecosystems, Indigenous Peoples, and other Arctic inhabitants. Snow accumulation affects ground temperature, light conditions, and moisture availability during winter (Rixen et al., 2022). Moreover, a decrease in Arctic snow cover has contributed to an increase in surface temperatures in the Arctic during spring and summer (Letterly et al., 2018). The warmer surface warms the lower atmosphere, which decreases air density and north-south horizontal pressure gradients, and thus influences wind patterns and the jet stream (Overland et al., 2019). The relationship between snowmelt and surface and air temperatures naturally also acts in the opposite direction, with higher temperatures as drivers of snowmelt (Letterly et al., 2018).

6.2.3 Knowledge gaps and recommendations

Trends in precipitation, snow depth and snow properties in the Arctic are not well quantified due to the large variability over small spatial scales, a sparse observation network, and uncertainties in the observations. There is a strong need to improve observation, data-assimilation, and modeling capabilities to reduce the large scatter in precipitation amounts and trends in atmospheric reanalyses. Also, to improve the synthesis of information on the occurrence and trends in precipitation extremes, more uniform use of metrics is recommended. Climate models have struggled to reproduce the historical trends in snow variables. Modeling challenges for both historical and future simulations are related to several processes acting across a broad range of spatial scales, including aerosol forcing on precipitation (Schmale et al., 2021), sublimation of blowing snow, and poleward atmospheric moisture transport. Further, for adaptation strategies and social-ecological resilience, methods are needed to convert climate model projections to characterizations of future snow cover and snow type from the perspective of, for example, reindeer herding (Eira et al., 2018, 2023).

6.3 Permafrost hydrology

- Permafrost thaw is likely to drive changes in the water balance in Arctic areas, but the relevant subsurface processes are difficult to observe directly at the catchment scale. Few direct observations of long-term changes in permafrost hydrology are therefore available. However, findings from both observation-based and modeling studies suggest that permafrost thaw has already impacted the water cycle in catchments across the Arctic region.
- Observed changes in streamflow dynamics and water chemistry indicate that permafrost thaw is influencing hydrological connectivity by creating deeper and longer waterflow pathways through catchments across the Arctic.
- Permafrost thaw is likely to continue to drive changes in the hydrology of Arctic landscapes, by promoting increased groundwater flow and storage. The impact of these changes on surface wetness across the Arctic remains an open question.

Permafrost underlies approximately 15% of the northern hemisphere land surface and can act as an impermeable barrier that limits interactions between the surface water system and the groundwater system (Obu, 2021). Permafrost thaw (see Chapter 5, Section 5.2) alters local hydrological processes through changes in subsurface pathways and fluxes, for example, through increased connectivity between deeper and shallower groundwater and surface water. Changes in the distribution and routing of water across Arctic landscapes influences terrestrial water balances and streamflow dynamics (Walvoord and Kurylyk, 2016). Changes in water flow pathways further affect the functioning of Arctic ecosystems by promoting changes in waterborne fluxes of nutrients, weathering products, and contaminants (Tank et al., 2016; Toohey et al., 2016; McKenzie et al., 2021; Mohammed et al., 2022).

Research on the impact of permafrost thaw on hydrology in recent years has been motivated not only by a need to improve understanding of the sensitivity of natural ecosystems to climate change, but also from natural resource perspectives, including safety of drinking water (e.g., Spence et al., 2020) and infrastructure (e.g., Chen et al., 2023). There have been advances in modeling and field-based research, especially considering process understanding at hillslope and catchment scales (e.g., Cochand et al., 2019; Lafrenière and Lamoureux, 2019; Chiasson-Poirier et al., 2020; Wright et al., 2022). However, direct observations of changes in these processes are generally difficult to make since they largely occur in the subsurface environment and across large areas. Therefore, much emphasis has been put on the development of models that can simulate both freeze and thaw processes and hydrology at the same time, so-called cryohydrology models (Grenier et al., 2018; Lamontagne-Hallé et al., 2020). These tools have been used to improve scientific understanding of the general behavior of hydrology in permafrost areas (Atchley et al., 2016; Jafarov et al., 2018; Jan et al., 2018a; Ghias et al., 2019; Gao and Coon, 2022) and to project future changes (Kurylyk et al., 2016; Dagenais et al., 2020). Computational challenges have restricted most of these studies to the single 2D hillslope scale, although the first 3D and catchment scale model studies have recently been published (Painter et al., 2023).

6.3.1 Observed changes and key drivers

As permafrost thaw is expected to increase subsurface connectivity and lower the water table, which may impact streamflow dynamics and water chemistry in streams and rivers, historic records of stream discharge and water chemistry have been used to infer changes in permafrost at the catchment scale, and still offer the most common observational evidence of changes in hydrological connectivity. For example, recession flow analysis has been used as a proxy for long-term changes in subsurface connectivity associated with permafrost thaw, and this method has been applied in catchments across the Arctic since Lyon et al. (2009) explored its potential for a subarctic catchment in Sweden. Expanding on these methods, Hinzman et al. (2020) showed that storage-discharge relationships have become increasingly non-linear with warming (1951–2018) in several catchments in northern Sweden and suggest a link to changes in seasonal frost and permafrost. Sergeant et al. (2021) found that the majority of 336 catchments studied across the Arctic exhibit the opposite trend to that expected with permafrost thaw. They suggested that differences in catchment characteristics such as topography and the extent of permafrost may explain these counterintuitive results. Hinzman et al. (2022) further explored the impact of such characteristics on the shape of streamflow recession using a mechanistic model and found that permafrost has the greatest impact on recession flow in steep catchments, while in flat catchments changes in permafrost do not result in any change in recession flow. Evans et al. (2020) carried out separate baseflow recession analyses for catchments with continuous and discontinuous permafrost, using 139 Eurasian streamflow gauging stations (1913–2003), and found that only catchments with continuous permafrost exhibit the trends in recession flow expected with thawing permafrost (i.e., increased subsurface connectivity). Cooper et al. (2023) developed and tested techniques for directly estimating changes in saturated soil layer thickness from baseflow recession and found increases comparable to observed increases in active layer thickness for the Kuparuk River in Alaska. Several recent studies have also documented increases in winter discharge or groundwater contributions to rivers, as described in Section 6.4. These studies show that permafrost thaw is likely to be influencing catchment-scale hydrological connectivity across the Arctic, but that local factors such as permafrost extent and topography control the extent to which this can be detected with current methods of streamflow analysis.

The records of stream water chemistry typically cover shorter periods than stream discharge records, but offer complementary insights into permafrost thaw. Tank et al. (2016) analyzed water chemistry data for the Mackenzie River and interpreted a positive trend in alkalinity as an indication of increased weathering of glacial till following permafrost thaw. On the other hand, permafrost thaw was interpreted as only one of several potential mechanisms behind observed increases in dissolved organic carbon in the same study. Increases in the fluxes of major ions and dissolved organic carbon (2001–2014) were interpreted as indicators of permafrost thaw in the Yukon and Tanana Rivers (Toohey et al., 2016). Using water isotope data from the western Siberian lowlands, Ala-aho et al. (2018) showed that the extent of permafrost as well as lakes and wetlands influences water pathways at catchment scales. Hindshaw et al. (2018) explored the use of lithium and uranium isotopes as proxies for water residence times and active layer thickness in two catchments in Svalbard for one summer season, and suggested that these elements can be useful for studying changes in active layer thickness also over longer time-scales. Other studies have focused on detecting and tracing the meltwater released from thawing permafrost throughout Arctic catchments. Streletskiy et al. (2015) detected no contribution of water from melting ground ice in the isotopic signature of streamflow in the lower Yenisey River. They found that spring streamflow was dominated by snowmelt water, while winter streamflow and frozen water in the active layer is dominated by late summer precipitation. Cochand et al. (2019) found no influence from permafrost or melting ground ice in groundwater and surface water in the discontinuous permafrost zone. This suggests that the main impact of permafrost thaw on hydrology is not the water released from melting ground ice, but the impact on water flow pathways which in turn influences both streamflow dynamics and water chemistry.

Empirically-based hydrological studies are often carried out at the catchment scale, which is therefore a scale where research on the impacts of permafrost thaw on hydrology has advanced in recent years. Modeling is also often used to complement field data for linking observed dynamics in hydrology to underlying mechanisms related to permafrost. In a study by Connon et al. (2014), permafrost thaw-induced land-cover change from forested peat plateaus to permafrost-free wetlands was linked to increases in hydrological connectivity and observed river discharge in the lower Liard River valley, in the taiga plains of western Canada (1996–2012). The rapid degradation of permafrost observed in this period led to a 43% loss of peat plateaus that transitioned into permafrost-free wetland areas. Similar processes in Arctic Sweden are illustrated in Figure 6.5. Kurylyk et al. (2016) set up a 3D model to simulate these observed changes and to quantify the thermal and hydrological processes driving these changes. Although lateral heat transfer was important for explaining the rapid permafrost thaw rates, groundwater and surface water flow rates were not, and permafrost thaw positively impacted groundwater flow rates. Using observations of groundwater levels from 2003–2017, Haynes et al. (2018) showed that the observed increases in stream discharge were associated with decreases in water storage in the landscape as it transitioned with the degradation of permafrost. Carpino et al. (2021) demonstrated that this landscape transition from forested peatlands with permafrost to permafrost-free wetlands is likely to continue with drying of wetlands to an endpoint with a permafrost-free forest landscape. Similar increases in stream discharge and runoff ratios (runoff/precipitation) have been observed in peatland-dominated catchments in several parts of the Arctic, but only in the taiga plains of western Canada have they both occurred in the absence of increases in precipitation (Mack et al., 2021).

For a small catchment near the Arctic tree line in the Northwest Territories, Canada, Krogh and Pomeroy (2018) simulated the streamflow response to changes in climate and land cover from 1960 to 2016. They found that a decrease in annual streamflow was lower than the decrease in annual precipitation, due to decreases in annual evapotranspiration and sublimation. Changes in climate and vegetation both impacted hydrological processes through evapotranspiration, which decreased by 8.5% for the full study period. Meanwhile in Alaska, Koch et al. (2022) studied the water budgets in headwater catchments

Figure 6.5 Rapid changes in hydrology have been observed following permafrost thaw in Arctic palsa and peat plateau environments. Observed changes include drainage of lakes (a) surrounded by degrading peat plateaus (b) and later terrestrialization and ingrowth of fen vegetation (c) of former lakes, and increased connection and drainage through fen areas (d). Photos from Dávvavuopmi, Sweden/Sápmi. Photo credit: Ylva Sjöberg.

near the tree line and used a space-for-time substitution for exploring the impact of changes in permafrost and vegetation on streamflow. In contrast to the results of Krogh and Pomeroy (2018), Koch et al. (2022) found that increasing vegetation cover and decreasing permafrost extent were associated with increasing rates of evapotranspiration. This was mainly driven by low evapotranspiration rates for bare ground cover. The absence of permafrost was also linked to increased infiltration which, combined with higher evapotranspiration, resulted in lower streamflow. The results thus suggest that permafrost thaw and increased vegetation productivity may lead to drying of headwater streams. The water quality of headwater streams may also be affected by permafrost thaw. Using observations from the same catchments (as studied by Koch et al., 2022) combined with physically-based hillslope-scale modeling, Sjöberg et al. (2021) explored the impact of permafrost on temperatures of groundwater discharge to streams. Simulations showed that deeper flow paths associated with decreasing permafrost resulted in colder summer groundwater discharge, which was also corroborated by observations of colder stream summer temperatures in catchments with less permafrost.

The Umiujaq catchment in Nunavik, Canada, is one of few catchments where groundwater and permafrost have been intensively monitored and modelled to advance understanding of the impact of permafrost on groundwater resources (for an overview see Lemieux et al., 2020). More than two decades of monitoring at this site has shown interannually varying permafrost conditions which are influenced by soil moisture and groundwater-advected heat fluxes (Fortier et al., 2023). Such high interannual variability indicates that long-term monitoring of subsurface hydrology and permafrost is needed to detect changes in hydrology driven by permafrost thaw.

Observations of the development of supra-permafrost taliks (unfrozen ground above the permafrost but below the active layer) have been made in Canada and Alaska (Connon et al., 2018; Walvoord et al., 2019; Fortier et al., 2023). These observations have been complemented by modeling for a better understanding of the controlling mechanisms (Devoie et al., 2019; Walvoord et al., 2019). It has been found that these taliks can speed up the degradation of permafrost below and allow for year-round groundwater flow, but too few observations of supra-permafrost taliks are available to detect any long-term or large-scale trends.

Permafrost thaw may also affect the occurrence of icings (or aufeis or naled), i.e., the accumulation of frozen water from groundwater discharge on the ground surface during winter, which may also contribute to streamflow during the summer (melt) season. The distribution of icings depends on climatic, hydrological, and geological conditions, and their response to changes in climate and permafrost is not fully understood (Ensom et al., 2020). Crites et al. (2020) mapped icings in northwestern Canada and found that they are more prevalent in the continuous, rather than the discontinuous, permafrost zone and that degradation of permafrost may lead to a decrease in icing occurrence. Several climatic factors have also been linked to icing occurrence, such as autumn precipitation, winter air temperatures, and snow conditions, and their projected changes may lead to increases or decreases in the frequency and size of icings (Morse and Wolfe, 2015, 2017; Ensom et al., 2020).

6.3.2 Projected changes and key drivers

There have been several efforts to assess and improve modeling capabilities of permafrost hydrology at pan-Arctic scales (e.g., Ekici et al., 2019; Cai et al., 2020; Gädeke et al., 2020), nevertheless few projections of expected changes in hydrology following permafrost thaw have so far been published. Andresen et al. (2020) compared the projections of near-surface soil moisture in the permafrost region by earth system models for the RCP8.5 scenario and the period 2010–2299. The model projections generally showed a drying of near-surface soils as the active layer deepened, even though P–ET (precipitation minus evapotranspiration) increased, but the spatial patterns and the magnitude varied between models. The models also showed large discrepancies in projected permafrost thaw for the Arctic region, and did not include lateral fluxes of groundwater, and may therefore not be representative for changes at local scales.

At the catchment scale, there are few studies that focus on projections of changes in hydrology following permafrost thaw. Debolskiy et al. (2021) simulated a 1 km^2 idealized catchment by mimicking the effects of permafrost thaw on hydrology, and found that thawing led to increases in annual runoff which were most pronounced in winter. Painter et al. (2023) simulated cryohydrology with ground subsidence using a model setup that spatially resolved a small polygon tundra catchment on the Alaska North Slope for the effects of thaw-driven landscape change on hydrology. Simulations with and without ground subsidence were carried out for the RCP8.5 scenario until 2100. Results showed that subsidence leads to minor increases in permafrost thaw compared to simulations without subsidence. Thawing and subsidence led to overall drier conditions, with no change in runoff, increases in evapotranspiration, and decreases in near-surface water storage (e.g., low center polygon ponds). These catchment-scale projections do not cover the full range of permafrost environments and may therefore not be representative of future impacts on hydrology from permafrost thaw across Arctic catchments. There is contrasting observational evidence showing that permafrost thaw may in fact lead to wetter soil conditions in areas with high ground-ice content (O'Neill et al., 2020; Rodenhizer et al., 2022).

In recent years, models using laterally coupled tiles have been applied to polygonal tundra environments (e.g., Jan et al., 2018b; Aas et al., 2019). Nitzbon et al. (2020) simulated the stability of permafrost under the current climate (1980–2040), but with varying hydrological conditions for polygonal tundra on Samoylov Island, Lena River delta. Results indicated that wetter conditions can trigger degradation of ice-wedge permafrost while drier conditions have a more stabilizing effect, which may explain the observed spatial heterogeneity in ice-wedge degradation. Using a similar model setup, Nitzbon et al. (2020) simulated regional-scale permafrost degradation for water-logged and well-drained conditions and the RCP2.6, RCP4.5, and RCP8.5 climate scenarios. They concluded that it is important to simulate small-scale lateral fluxes and ice melt, which are central processes in thermokarst. Widespread permafrost degradation followed the RCP4.5 and RCP8.5 climates and was considerably exaggerated in the simulations with water-logged conditions. However, the model did not simulate regional-scale hydrological dynamics and could therefore not predict trajectories in surface wetness.

In summary, these studies, including those of Painter et al. (2023), show that hydrological conditions control the rates of permafrost thaw in these environments, and models are now becoming capable of simulating coupled changes in permafrost and hydrology, which are needed to project future changes in these landscapes.

Apart from studies at the catchment and landscape scale, there are also recent studies focusing on changes in hydrology following permafrost thaw at the hillslope scale using cryohydrology models. Evans and Ge (2017) compared generic hillslopes with permafrost and seasonal frost with representative high latitude and high elevation parameterizations for the RCP2.6 and RCP8.5 climate scenarios over 100–year simulations. They found that groundwater discharge increased with warming and thawing in all simulations, but that the increase was higher in permafrost hillslopes and highest in permafrost hillslopes at high elevations. Lamontagne-Hallé et al. (2018) presented a hillslope model with RCP8.5 warming which also yielded increasing (winter) groundwater discharge, and they also found that groundwater discharge areas moved further downslope with warming and permafrost thaw. Dagenais et al. (2020) simulated permafrost thaw following a projected regional warming scenario for a site in the discontinuous permafrost zone in Canada and found that heat advected by groundwater flow considerably impacts the thaw rates of permafrost, especially at the base of permafrost where thaw rates reached 80 cm/y in the simulations. Calibration against field observations showed that disregarding heat advection in simulations led to unrealistically cold and thick permafrost at the site. Walvoord et al. (2019) applied a hillslope model to explore the impact of forest fires on supra-permafrost talik development. Using an RCP8.5 climate over 100 years, they found that reduced shading and absence of an organic layer (representing effects of fire) led to intensified thawing. With thaw, groundwater discharge increased, as did the length of the season with active groundwater discharge to a model stream boundary. Guimond et al. (2022) showed that increases in discharge may be expected in coastal areas experiencing permafrost thaw where sea-level rise is limited, while in areas where sea-level rise is greater, groundwater discharge may decrease for warming scenarios RCP2.6, RCP4.5, and RCP8.5. Cryohydrology models can also be coupled to chemical transport models. Mohammed et al. (2022) showed that dissolved organic carbon (DOC) fluxes from previously frozen carbon increase with thaw and groundwater discharge but peak before groundwater discharge peaks, in a model forced by an RCP8.5 climate scenario. They also found that rising ground temperatures and new supra-permafrost flow paths contribute more to the increase in DOC export than does the development of a deep regional flow system.

In summary, most studies projecting changes in hydrology following permafrost thaw are relatively small scale and cover a broad range of environmental conditions. There is broad agreement that groundwater flow and discharge to streams will increase with permafrost thaw, which is most clearly observable in winter stream discharge. This is in line with earlier research (see, e.g., Walvoord and Kurylyk, 2016). In coastal areas, however, thaw impacts on groundwater discharge may also depend on changes in sea level (Guimond et al., 2022). Shifts in the location of groundwater discharge areas are also projected (Lamontagne-Hallé et al., 2018), as regional groundwater systems develop which may lead to water bypassing present-day headwater stream systems (Walvoord et al., 2012; Koch et al., 2022). There is little agreement and few studies on the impact of thaw on evapotranspiration. Koch et al. (2022) project increases in evapotranspiration based on observations in the boreal-Arctic transition zone in Alaska, while Krogh and Pomeroy (2018) found decreases in evapotranspiration in the Northwest Territories, Canada. Future model projections indicate increases in evapotranspiration (Andresen et al., 2020; Jan, 2022; Painter et al., 2023). Some studies indicate that this will lead to drier surface conditions (Andresen et al., 2020; Painter et al., 2023) and reductions in total streamflow of headwater streams as infiltration increases (Koch et al., 2022). But more research is needed to reach consensus on ongoing and future changes in evapotranspiration and surface wetness across the heterogeneous Arctic landscape mosaic. Recent research in permafrost hydrology also clearly demonstrates the need for understanding of hydrological dynamics to accurately project changes in permafrost (Nitzbon et al., 2020).

6.3.3 Knowledge gaps and recommendations

Detecting changes in hydrological systems driven by degrading permafrost requires knowledge of baseline conditions that is generally lacking. This is largely due to difficulties in directly observing permafrost and groundwater at the scales of interest. Such knowledge gaps could partially be addressed through continued modeling efforts focusing on basic process understanding of these systems, but also to some extent through the use of increasingly available remote sensing-based data products. While progress has been made in both modeling and observation-based research, there is still no consensus on how permafrost thaw may affect surface wetness and evapotranspiration fluxes. Such knowledge will be crucial for understanding future water availability for plants and animals in the Arctic.

6.4 River discharge

- Increasing trends in annual river discharge to the Arctic Ocean from both continents have continued, providing compelling evidence of intensification of the Arctic water cycle.
- A significant increase in base streamflow during the cold season associated with permafrost thaw, autumn precipitation change, lake drainage and river-ice thinning is observed across most regions of the pan-Arctic drainage basin.
- The magnitude of maximum river discharge has not changed significantly; however, the timing of snowmelt freshet has become earlier almost everywhere across the pan-Arctic.
- The general pattern of future changes in discharge is a small increase or even decrease in dry regions with a temperate continental climate, and the greatest increase in discharge is in regions adjacent to the Arctic Ocean.

River discharge (streamflow) is a key indicator of changes in the hydrological cycle associated with environmental changes in the watersheds. The Arctic Ocean is the most river-influenced and land-locked of all oceans and is the only one with a contributing land area greater than its surface area. Thus, river flow to the Arctic Ocean plays an important role in the oceanic freshwater budget, accounting for about two-thirds of the total freshwater flux to the Arctic Ocean (Serreze et al., 2006). Ocean salinity and sea-ice formation are strongly affected by river input (Tang et al., 2018), and changes in the freshwater and heat fluxes to the ocean can exert significant control over global ocean circulation via the North Atlantic deep-water formation (Rahmstorf, 2002). River discharge integrates signals of numerous environmental processes and their changes aggregated over the large areas of upstream watersheds. Changes in permafrost temperature, active layer thickness, thermokarst lake coverage as well as changes in precipitation, snow storage and intensity of snowmelt play an important role in alterations of river discharge to the Arctic Ocean.

The river flow analysis discussed in this section is mainly based on observational data from hydrological gauging stations. However, it should be noted that the monitored area in the pan-Arctic drainage basin has significantly decreased since the end of the 1980s (Shiklomanov and Lammers, 2013), and a considerable part of the basin (about one-third) is currently completely ungauged, including the Canadian Arctic Archipelago, Chukotka, and other regions.

6.4.1 Observed changes and key drivers

6.4.1.1 Annual discharge

Changes in freshwater flux into the Arctic Ocean have been estimated from downstream gauges on the six largest rivers of Eurasia (Yenisey, Lena, Ob, Pechora, Severnaya Dvina, Kolyma) and the two major North American rivers (Mackenzie, Yukon). Their locations are shown in Figure 6.1. Collectively, the watersheds of these eight rivers comprise approximately 70% of the pan-Arctic drainage area and account for most stream-water input to the Arctic Ocean (Holmes et al., 2021). However, this value varies depending on the study, as there are many different assessments of pan-Arctic drainage areas and these range from 12×10^6 km^2 to 24×10^6 km^2, with most of the differences attributed to how each research group defined the drainage system in North America and Greenland (Prowse et al., 2015a; Shiklomanov et al., 2021). The following estimates of river flow to the Arctic Ocean are based on the eight largest monitored watersheds only, with river flow from the smaller river basins and unmonitored sections assumed to behave similarly to the large rivers.

Observations on discharge to the Arctic Ocean have been available since 1936 for the Eurasian rivers and since 1970 for the North American rivers. These records indicate a significant increase of 222 km^3 in total freshwater influx over the period 1970–2023 (Figure 6.6), providing compelling evidence of the intensification of the Arctic water cycle (Déry et al., 2016; Holmes et al., 2021; Shiklomanov et al., 2021; Data ref. 6.2). However, over this period only three rivers (Lena, Kolyma, Yukon) show statistically significant positive trends with

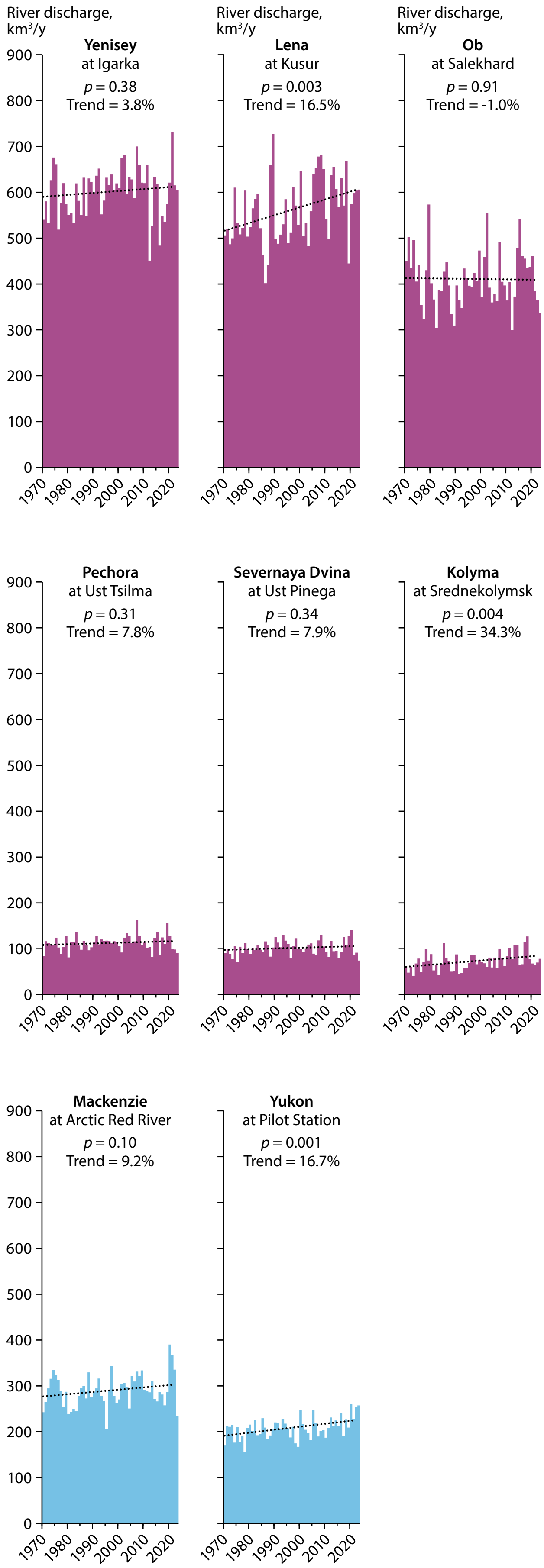

Figure 6.6 Long-term annual river discharge (1970–2023) for the eight largest rivers in the pan-Arctic drainage basin; provisional data from ArcticGRO were used to estimate the annual discharge of the Russian rivers for 2021–2023 and the American rivers in 2023. Source: Data ref. 6.2.

95% confidence (Figure 6.6). The two largest Arctic rivers (Yenisey, Lena) contributed 73% to the observed 1936–2023 trend over Eurasia and more than 55% to the pan-Arctic trend for 1970–2023 (Figure 6.7). It should be noted, however, that the reliability of observational discharge data for these two rivers has declined significantly since 2002 (McClelland et al., 2015; Bring et al., 2016) due to inconsistent streamflow measurements (Shiklomanov et al., 2006; Tretiakov et al., 2022). However, discharge estimates based on remote-sensing data show similar trends for these rivers in the 2000s (e.g., Scanlon et al., 2016; Feng et al., 2021; Lin et al., 2022). The two largest pan-Arctic rivers across North America (Mackenzie, Yukon) also demonstrate increases in annual discharge since 1970 (Figure 6.6) (Rood et al., 2017; Data ref. 6.2), and although the Yukon discharges into the Pacific Ocean, most of its water moves into the Arctic Ocean through the Bering Strait and plays an important role in its freshwater balance (Solomon et al., 2021). Together, the two largest North American Arctic rivers contributed about 28% to the total increase in river flow to the Arctic Ocean since 1970 (from the eight largest river basins; Figures 6.6 and 6.7). It should be noted that the contributions of these American rivers to the total annual river flow to the ocean have significantly increased due to extremely high observed annual discharge during the past few years (Figure 6.6). A significant increase in annual discharge was also reported for most Canadian rivers flowing into Hudson Bay (Déry et al., 2016; Durocher et al., 2019).

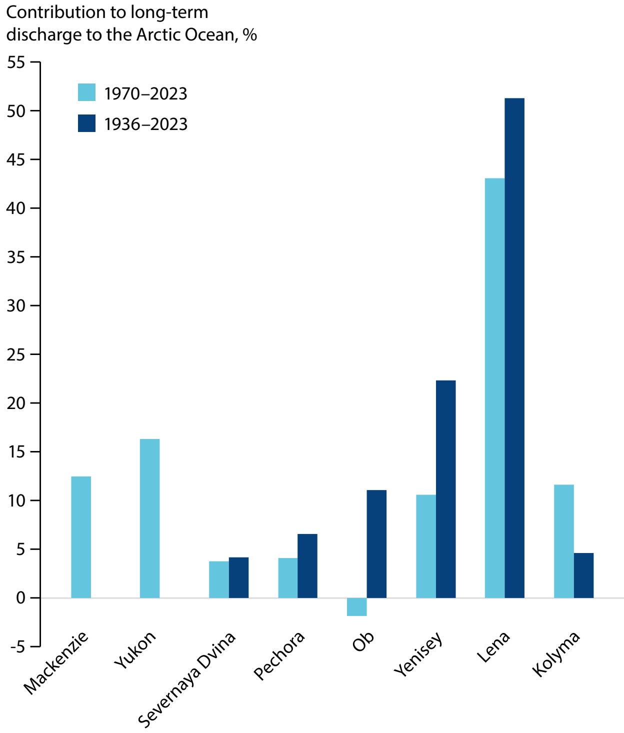

Figure 6.7 Percentage contribution for the eight largest rivers in the pan-Arctic drainage basin to the total long-term discharge trends to the Arctic Ocean. Source: Data ref. 6.2.

Despite a consistent increase in total annual river discharge to the Arctic Ocean from both continents, the changes in discharge across the pan-Arctic drainage basin are not spatially uniform. A significant increase of 5–20% in annual river discharge over 1976–2018 relative to 1946–1975 is observed for a large area of Eurasia north of 58°–60°N (Gelfan et al., 2023). Simultaneously, there are two large areas in Siberia with decreasing annual streamflow attributable to the observed decrease in precipitation and snow accumulation (Nesterova et al., 2020). These areas include the southern parts of the Yenisey watershed and the area east of the Kolyma basin (Magritsky et al., 2018; Frolova et al., 2022). The most significant decreasing discharge trend has been observed in the Selenga River basin (Shiklomanov and Lammers, 2013; Frolova et al., 2022), especially over its Mongolian section where the mean annual discharge for 1976–2016 was 22% lower than for 1950–1975 (Frolova et al., 2017; Zorigt et al., 2019). There is no consistency in observed annual discharge changes over North America (Bonsal et al., 2019), where opposing trends can be detected depending on the time-scale of the analysis (Bennett et al., 2015; Bring et al., 2016; Shiklomanov et al., 2021). There is a general tendency in Canada for discharge to the Arctic Ocean from the western part of the Hudson Bay watershed and regions along the Arctic seacoast to show mostly positive trends, while discharge from the south and east of Hudson Bay and the southern part of the Mackenzie Basin demonstrates mostly negative trends (Déry et al., 2016; Durocher et al., 2019; Feng et al., 2021; Mack et al., 2021). Declining water levels have also been observed by the Indigenous Peoples within the Mackenzie River basin for Hay River, Sandy Creek, Buffalo River, Great Slave Lake and other smaller streams and creeks (Stenekes et al., 2020). The low water levels have, among other things, limited their access to some areas by boat. Similar observations have been made by other Indigenous Peoples across the Arctic (Knopp et al., 2022). In Alaska, annual discharge from the North Slope has increased significantly over the past 20 years (Arp et al., 2020b). Simultaneously, a decrease in discharge has been observed for most boreal watersheds of central Alaska, including glaciated basins (Bennet et al., 2015).

6.4.1.2 Seasonal and extreme discharge

The typical pan-Arctic natural river flow regime, consisting of a low winter discharge, high spring-summer discharge driven by snowmelt and/or glacial melt, and rain-induced summer-autumn floods, has shown a noticeable alteration during recent decades due to accelerated warming in the upper portions of the watersheds (Ballinger et al., 2021). There is a growing body of research addressing changes in seasonal patterns and extremes of discharge in the pan-Arctic drainage basin (e.g., Georgievskii et al., 2019a,b; Ahmed et al., 2020; Shiklomanov et al., 2021; Whitfield et al., 2021; Frolova et al., 2022; Gelfan et al., 2023). The changes are usually attributed to warmer and wetter climate conditions (e.g., Suzuki et al., 2020; Holmes et al., 2021; Liu et al., 2021; Hiyama et al., 2023) and/or to cryospheric changes such as permafrost thaw (e.g., Panyushkina et al., 2021; Wang et al., 2021; Han and Menzel, 2022; Cooper et al., 2023; see also Section 6.3), glacier melt (e.g., O'Neel et al., 2014; see also Section 6.8), and river ice (e.g. Gurevich, 2009; Shiklomanov and Lammers, 2014; Yang et al., 2021; see also Section 6.6). Water management such as construction of large reservoirs, inter-basin water diversions, and water withdrawals can also significantly affect discharge seasonality and extremes (Shiklomanov and Lammers, 2009; Magritsky et al., 2018). In some cases, reservoir regulation has a more significant influence on river flow regime than climate change (Arheimer et al., 2017). Anthropogenic impacts are important for many Arctic rivers and include flattened average annual hydrographs, effects on interannual variability, and increased weekly periodicity (Déry et al., 2018). Quantitative assessments of the human impacts on river runoff are required in order to isolate them from the effects of climate change. Such investigations have previously been undertaken for the Yenisey (e.g., Shiklomanov and Lammers, 2009; Stuefer et al., 2011), Ob (e.g., Hu et al., 2022), Lena (e.g., Magritsky et al., 2018; Georgiadi and Milyukova, 2023), all large Russian Arctic rivers (e.g., Georgiadi et al., 2019; Koronkevich et al., 2019), and rivers in the Hudson Bay drainage basin (Déry et al., 2018). Shiklomanov et al. (2021) summarized the results of human impacts on Arctic river flow as a whole. The present chapter focuses on the long-term climate-induced changes in discharge seasonality and extremes, and as a result, the analysis is based on rivers with minimal human impact on the hydrological regime (Shiklomanov and Lammers, 2013).

A general pattern of changes in discharge seasonality and extremes across the pan-Arctic is characterized by a significant increase in base streamflow during the cold season and a change in the timing of snowmelt freshet (Déry et al., 2016; Mack et al., 2021; Shiklomanov et al., 2021; Wang et al., 2021; Frolova et al., 2022; Liu et al., 2022; Gelfan et al., 2023). The analysis of long-term monthly discharge records from gauges with minimal anthropogenic impact shows a consistent increase in winter runoff throughout the Russian Arctic drainage basin over the 1950–2018 period (Katsov, 2022). This increase ranges from 20% in eastern Siberia (Lebedeva and Gustafsson, 2021; Hiyama et al., 2023) to 30–50% in the north of Yenisey basin (Burenina et al., 2021) and southwest of the Ob watershed (Katsov, 2022; Savichev et al., 2022). Similar increases in winter runoff were found in other Arctic regions, including in Scandinavia (Gohari et al., 2022), Canada (Bawden et al., 2015; Rood et al., 2017; Whitfield et al., 2021) and Alaska (Rawlins et al., 2019; Shrestha et al., 2021). The rise in winter runoff can be attributed to the accelerated warming observed at high latitudes and associated mobilization of subsurface water due to thawing permafrost (Evans et al., 2020; Cooper et al., 2023; see also Section 6.3), decreased winter freezing of soils (Kalyuzhny and Lavrov, 2016; Ala-Aho et al., 2021a) and the increased frequency and magnitude of winter snowmelt events in southern parts of the pan-Arctic drainage basin (Pavlovskii et al., 2019). Changes in streamflow during summer and autumn are less consistent throughout the pan-Arctic drainage basin. The general pattern of changes during this period consists of negative or no trends in discharge during June–July, mainly due to the earlier onset of snowmelt, insignificant positive trends in August, and a significant increase in discharge for September–October before freeze-up (Shiklomanov et al., 2021). Significant increases in discharge from August to October were found on many rivers of eastern Siberia in the continuous permafrost zone (Lebedeva et al., 2019; Makarieva et al., 2019). These changes were associated with thawing permafrost and increased active layer thickness due to accelerated warming (Makarieva et al., 2019; Hiyama et al., 2023). Accelerated retreat of glaciers in the headwaters of some major Arctic rivers may be an additional factor for increasing discharge over this period. There are no consistent changes in summer-autumn precipitation in this region except for the Kolyma River basin, where a significant increase in autumn (September–October) precipitation has been reported (Vyazilova et al., 2022). Similar increasing tendencies in summer–autumn runoff were found on the Alaskan North Slope (Arp et al., 2020b). These observations were attributed to more frequent large late summer rainfall events due to higher air temperature and declining sea ice.

6.4.2 Projected changes and key drivers

There are two general approaches to the assessment of potential changes in river flow under projected climate change: one based on the results of modeling hydrological processes in global climate models (GCMs), and the other based on global or basin-scale hydrological models using GCM climate projections as the input. Although the latter approach is more accurate and has less uncertainty for estimating future streamflow changes (Krysanova et al., 2018), representations of terrestrial hydrological processes in many GCMs have substantially improved such that GCM simulations can now be used to evaluate potential changes in water resources at the regional scale (Georgievsky et al., 2021; Gelfan et al., 2023). Most GCMs under CMIP5 and CMIP6 project a significantly warmer and wetter future Arctic climate (see Sections 6.2.2.1 and 6.2.2.2) and there is very good agreement between their results in terms of further increase in Arctic runoff (Bring et al., 2016).

Depending on the model used, the climate scenarios, and the timescale of interest, annual runoff is projected to increase after 2050 in the range of 5–15% for western Siberia and western Hudson Bay, to 35–60% for eastern Siberia, north-eastern Canada and northern Alaska (Bring et al., 2017; Ferguson et al., 2018; MacDonald et al., 2018; Stadnyk et al., 2021). Especially significant increases in annual river discharge (50% and more) under the most ‘rigid’ (‘business as usual’) greenhouse gas emissions scenarios are projected for the East Siberian rivers (Indigirka, Yana, Kolyma, Anadyr) (Nasonova et al., 2019, 2021, 2022; Gelfan et al., 2022). DeBeer et al. (2021) investigated future changes in runoff for the interior of western Canada using the fine-scale Cold Regions Hydrological Modelling (CRHM) platform. They projected an increase in annual runoff by the end of the 21st century, ranging from 15% in the Cordilera Mountains to 100% in the northern part of Mackenzie Basin and along the Arctic Ocean seacoast, and that peak discharge would decline in the western mountains by up to 30% and increase in the boreal plain region (south of the Mackenzie watershed) by 100% (DeBeer et al., 2021). The overall pattern of future changes in runoff is a small increase or even decrease in dry regions with a temperate continental climate such as the southern Ob and Yenisey watersheds (including territories of Kazakhstan, China, and Mongolia) and the Canadian prairies, with the greatest increase in runoff occurring in the Eurasian and North American Arctic regions adjacent to the Arctic Ocean (Bring et al., 2017; Saito et al., 2021; Stadnyk et al., 2021; Gelfan et al., 2022). Although the projected rates of future changes in seasonal and extreme discharge vary considerably depending on the approach and timeframe used, they do show several common features:

- more uniform discharge distribution throughout the year owing to an increase in discharge during low flow periods, which is already being observed in many regions and which is projected to continue in the future (Saito et al., 2021; Stadnyk et al., 2021);
- a shift to earlier snowmelt and spring freshet due to rising air temperatures (Nasonova et al., 2019, 2021; McCrystall et al., 2021; Stadnyk et al., 2021);
- greater streamflow during late summer and autumn due to higher precipitation and accelerated permafrost thaw associated with warmer temperatures and sea-ice decline in the Arctic Ocean (Dou et al., 2022; Ford and Frauenfeld, 2022).

6.4.3 Knowledge gaps and recommendations

The accuracy of daily discharge estimates used for computing constituent fluxes depends on the number of river discharge measurements (Shiklomanov et al., 2006). Unfortunately, regular streamflow measurements have declined substantially at downstream gauges on the Yenisey, Lena and Kolyma rivers since 2003 (Tretiakov et al., 2022). Roshydromet (the agency responsible for hydrological observations in Russia) continues to evaluate and publish daily streamflow data using a long-term stage-discharge rating curve for open water and historical relationships for winter discharge correction coefficients. Despite the relative stability of river channels and stage-discharge rating curves for these gauges, it is likely that the daily discharge data for these gauges is of lower accuracy especially during high flow periods because they are not supported by regular discharge measurements (McClelland et al., 2023). Reliability of discharge estimates is very important for downstream gauges; unfortunately, many gauges in the Lena, Yenisey, and Yukon watersheds have gaps in recent years and some gauges have very limited or no discharge measurements during open-water conditions. A new methodological approach for estimating river discharge based on remote sensing information and the Mass-conserved Flow Law Inversion (McFLI) method has recently found widespread applications (Ishitsuka et al., 2021). This approach does not need in-situ data to estimate discharge although the results will improve markedly with gauge data (Durand et al., 2016). Nonetheless, the discharge estimates are temporally and spatially limited by satellite overpass geometry and sensor-specific limitations (e.g., cloud cover). These disadvantages, however, may be partly overcome by the recent launch of a new satellite mission such as the NASA/CNES/CSA/UKSA Surface Water and Ocean Topography mission (SWOT; Biancamaria et al., 2016). Another very promising approach to evaluate discharge with high temporal resolution is to combine the data from orbital satellites and hydrological modeling (Feng et al., 2021; Ishitsuka et al., 2021). Use of global hydrological models makes it possible to estimate daily discharge and obtain extreme values. Most such models, however, assume natural flow and ignore the impact of human activities (such as dam operations or water extraction). Despite this drawback, the use of satellite data with models can provide very valuable information, especially for unmonitored areas of the pan-Arctic drainage basin where direct human impact is very limited.

6.5 Surface water (lakes)

- Lake area is declining across the discontinuous permafrost zone. In the continuous permafrost zone, however, the number of sites with decreasing lake area is similar to the number with increasing lake area. Stronger lake area declines in the discontinuous permafrost zone is consistent with permafrost thaw being further advanced there than in the continuous permafrost zone.
- Increasing precipitation, intensified precipitation events, and warming are hastening permafrost thaw and leading to continued lake area declines.

Lakes are a cornerstone of Arctic ecosystems; they constitute 20–40% of Arctic lowlands and provide feeding and nesting sites for migratory birds, as well as year-round habitat for fish and mammals (Grosse et al., 2013; Haynes et al., 2014; Roach and Griffith, 2015). People also rely on Arctic lakes for drinking water, subsistence activities, and industrial operations (Berkes and Jolly, 2001; Jones et al., 2009, 2023; Turner et al., 2018). While natural fluctuations in the number and size of Arctic lakes are common on millennial timescales (Brosius et al., 2021; Jones et al., 2022), modern climate change is shifting these systems towards landscape-scale wetting (lake formation and/or expansion) or drying (lake drainage, desiccation, or infilling) (Shugar et al., 2020; Webb and Liljedahl, 2023).

Climate change can alter lake area through several processes. First, mass loss from retreating glaciers contributes to increases in lake area, although this effect is mostly limited to ice-marginal environments (Shugar et al., 2020; Mallalieu et al., 2021). Second, perturbations in the precipitation/evapotranspiration balance (i.e., increases in evaporative demand from warming temperatures or warming-induced changes in precipitation phase, timing, and magnitude) may increase or decrease lake area, depending on the net change in the evaporation to inflow ratio. The susceptibility of regional lake storage to evaporative desiccation varies depending on the interactive effects of local climate (e.g., evapotranspiration, precipitation, and length of the open-water period), and landscape characteristics such as vegetation, topographic position, lake depth, lake abundance, and permafrost conditions (Vulis et al., 2020; Woolway et al., 2020; Young et al., 2021), and some Arctic regions are likely to be resistant to desiccation (MacDonald et al., 2017; Wilcox et al., 2023). Lastly, permafrost thaw can cause both increases and decreases in lake area through several processes (as described below) (Smith et al., 2005; Webb and Liljedahl, 2023).

New lakes are formed when ice-rich permafrost thaws and the land surface formerly sustained by ice collapses to create a topographically low spot where water pools (Czudek and Demek, 1970; Burn, 1992; Grosse et al., 2013; Bouchard et al., 2020; Coulombe et al., 2022). Lakes expand as lake margins thermally and mechanically erode (Brewer, 1958; Grosse et al., 2013; Bouchard et al., 2020). Concurrently, lake drainage may occur through surface or subsurface drainage channels created by thawing permafrost (Mackay, 1988; Yoshikawa and Hinzman, 2003; Lantz and Turner, 2015; Carpino et al., 2021), or through high lake levels overtopping the banks and eroding new drainage pathways (Jones and Arp, 2015). Lake area may also decline as a result of increasing sedimentation, which occurs when lake-adjacent permafrost thaw results in slope

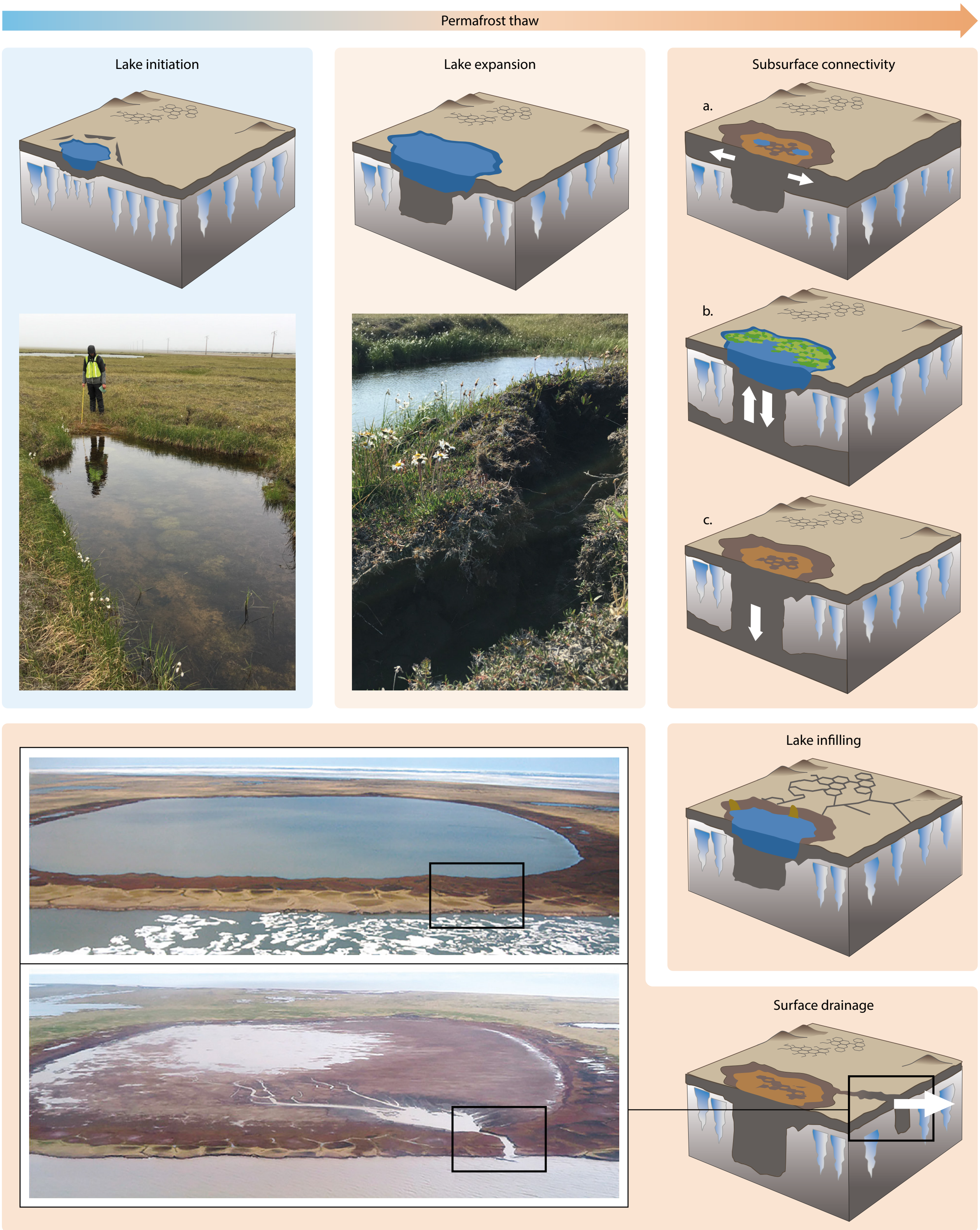

Figure 6.8 Evolution of thaw lakes in ice-rich soils undergoing permafrost thaw. Initially, permafrost degradation results in lake initiation and expansion, with continued thaw leading to lake drainage. Lake infilling may occur due to slope failure or as a result of enhanced sediment transfer into the lake from the surrounding catchment. Surface lake drainage may also occur when a new outlet forms as a result of melting excess ground ice or extreme precipitation causes water to overtop the lake edge, initiating mechanical and thermal erosion. Source: Webb and Liljedahl (2023).

failure, mass wasting, and subsequent lake infilling (Lantz and Kokelj, 2008; Lewkowicz and Way, 2019), or when enhanced terrestrial-aquatic connectivity increases sediment transport to lakes (Kuhn and Butman, 2021). These processes are illustrated in Figure 6.8, which shows the evolution of thaw lakes in ice-rich soils undergoing permafrost thaw. Permafrost thaw-driven lake area change is hypothesized to be a continuum, whereby initial permafrost thaw leads to increasing lake area, with advanced thaw leading to lake area decline (Smith et al., 2005).

6.5.1 Observed changes and key drivers

In glacial landscapes, climate change-driven glacial mass loss is increasing both the number and the area of glacial lakes (Carrivick and Quincey, 2014; Shugar et al., 2020; Mallalieu et al., 2021; Dye et al., 2022), with the rate and magnitude of these increases dependent on landscape features like dam type and topographic position (Field et al., 2021; Rick et al., 2022).

In unglaciated or post-glacial landscapes, some evidence suggests that climate warming and associated changes to the precipitation/evapotranspiration ratio are leading to lake desiccation (Smol and Douglas, 2007; Bouchard et al., 2013; Campbell et al., 2018; Carroll and Loboda, 2018) or to increases in lake area (Cheţan et al., 2020; Veremeeva et al., 2021). Concurrently, permafrost thaw is also driving long-term surface water and lake-area trends (Swanson, 2019; Travers-Smith et al., 2022; Webb et al., 2022; Webb and Liljedahl, 2023), although the net direction of these trends is highly uncertain at both the local and regional scales (Olthof et al., 2023; Webb and Liljedahl, 2023; Webb et al., 2023).

A review of 139 sites from 57 remote sensing studies focusing on Arctic lake area found that most (63%) landscape-scale studies report negative trends in lake area in the discontinuous permafrost zone, while in the continuous permafrost zone, reports of increasing and decreasing lake area were nearly equal (40% increasing, 38% decreasing, 22% no change) (Webb and Liljedahl, 2023) (Figure 6.9). Evidence of stronger lake area declines in the discontinuous permafrost zone is consistent with the continuum concept of permafrost thaw, whereby permafrost thaw is further advanced in the discontinuous compared to the continuous permafrost zone (Smith et al., 2005). A near-equal number of studies documenting positive and negative trends in the continuous permafrost zone suggests that the hydrological consequences of permafrost thaw have already progressed towards the latter part of the continuum, where the rate of lake drainage is equal to the rate of lake formation/expansion in the continuous permafrost zone (Webb and Liljedahl, 2023).

Similarly, a pan-Arctic analysis of surface-water trends found widespread surface-water declines over the past two decades, with stronger declines observed in the discontinuous than in the continuous permafrost zone (Webb et al., 2022). Drying and draining of lakes and declining water levels have also been observed across the Arctic by Indigenous Peoples (Knopp et al., 2022). Uncertainty remains about the net direction of change across large regions of the Arctic, however, because independent studies sometimes report directionally opposite lake-area trends in the same region (i.e., some research shows increasing surface water in the same region that other research shows decreasing surface water) (Olthof and Rainville, 2022; Webb et al., 2022; Webb and Liljedahl, 2023). Such inconsistencies are likely to

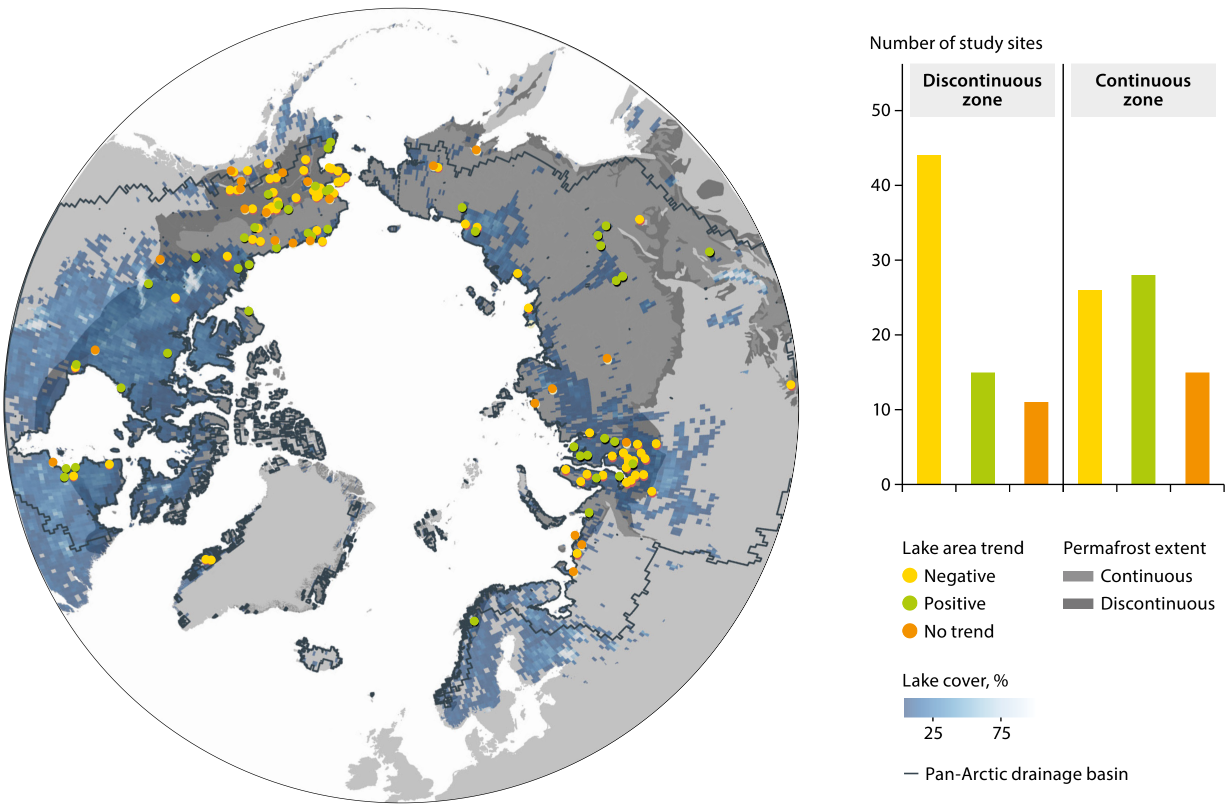

Figure 6.9 Observations of net change in lake area binned by permafrost zone and mapped by geographic location. Percentage lake cover (Olefeldt et al., 2021) is mapped for regions with >3% lake cover. Individual studies are represented more than once if they investigated multiple regions. There are 69 and 70 study sites in the discontinuous and continuous permafrost zones, respectively. Regardless of study area extent, each study site is represented as a single point. Source: adapted from Webb and Liljedahl (2023).

be due to methodological approach, and further research is needed to resolve discrepancies among analyses.

Lake area change is highly heterogeneous at the kilometer scale (Labrecque et al., 2009; Jones et al., 2011; Lindgren et al., 2021; Webb et al., 2022), probably resulting from the interaction between climate variables, bedrock and surficial geology, and local landscape characteristics (Carroll and Loboda, 2018), particularly ground ice content. Melting ground ice can promote both lake initiation/expansion and lake drainage/infilling (Hopkins, 1949; Czudek and Demek, 1970; Mackay, 1988), with recent work documenting net positive and net negative surface water trends associated with ice-rich permafrost (Swanson, 2019; Travers-Smith et al., 2022; Webb et al., 2022). Drainage networks formed by melting ice wedges may establish rapidly (Fortier et al., 2007; Jones et al., 2023) and are likely to remain on the landscape for decades, if not longer, further increasing the potential for landscape-scale drainage (Haynes et al., 2018). Indeed, lake drainage rates have increased in recent years, reflecting gradual increases in temperature and precipitation as well as extreme weather events (Lantz and Turner, 2015; Nitze et al., 2020; Lara et al., 2021). Disturbance regimes, such as wildfires (see Chapter 4), are also impacting lake area change. Travers-Smith et al. (2022), for example, found generally decreasing lake areas within fire scars in Canada between 1985 and 2020 due to accelerated permafrost thaw, compared to lakes outside burned areas that generally showed increasing lake areas.

6.5.2 Projected changes and key drivers

Glacier melt and retreat are directly related to temperature increases (Rounce et al., 2023), and as a result, future climate warming is expected to lead to continued growth of glacial lakes (Shugar et al., 2020). However, glacial lakes will remain highly dynamic systems, as glacial thinning (Jakob et al., 2021) could also lead to accelerated drainage of ice-dammed lakes, and as glaciers retreat off their terminal moraines, the rate of moraine dammed lake formation could slow (Rick et al., 2022).

Precipitation and temperature interact to influence lake area change through the precipitation/evapotranspiration balance (Smol and Douglas, 2007; Bouchard et al., 2013; Campbell et al., 2018; Carroll and Loboda, 2018; Cheţan et al., 2020; Veremeeva et al., 2021), and through permafrost-thaw (Lantz and Turner, 2015; Swanson, 2019; Nitze et al., 2020; Lara et al., 2021; Webb et al., 2022). Climate models project both warming air temperatures and increasing precipitation across the Arctic (Box et al., 2019; McCrystall et al., 2021; Cai et al., 2024) and observed trends in precipitation are stronger than trends in evapotranspiration (Rawlins et al., 2010), suggesting a wetter future Arctic (McCrystall et al., 2021; Cai et al., 2024). However, warmer air temperatures also increase evapotranspiration, and some Arctic regions may experience water deficits (Zhang et al., 2021). Such changes to the water balance could lead to regional increases (positive water balance) or decreases (negative water balance) in lake area.

Increasing temperatures and precipitation are also likely to accelerate permafrost thaw, leading to net lake-area decreases. For example, increasing air temperatures and rain can increase soil temperature and thaw depth (in the case of rain, this occurs when the rain is warmer than the soil) (Iijima et al., 2010; Natali et al., 2011; Douglas et al., 2020), which destabilizes permafrost and accelerates thermal erosion (Kokelj et al., 2015; Christensen et al., 2021). Additionally, extreme heat and precipitation events can cause lake-adjacent slope failure, which results in mass wasting and lake infilling (Kokelj et al., 2015; Lewkowicz and Way, 2019). Lastly, precipitation increases may cause high lake levels, which can lead to lake overtopping and new drainage channel formation (Mackay, 1988; Jones and Arp, 2015; Nitze et al., 2020). With climate change, Arctic air temperatures and precipitation are expected to continue increasing (Bintanja and Selten, 2014; McCrystall et al., 2021), suggesting that the Arctic is on a trajectory toward continued surface water declines.

Models did not project net lake area decline until the mid-21st to 22nd centuries (Van Huissteden et al., 2011; Turetsky et al., 2020), but remote sensing-based studies report that declining lake area is prevalent across the Arctic (Webb and Liljedahl, 2023). This indicates that current models do not adequately represent the processes controlling Arctic lake-area change. Integration of both landscape characteristics (e.g., ground-ice content) and climate variables (i.e., temperature and precipitation) into existing models will improve the ability to project future changes in lake area.

6.5.3 Knowledge gaps and recommendations

Time series analysis of remote sensing images is the primary tool for analyzing multi-decadal changes in surface water area. However, limitations inherent to these data sources such as the availability of historical imagery, the availability of cloud-free repeat imagery, and the difficulty of using coarse resolution imagery to track changes that occur on the meter scale means that uncertainty remains about the net direction of lake area change. In addition, studies observing decadal-scale changes in lake area are not evenly distributed across the Arctic, with large regions such as the Canadian shield and the Russian Far East understudied in comparison to better-studied regions such as Alaska and the West Siberian Lowlands (see Figure 6.9) (Webb and Liljedahl, 2023). Given that lake distribution and storage dynamics vary depending on the underlying geology and local changes in climate, such uneven geographical distribution of existing studies could bias current understanding, and further research in these understudied regions is needed to fully characterize lake area dynamics at the pan-Arctic scale.

6.6 River ice

- Ice-cover duration on rivers has declined significantly in cold regions over the past several decades due to later freeze-up and earlier breakup. The observed decline in river ice is likely to continue in the future due to the projected increase in air temperature.
- Maximum river ice thickness has decreased significantly on most pan-Arctic rivers over the past 50 to 60 years, with the greatest decrease observed before 2000.

River ice forms on more than half of Earth's rivers (Yang X. et al., 2020), and it is estimated that river ice periodically occupies an area of around 120,000 km^2 and a volume of up to 140 km^3 (Brooks et al., 2013). At high latitudes, small and even medium-sized rivers can freeze to the bottom (Shiklomanov and Lammers, 2014). Ice conditions can have strong impacts on the physical environment of rivers, affecting light, oxygenation, temperature, and mixing, and strongly influencing sediment transport and bank erosion (Fukś, 2023). As such, river ice can have both direct and indirect effects on the flora, fauna, and water quality of freshwater systems in cold regions. River ice is also widely used by people for winter transportation and fishing, and a reduction in river ice could negatively impact these human activities. At the same time, the probability of ice-jam floods is expected to decrease with thinner river ice and this could be beneficial for many communities (Rokaya et al., 2022).

6.6.1 Observed changes and key drivers

The impact of climate change on ice cover is due to the natural relationship between heat fluxes and water temperature. The annual variation in air temperature is one of the primary factors affecting heat exchange conditions at the boundaries between water, ice, and the atmosphere, and consequently the heat balance of the water surface and ice formation (Shen, 2016). The discharge regime during winter is also strongly related to river-ice conditions (Yang et al., 2021). Winter streamflow has significantly increased in most regions of the pan-Arctic drainage basin (see Section 6.4). This increase could be partly explained by changes in river ice condition because a shorter ice-cover period and thinner ice enhance the exchange between ground and surface water, leading to higher runoff rates (Yang et al., 2021). Besides the higher flow velocity and stronger turbulence associated with the higher winter discharge, it may also promote later and thinner ice formation.

6.6.1.1 Ice phenology

Ice-cover duration on rivers has declined significantly in cold regions over the past several decades (Newton and Mullan, 2021; Yang et al., 2021; Fukś, 2023). Later freeze-up and earlier breakup have been reported for many pan-Arctic rivers based on in-situ observations (Shiklomanov and Lammers, 2014; Vuglinsky and Valatin, 2018; Yang et al., 2021), Indigenous knowledge (Knopp et al., 2022), remote sensing (Yang X. et al., 2020; Zakharova et al., 2021; Podkowa et al., 2023), and modeling (Park et al., 2016). Fukś (2023) and Burrell et al. (2023) summarized observed changes in river-ice phenology. Later freeze-up dates in the range of 0.2–5.7 days/decade have been found across most of the Eurasian Arctic rivers (Obyazov and Smakhtin, 2014; Shiklomanov and Lammers, 2014; Agafonova and Vasilenko, 2020; Yang et al., 2021). The observed rate of delay in ice formation in North America (western Canada, Mackenzie, and Yukon basins) is between 0.6 and 5 days/decade (Rokaya et al., 2019; Newton and Mullan, 2021; Yang et al., 2021). Tendencies to earlier breakup dates have been recorded for many Arctic rivers (Burrell et al., 2023). Chen and She (2020) explored the spatiotemporal variations in breakup timing across Canada over 1950–2016 and found significant trends toward earlier breakup in the Arctic regions, western mountains, and central plains. In the Eurasian Arctic, observed times of breakup and the end of ice conditions were shifting to earlier dates at a rate of up to 2.8 days/decade

River	Change in river-ice phenology between 1955 and 2023		
	Start of ice events, days	End of ice events, days	Duration of ice events, days
Severnaya Dvina	**8.8**	**-8.0**	**-16.8**
Ob	**13.2**	**-5.3**	**-19.1**
Yenisey	4.8	**-7.2**	**-11.4**
Lena	**5.9**	**-5.5**	**-11.5**
Yana	**8.0**	**-3.0**	**-11.2**
Kolyma	**7.9**	-3.0	**-10.5**

Figure 6.10 Location of Eurasian river gauges used for river-ice analysis (see map) and changes in river ice phenology for downstream sites on some large Eurasian Arctic rivers over the period 1955–2023 estimated from linear trends (see table). Significant trends ($p<0.05$) are shown in bold. Source: updated from AMAP (2021).

(Obyazov and Smakhtin, 2014; Shiklomanov and Lammers, 2014; Sharma et al., 2016; Podkowa et al., 2023). Due to changes in freeze-up and breakup dates, ice-cover duration on most Arctic rivers has decreased significantly (Burrell et al., 2023; Fukś, 2023). This trend has been recorded since the beginning of the 20th century and has intensified since the beginning of the 21st century (Newton and Mullan, 2021). The decline in ice-cover duration has ranged from <1 day/decade to as many as 12 days/decade since 2000 in the southern regions of the pan-Arctic drainage basin (Cooley and Pavelsky, 2016; Vuglinsky and Valatin, 2018; Chen and She, 2020; Zakharova et al., 2021). Agafonova and Vasilenko (2020) analyzed changes in duration of ice cover for 100 Russian Arctic river gauges and found some common spatial patterns. The most significant decline (up to 12 days) was observed in the European part and decreased eastward to 2–3 days in eastern Siberia. The table in Figure 6.10 shows long-term changes in the start/end of ice phenomena and their duration for six large Eurasian Arctic rivers over the period 1955–2023. All rivers experienced a significant decline in the duration of ice cover, ranging from 10 days (Kolyma) to 19 days (Ob).

6.6.1.2 Ice thickness

Ice thickness measurements are usually made manually, and considerably fewer long-term datasets are available for ice thickness than for ice phenology, especially for the North American Arctic (Fukś, 2023). Decreasing ice thickness has been recorded on the Peace River (Beltaos and Bonsal, 2021), and lower Mackenzie and Back rivers (AMAP, 2021). At the same time, an increasing trend in ice thickness was observed on the upper Yukon River (Imrit et al., 2022). Across Alaska,

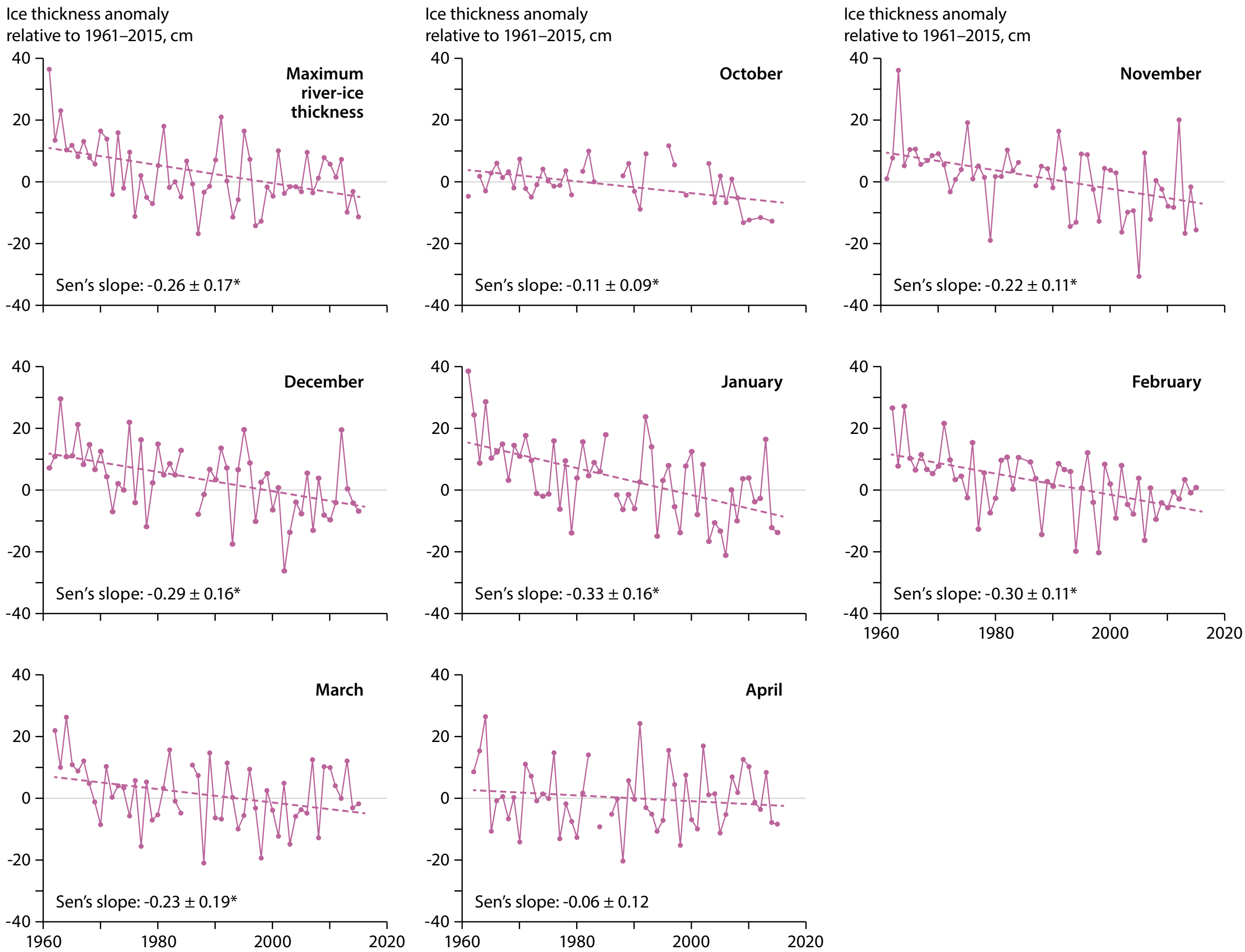

Figure 6.11 Changes in river-ice thickness across Alaska based on sites with records from 1961 to 2015. The plots show mean maximum river-ice thickness and seasonal river-ice thickness for October through April (* $p < 0.05$). Source: Yang and Zhang (2022).

maximum river-ice thickness (MRIT) has declined significantly (Arp et al., 2020a; Yang and Zhang, 2022). Figure 6.11 demonstrates average changes in seasonal river-ice thickness over 1961–2015, based on data from 15 sites (Yang and Zhang, 2022). A significant decrease in river-ice thickness was found each month from October to March, although most changes were observed before 1990. Arctic Indigenous Peoples have also documented localized observations of decreasing ice thickness across North America (Knopp et al., 2022). Yang and Zhang (2022) analyzed the contributions of primary climatic drivers to changes in river ice and concluded that an increase in air temperature was the primary cause of MRIT decrease across Alaska, with a relative contribution of about 74%, while increasing snowfall enhanced MRIT decline with a relative contribution of 26%. It should be noted that the authors ignored the potential hydrological drivers of changes in MRIT, such as higher winter river flow and the corresponding increase in velocity and turbulence of the flow (see Section 6.4).

More data are available for the Eurasian Arctic because regular ice thickness measurements are included in the standard observation program of Russian hydrometric gauges. Declining trends in river-ice thickness were recorded on most Siberian rivers over 1980–2014, with an average decrease of 3.5 cm/decade in western Siberia and 3.6 cm/decade in eastern Siberia (Vuglinsky, 2017; Vuglinsky and Valatin, 2018; Zakharova et al., 2021). Maximum river-ice thickness has decreased significantly at downstream sites of the large Russian Arctic rivers (see Figure 6.12). However, it should be noted that the greatest decrease in MRIT was observed before 2000, and during the past two decades, ice thickness has stabilized on most Eurasian rivers similar to the situation in Alaska (Yang and Zhang, 2022).

6.6.2 Projected changes and key drivers

The observed decline in river ice is likely to continue in the future due to the projected increase in air temperature. Yang X. et al. (2020) used an observationally calibrated model, based on temperature and season, and applied it to future climate projections. They estimated that river-ice duration under RCP4.5 and RCP8.5 would decline on average by 7.3 and 16.7 days, respectively, by 2080–2100. The projection was based on the assumption that river ice is likely to continue to decline linearly at a rate of 6.1 days per 1°C increase in global mean surface-air temperature (Yang X. et al., 2020). Agafonova et al. (2017) estimated future changes in river-ice duration for Russian rivers using the RCP8.5 scenario and empirical relationships with air temperature. A significant decline in the duration of the ice cover was projected for the Eurasian Arctic, ranging from 20 days in the central part of the Lena River basin to 90 days in the north of European Russia and western Siberia. Such discrepancies in future estimates are likely to be due to the simplified method based on a direct relationship with air

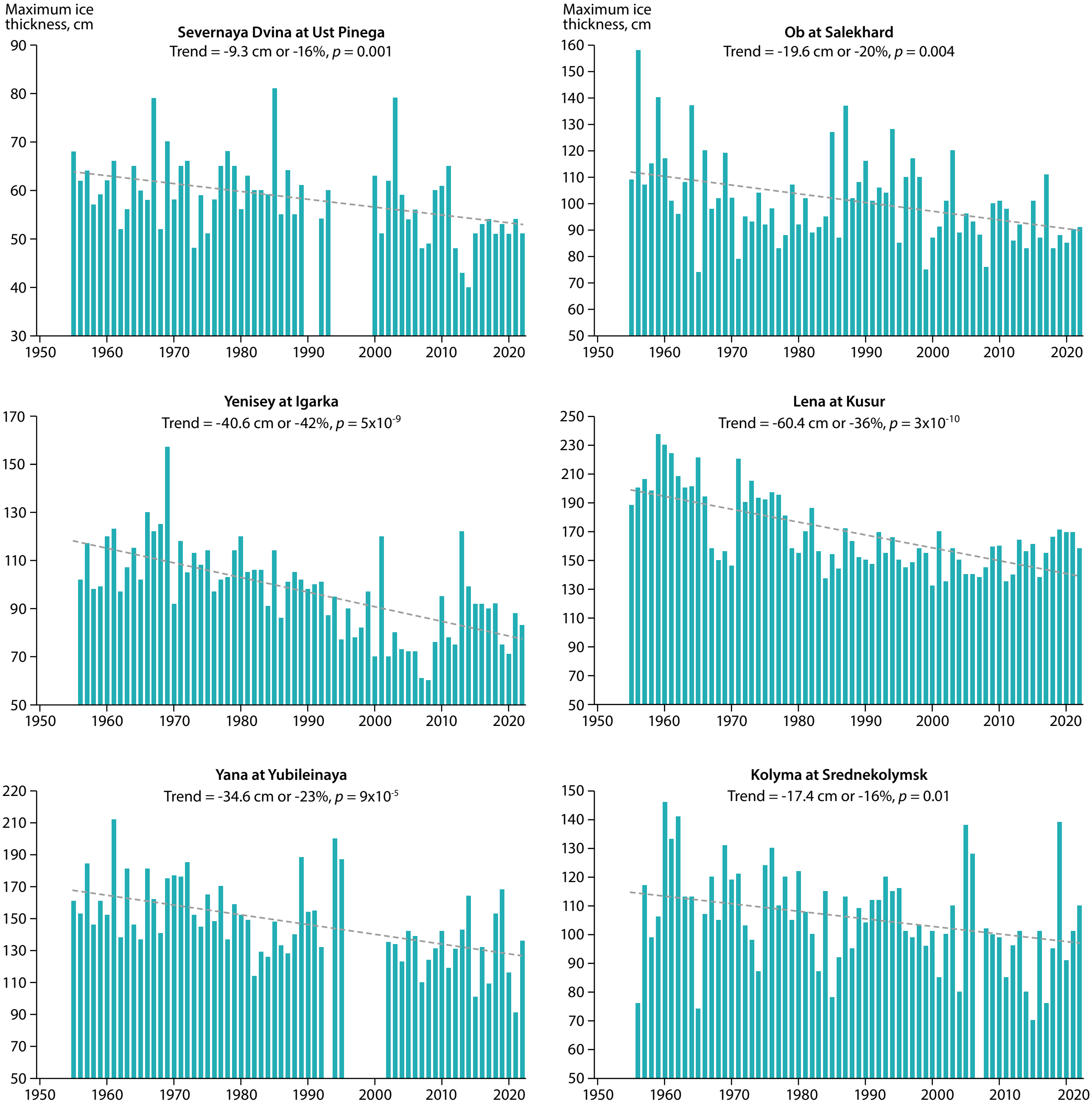

Figure 6.12 Maximum winter ice thickness for downstream gauges on large Eurasian rivers flowing to the Arctic Ocean. The linear trend is shown as a dashed line. Source: updated from Shiklomanov and Lammers (2014).

temperature. In this case, rivers in the temperate zone with an annual mean temperature close to zero will show the most substantial changes in river-ice phenology. More robust model-based methods are needed for reliable future projections.

Mean maximum river-ice thickness is projected to decrease by 10–50 cm by mid-century, with a more pronounced decrease in the eastern Canadian High Arctic. For the lower Peace River in northern Alberta, Canada, Beltaos and Bonsal (2021) projected a thickness reduction of ~0.2 m between the 1980s and 2050s, and by an additional ~0.1 m by the 2080s under the RCP8.5 scenario. Ice-thickness reduction in rivers of the Russian Arctic is projected to be in the range of 20–50 cm by the end of the 21st century under RCP8.5, with the greatest values in the northern regions of Siberia and the Russian Far East (Agafonova et al., 2017).

6.6.3 Knowledge gaps and recommendations

River ice is an important component of the cryosphere and its changes impact numerous biophysical processes and various human activities. Thus, reliable data for river ice timing and thickness are very important to quantify and understand the river ice response to global climate change. Recent development of new datasets based on remote sensing (de Rham et al., 2020; Yang X. et al., 2020) provide information for comprehensive analysis of river-ice phenology. The data for river-ice thickness are still very limited, especially for the North American Arctic. A few databases are available for Russian river-ice thickness (e.g., Data refs 6.3 and 6.4) but these need updating to include more recent information. Great prospects lie in using new algorithms for retrieval of ice thickness information from satellite altimetry (Zakharova et al., 2021). Most hydrological models ignore river-ice processes although they are very important for simulating river flow in cold regions. There is thus a need to enhance the global hydrological models with modules for simulating water temperature and river-ice dynamics. This will allow better understanding of present and future changes in river ice across cold regions of the planet.

6.7 Lake ice

- Lakes are rapidly losing ice across the Northern Hemisphere, with later ice-on dates, earlier ice-off dates, and in some years, some lakes not freezing at all.
- Lake ice loss is forecast to continue to decline in the future under scenarios of climate change.

Arctic Indigenous Peoples, and other Arctic inhabitants, have relied on lake ice for centuries because of its importance for refrigeration, transportation, recreation, food acquisition, spirituality, and social connections (Magnuson and Lathrop, 2014; Knoll et al., 2019). Lake ice responds rapidly to regional and large-scale climatic factors and can be considered a sentinel of climate change (Adrian et al., 2009; Magnuson et al., 2000). Lake-ice phenology (the timing of lake ice-on and ice-off) requires freezing temperatures (consistent air temperatures below 0°C) to form and maintain the presence of ice on the lake surface, integrating air temperatures from autumn through spring (Brown and Duguay, 2010). Long-term records of ice phenology reflect how the climate has changed, with some of these records extending back long before the advent of meteorological stations (Sharma et al., 2016). Early observations of ice phenology were recorded by citizen scientists and environmental monitoring networks (Sharma et al., 2022), and the combination of these in-situ records with newer approaches has enabled global records of ice phenology through remote sensing by satellites and process-based modeling (Sharma et al., 2020b).

6.7.1 Observed changes and key drivers

Because lake-ice records have existed for hundreds of years in some cases, these records make it clear that lake-ice phenology is changing (Magnuson et al., 2000; Benson et al., 2012). The culmination of lake ice studies points towards later ice-on and earlier ice-off, with the overall effect of diminishing winter ice cover on lakes in the Northern Hemisphere. Recent global process-based modeling studies indicate that ice duration declined by six days per decade during 1980–2010 (Huang et al., 2022) and by nine days of ice cover during 1981–2019 (Grant et al., 2021), whereas a remote sensing and modeling study for 30,063 lakes suggested that on average lakes lost a total of four days of cover in the 20th century (Wang et al., 2022). More specifically, in the Arctic, remote sensing observations for over 13,000 lakes reported by Šmejkalová et al. (2016) found that ice breakup began and ended earlier across 14 years (2000–2013) of observations. In northern Europe, ice-off occurred 5.2 days/decade earlier. In northeast Canada, ice-off occurred 9.2 days/decade earlier. In the Alaskan Arctic, ice-off occurred 8.7 days/decade earlier. In central Siberia, ice-off occurred 11 days/decade earlier. Finally, in northeast Siberia, ice-off occurred 9.2 days/decade earlier (Šmejkalová et al., 2016). Moreover, in-situ observations from 60 lakes with 107 to 204 years of data scattered across the Northern Hemisphere suggested that ice-on was delayed by 11 days/century, while ice-off was earlier by 6.8 days/century, and ice duration 17 days shorter/century (Sharma et al., 2021). It is notable that these lakes have lost ice particularly quickly in the past 25 years, such that ice loss was six times faster than the long-term trend at a rate of 106 days/century (Sharma et al., 2021). Plus, 14,800 lakes that had reliably frozen over for centuries are now even experiencing intermittent ice cover (i.e., ice-free winters) (Sharma et al., 2019) and 179 have lost ice cover completely (Sharma et al., 2021). Changes in the timing of ice-on and ice-off have also been documented by Indigenous Peoples, where later freeze-up and earlier breakup were observed across much of the Arctic (Knopp et al., 2022).

Warming air temperatures are the overwhelming driver of lake-ice loss (e.g., Palecki and Barry, 1986; Vavrus et al., 1996; Higgins et al., 2021; Imrit and Sharma, 2021). Increasing air temperatures preceding and throughout the ice-cover period delay ice formation, enhance ice breakup, and reduce ice thickness. Higher air and water temperatures during autumn limit evaporative heat loss, that is, increasing lake heat budgets delay the 0°C isotherm, which plays an essential role in ice formation and ice growth (e.g., Duguay et al., 2006; Brown and Duguay, 2010 for a review; Shuter et al., 2013). Another primary driver of ice cover is solar radiation, which can inhibit ice formation and increase melt rates throughout the ice column (Leppäranta et al., 2010). Solar radiation enhances under-ice convection, causing warmer underlying water to interact with the ice cover, further enhancing melt (Kirillin et al., 2012; Bertilsson et al., 2013; Yang B. et al., 2020).

These primary drivers interact with secondary drivers, including precipitation, wind, and large-scale climate oscillations. Precipitation as snow during the winter enhances albedo and contributes to ice-cover insulation, which contributes to prolonged ice cover and ice growth into the spring melt season (Preston et al., 2016; Smits et al., 2020). However, precipitation as rain during the ice-cover period can cause early melt by adding liquid water to the ice surface (Bartosiewicz et al., 2021). Similar can be observed with meltwater from glaciers (Kirchner et al., 2024). Wind action during ice formation and ice breakup accelerates ice loss. During the ice-on period, wind breaks initial skim ice, limiting the growth of congelation ice and thereby stable ice cover (Bartosiewicz et al., 2021). During spring, enhanced winds can mechanically break the ice cover and so enable the upwelling of warmer waters, further enhancing ice breakup (Williams, 1965; Brown and Duguay, 2010). A suite of large-scale climate drivers acting at multi-annual and multi-decadal scales are often associated with ice cover, although they do not explain nearly as much variation as weather variables (Sharma et al., 2013; Imrit and Sharma, 2021). Shifts in the Quasi-Biennial Oscillations, El Niño Southern Oscillation, North Atlantic Oscillation, Arctic Oscillation, and solar sunspot cycles have all been associated with changes in ice cover (Ghanbari et al., 2009; Lopez et al., 2019; Livingstone, 2000; Imrit and Sharma, 2021). These secondary drivers can be enhanced or mediated by local-scale landscape characteristics, such as topographic aspect, surface area, and mean depth (Sharma et al., 2020b; Higgins et al., 2021).

6.7.2 Projected changes and key drivers

The rate of lake-ice loss is projected to accelerate in the future under scenarios of climate change, attributed to anthropogenic activity (Grant et al., 2021). However, the projections vary across studies and methodologies. For example, based on the CESM2 model, across the Northern Hemisphere ice duration is projected to decrease by 8.9 days for a 1°C increase in local warming (Huang et al., 2022). Using a combination of observations from the ERA5 model and forecasts using simulations with five lake models and four global climate models, ice duration is projected to decline by 46 days on average by 2100 under the RCP8.5 scenario, although varying between 28 and 80 days (Grant et al., 2021). Based on remote sensing of over 30,000 northern hemisphere lakes, Wang et al. (2022) concluded that ice duration could decline by 17.9 days (RCP2.6), 33.1 days (RCP6.0), or 49.9 days (RCP8.5) by the end of the century depending on the scenario used (Wang et al., 2022). Similarly, Sharma et al. (2019) projected that intermittent ice cover (i.e., ice-free winters) could occur on 27,000 to 48,000 lakes (RCP2.6) or 41,000 to 90,000 lakes (RCP6.0) by the end of the century depending on the scenario used (Sharma et al., 2019; Figure 6.13). In the most extreme case, 179 lakes (RCP2.6), 429 lakes (RCP6.0) or 5679 lakes (RCP8.5) could become permanently ice free by 2100 depending on the scenario used (Sharma et al., 2021).

6.7.3 Knowledge gaps and recommendations

Despite the importance of lake ice, knowledge gaps remain. For example, very few studies record ice thickness or ice quality (e.g., Imrit et al., 2022; Li X. et al., 2022; Weyhenmeyer et al., 2022), observe lake-ice conditions in more remote or alpine regions (Christensen et al., 2021; Kirchner et al., 2021, 2024), or account for the apparent increase in freeze-thaw events in the seasonal ice cycle. Establishing the linkages between lake ice and other cryospheric elements, such as snow, permafrost, and glaciers, would improve understanding of how climate change is affecting the cryosphere globally (O'Neill et al., 2020; Dauginis and Brown, 2021; Robinson et al., 2021; Saros et al., 2023). There are many research opportunities for interdisciplinary collaboration; for example, further identifying the connection between snow and lake ice because snow cover can influence the evolution of lake-ice formation, rate of ice thaw, ice quality, and albedo (Brown and Duguay, 2010). Another area of interest is to explore the linkages between lake ice and permafrost because thermokarst lakes that no longer freeze to the bottom are vulnerable to the formation of taliks below them (O'Neill et al., 2020). The increased interest in winter processes (Hampton et al., 2017), implementation of new methodologies and tools, and collaboration across disciplines will be instrumental in filling these knowledge gaps (Sharma et al., 2020b) as understanding of lake-ice dynamics and the role of lake ice within the broader cryosphere and climate change expands.

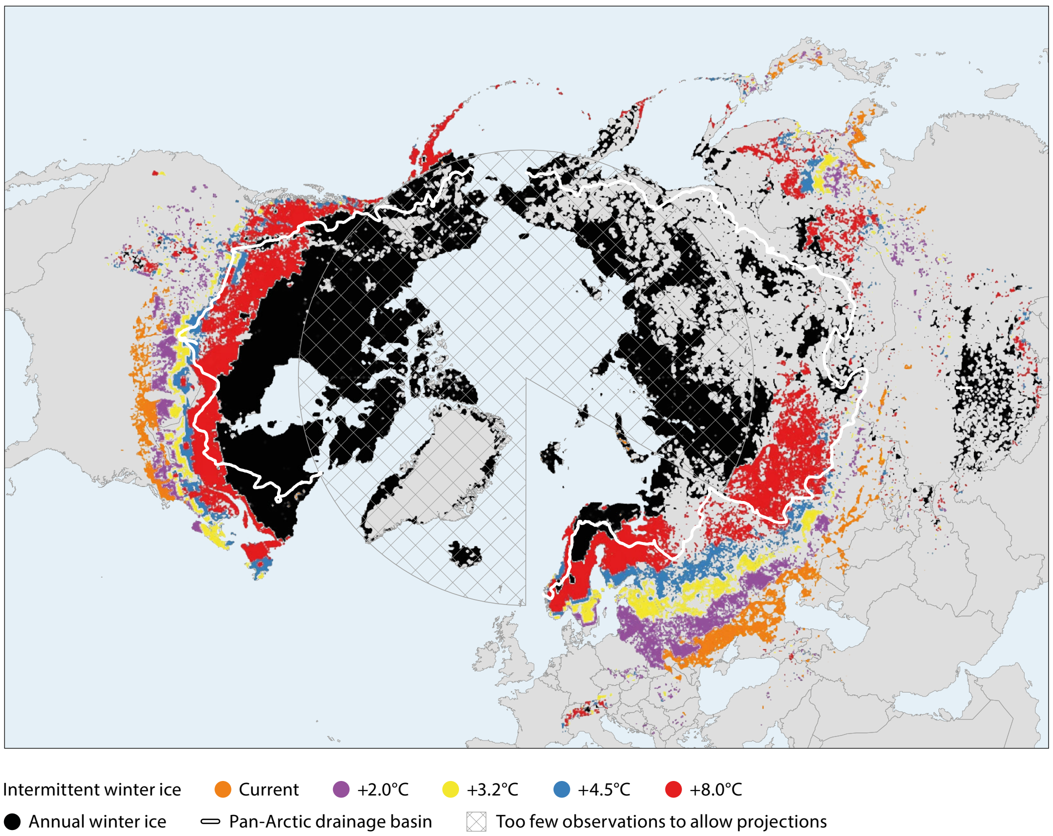

Figure 6.13 Spatial distribution of current and future northern hemisphere lakes that could experience intermittent winter ice cover (i.e., ice-free winters) with climate warming. Projections were generated by applying the classification tree model to the global HydroLAKES database (Duguay et al., 2006) (lakes larger than 10 ha) and limited to the south by 1970–2010 mean winter temperatures below -0.4°C. Projections north of 60°N in North America and Asia could not be achieved owing to a paucity of ice-cover observations (see hatched region). Intermittent winter-ice cover projections were based on current conditions and established air temperature projections of +2.0°C, +3.2°C, +4.5°C and +8.0°C. Source: Sharma et al. (2019).

6.8 Freshwater contributions from land ice

- The reduction of glaciers and ice caps and Greenland Ice Sheet mass loss are increasing the freshwater flux into the ocean.
- A further increase in freshwater flux from land ice reduction is likely to continue with the projected future increase in Arctic warming.

This section focuses on changes in the freshwater flux from glacial runoff from the largest land ice bodies in the Arctic. The growing mass deficit of Arctic land ice is contributing to an elevated freshwater flux into the Arctic environment, especially the marine sector. One potential impact is disruption of the Atlantic Meridional Overturning Circulation (AMOC) that influences northern hemisphere climate via extremes over Europe (Buchan et al., 2014), the North American Arctic (Yin and Zhao, 2021), and with long-theorized ties with global climate (e.g., Rahmstorf, 2002; IPCC, 2021). And while AMOC stability could already be threatened by Greenland deglaciation (Devilliers et al., 2021; Swingedouw et al., 2022; Ditlevsen and Ditlevsen, 2023; Martin and Biastoch, 2023), it remains unclear whether AMOC shutdown is likely to become a reality and whether meltwater from Greenland would be sufficient to disrupt the AMOC. See also Chapter 8.

6.8.1 Observed changes and key drivers

The magnitude of freshwater delivery from the Arctic land-ice area shown in Figure 6.14 (626±164 km^3/y) is roughly equivalent to that from North American river discharge (502±45 km^3/y). Eurasian river discharge is roughly three times higher (1884±144 km^3/y). The increase in Arctic river discharge was 1.6 times smaller than the increase in net freshwater flux from Arctic land ice. The freshwater flux increase from land ice reduction between 1971 and 2022 totals 402 km^3/y. The increase from these Arctic rivers was 257 km^3/y relative to an average river discharge of 2407±148 km^3/y (see Chapter 2). Most of the increased land-ice freshwater discharge has originated from Greenland and Arctic Canada and thus discharges into Baffin Bay and the North Atlantic Ocean, rather than the Arctic Ocean.

The surface waters downstream of glacierized regions contain significantly more macronutrients (nitrogen, silica, phosphorus) and micronutrients (iron, manganese) than their non-glacierized counterparts (Bhatia et al., 2021). Given that land-ice reduction has already increased and is expected to increase further with continued warming (Rounce et al., 2023), the impacts of land-ice loss on marine ecosystems are expected to further increase.

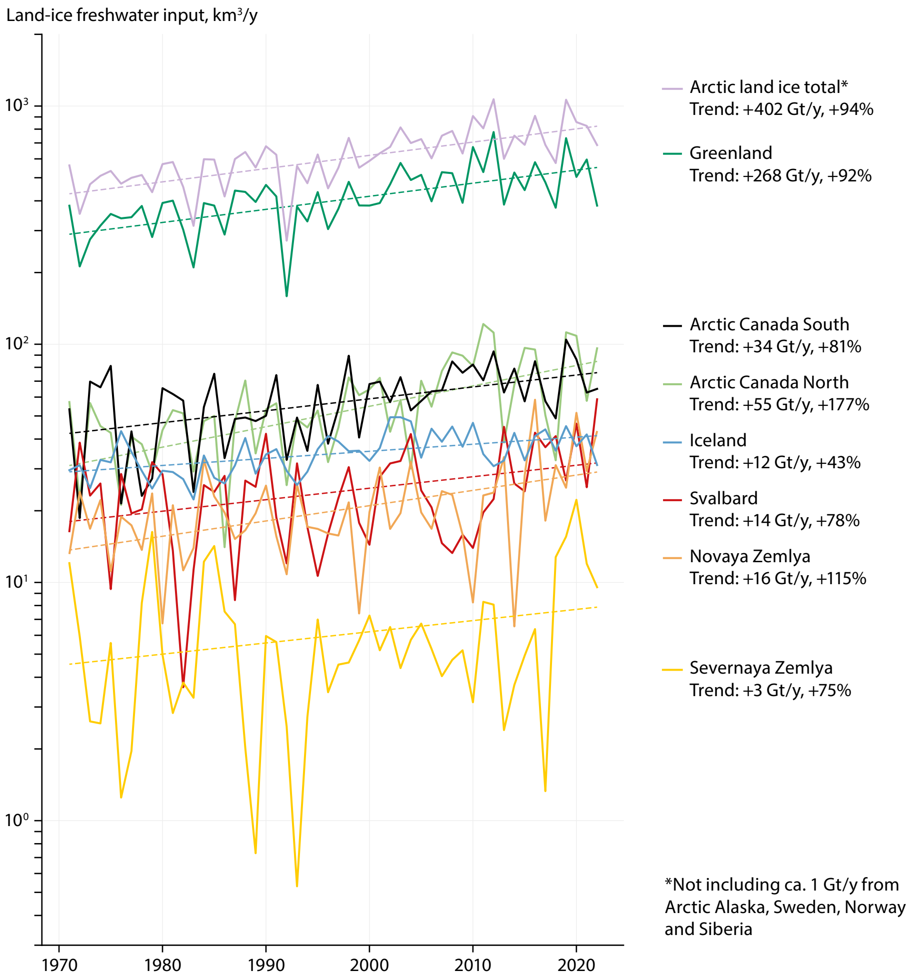

Figure 6.14 Multi-regional Arctic land-ice freshwater contribution into surrounding seas from the atmospheric reanalysis-driven Modèle Atmosphérique Régional (MAR) version 3.12.1 (Antwerpen et al., 2022). Note the logarithmic vertical axis. The percentage changes are the trend slope (dashed line) multiplied by the number of years and divided by the average. Source: Data ref. 6.5.

6.8.2 Projected changes and key drivers

Using CMIP6 climate projections to 2100, Edwards et al. (2021) concluded that Arctic glacier mass loss increases linearly with global mean surface air temperature, with respective 2100 sea-level contributions of approximately 11 cm (26 cm) at a global warming of 2°C (4°C), equivalent to a net freshwater influx of 40,000 km^3 (94,000 km^3). The Glacier Model Intercomparison Project (Hock et al., 2019) found future Arctic land-ice loss (excluding the inland Greenland Ice Sheet) to be the leading source of global sea-level rise. The results indicate an acceleration of ice loss with time, consistent with results found by van Pelt et al. (2021) for Svalbard.

For the high greenhouse gas emissions scenario SSP5-8.5, the IPCC AR6 Greenland Ice Sheet model projections (Goelzer et al., 2020; Edwards et al., 2021) suggest a +13.0 cm (likely range 9–18 cm) sea-level rise (SLR) contribution by 2100 for the Greenland Ice Sheet only. Under a Paris Climate Agreement-like future scenario (SSP2-4.5), the SLR projection is 62% of the high emission amount: 8.0 cm (likely range 4–14 cm). The projections appear roughly linear until mid-century, after which the SSP2-4.5 and SSP5-8.5 scenarios increasingly diverge.

6.8.3 Knowledge gaps and recommendations

Key knowledge gaps for Arctic land ice (including the Greenland Ice Sheet) include observed physical processes that are not fully incorporated by ice sheet models. These include: (a) tidewater glacier acceleration and destabilization by submarine melting (Truffer and Fahnestock, 2007; Khazendar et al., 2019; Wood et al., 2021; Holmes et al., 2024); (b) that observed destabilizing effects operate faster than in conventional modeling (Schulz et al., 2022), including loss of the buttressing effect from ice-shelves (Mouginot et al., 2015), accelerating inland motion from increased melt and rainfall (Doyle et al., 2015); (c) enhanced basal thawing due to hydraulically-released latent heat and viscous warming (Phillips et al., 2010); (d) amplified surface runoff due to bio-albedo darkening (Stibal et al., 2017); and (e) increased meltwater runoff decreasing the permeability of multi-year snow, also known as firn layers (MacFerrin et al., 2019).

While these effects may be partly covered by the empirically-derived retreat parameterization for marine-terminating outlet glaciers applied in the projections by the Ice Sheet Model Intercomparison Project (ISMIP6) for CMIP6 (Slater et al., 2019, 2020; Goelzer et al., 2020), there is an urgent need for model improvements to incorporate physically-based representations of those processes.

Ice-sheet modeling is further challenged by coarse coupling to atmospheric and oceanic boundaries (Pattyn et al., 2018; Hanna et al., 2024). Finer resolution ocean circulation modeling would enable more realistic heat delivery to fjord glaciers from large-scale ocean currents and the exchange of freshwater fluxes from beneath tidewater glaciers (e.g., Siegert et al., 2020; Prakash et al., 2022).

6.9 Impacts of hydrological change on ecosystems and Arctic livelihoods

A changing hydrological system is expected to have various effects on ecosystems and northern communities, including Indigenous Peoples. Snow changes, for example, have numerous impacts on Arctic ecosystems. Snow pack affects the start and end of the growing season, plant phenology and growth, community composition, plant access to moisture and nutrients, soil biogeochemistry, and trophic interactions (Rixen et al., 2022). Particularly important snow processes include the frequency and intensity of freezing events, freeze-thaw cycles, and rain-on-snow events (Walsh et al., 2020; Rixen et al., 2022). Many of the impacts on ecosystems are further reflected as impacts on Arctic Indigenous Peoples, and other Arctic inhabitants (e.g., Forbes et al. 2016; Ocobock et al., 2022; Rosqvist et al., 2022). Other impacts on Arctic Indigenous Peoples, and other Arctic inhabitants, include issues concerning freshwater availability (Bring et al., 2016; Thackeray et al., 2019), hydropower production, avalanches (Hancock et al., 2018), transportation, and reindeer herding (Forbes et al., 2016; Eira et al., 2018; Jaakkola et al., 2018; Markkula et al., 2019; Gagnon et al., 2020; Johnsen et al., 2023). For example, Indigenous Sámi reindeer herding communities in Sweden have been forced to undertake earlier spring moves due to shorter snow-cover duration (Löf, 2013).

Research has been motivated not only by a need to improve understanding of the sensitivity of natural ecosystems to climate change, but also from the perspective of natural resources, including safety of drinking water and infrastructure. Drivers of changes in streamflow, such as increased winter streamflow and decreased flow in headwater streams, set the basic conditions for life in riverine ecosystems, on which many Arctic Indigenous Peoples, and other Arctic inhabitants, depend (e.g., freshwater fish). Changing permafrost hydrology also drives changes in streamwater quality, including temperature and chemistry. This was highlighted in a study by Spence et al. (2020), who developed a Canadian Water Vulnerability Index to Permafrost Thaw. They identified stressors related to permafrost that can influence water budgets and chemistry, and their results imply that the western Northwest Territories and Hudson Bay Lowlands are the most vulnerable to permafrost thaw. Permafrost thaw can also open new flow paths for contaminant transport (e.g., McKenzie at al., 2021), as well as lead to changes in water availability for Arctic vegetation (e.g., Jin et al., 2021; Koch et al., 2022).

An increase in river discharge into the Arctic Ocean will lead to stronger ocean stratification, warmer subsurface water (Nummelin et al., 2016) and the potential for a weakening of the Atlantic Meridional Overturning Circulation (Shu et al., 2017), with adverse consequences for heat balance and climate in the Northern Hemisphere (Peterson et al., 2006). River flow acts as a nutrient supplier in estuarine and nearshore ecosystems and any increase would have a positive impact on biological production (Carmack et al., 2016; McMahon et al., 2021). Changes in seasonal runoff may have both positive and negative impacts on human activity and local ecosystems. More uniform discharge distribution throughout the year would benefit hydropower production, navigation, and water availability for different human needs, especially during low-flow seasons. In contrast, more intensive snow melt and greater spring freshet would increase the probability of extreme floods, and increased discharge during the summer-autumn period would enhance erosion of permafrost river channels, potentially resulting in damage to riverside infrastructure, and a change in subsistence resources and subsistence harvest practices (Arp et al., 2020b).

Long-term changes in lake area would affect Indigenous Peoples, and other Arctic inhabitants, that rely on lakes for water sources and subsistence hunting and fishing, wildlife that depends on lakes for habitat and feeding and nesting sites, and industries that rely on surface water for resource extraction (White et al., 2007; Cott et al., 2008; Roach and Griffith, 2015; Medeiros et al., 2017). Long-term changes in lake area can also accelerate or mitigate climate feedbacks (Walter et al., 2006; Van Huissteden et al., 2011; Turetsky et al., 2020; Webb et al., 2021). For example, decreased lake area increases summertime albedo, resulting in a negative climate feedback at the regional to pan-Arctic scale (Webb et al., 2021). Drained thaw lakes are also a net carbon sink over millennial timescales (Jones M.C. et al., 2012; Sturtevant and Oechel, 2013; Jones B.M. et al., 2022), while thaw lake initiation and expansion increase methane and carbon dioxide fluxes to the atmosphere (Walter Anthony et al., 2016, 2018; Wik et al., 2016). Thus, tracking the magnitude and extent of Arctic surface-water change is a crucial element of future planning for northern communities and for accurate projections of global climate feedbacks.

Losing lake ice has substantial ecological and societal consequences. Ecologically, this loss can contribute to increased under-ice chlorophyll concentrations, primary production, and the formation of algal blooms (Hampton et al., 2017), among the consequences of freshwater availability and water quality throughout the open-water season (Woolway et al., 2022). Decreasing ice duration implies longer periods of open water, during which solar radiation and conduction increase lake water heat budgets (Smits et al., 2020). Increasing energy input to surface waters leads to enhanced and more stable thermoclines, which in turn both diminishes oxygen reaeration to bottom waters – leading to prolonged hypoxia in the hypolimnion of stratified lakes (Jane et al., 2021) – and reduces oxythermal habitat for all freshwater fishes (Kraemer et al., 2021). Culturally, the loss of ice may result in delayed or cancelled recreation tournaments, such as skating and ice-fishing competitions (Knoll et al., 2019); delays in the construction of winter ice roads, which can affect the transport of goods to remote northern communities (Hori et al., 2018; Woolway et al., 2022); and to increased winter drownings through less predictable ice (Sharma et al., 2020a). The cultures and livelihoods of Arctic Indigenous Peoples are particularly vulnerable to the loss of ice. For example, central migration routes for Sámi reindeer husbandry traverse frozen lakes and rivers in many areas around Sápmi (Johnsen et al., 2023; Laptander et al., 2024). Loss of ice, thinner ice, or weaker ice with degraded ice quality conditions, not only presents drowning risks for herders and reindeer (Sharma et al., 2020a), but also the loss of migration routes in regions that might already be fragmented, suggesting that alternative migration routes might not be available.

References

Text references

Aas, K.S., L. Martin, J. Nitzbon, M. Langer, J. Boike, H. Lee, T.K. Berntsen and S. Westermann, 2019. Thaw processes in ice-rich permafrost landscapes represented with laterally coupled tiles in a land surface model. The Cryosphere, 13:591-609. doi:10.5194/tc-13-591-2019

Adrian, R., C.M. O'Reilly, H. Zagarese, S.B. Baines, D.O. Hessen, W. Keller, D.M. Livingstone, R. Sommaruga, D. Straile, E. Van Donk, G.A. Weyhenmeyer and M. Winder, 2009. Lakes as sentinels of climate change. Limnology and Oceanography, 54:2283-2297. doi:10.4319/lo.2009.54.6_part_2.2283

Agafonova, S.A. and A.N. Vasilenko, 2020. Hazardous ice phenomena in rivers of the Russian Arctic zone under current climate conditions and the safety of water use. Geography Environment Sustainability, 13:43-51. doi:10.24057/2071-9388-2020-12

Agafonova, S.A., N.A. Frolova, G.V. Surkova and K.P. Koltermann, 2017. Modern characteristics of the ice regime of Russian Arctic rivers and their possible changes in the 21st century. Geography Environment Sustainability, 10:4-15. doi:10.24057/2071-9388-2017-10-4-4-15

Ahmed, R., T. Prowse, Y. Dibike, B. Bonsal and H. O'Neil, 2020. Recent trends in freshwater influx to the Arctic Ocean from four major Arctic-draining rivers. Water, 12:1189. doi:10.3390/w12041189

Ala-aho, P., C. Soulsby, O.S. Pokrovsky, S.N. Kirpotin, J. Karlsson, S. Serikova, R. Manasypov, A. Lim, I. Krickov, L.G. Kolesnichenko, H. Laudon and D. Tetzlaff, 2018. Permafrost and lakes control river isotope composition across a boreal Arctic transect in the Western Siberian lowlands. Environmental Research Letters, 13:034028. doi:10.1088/1748-9326/aaa4fe

Ala-Aho, P., A. Autio, J. Bhattacharjee, E. Isokangas, K. Kujala, H. Marttila, M. Menberu, L.-J. Meriö, H. Postila, A. Rauhala, A.-K. Ronkanen, P.M. Rossi, M. Saari, A.T. Haghighi and B. Kløve, 2021a. What conditions favor the influence of seasonally frozen ground on hydrological partitioning? A systematic review. Environmental Research Letters, 16:043008. doi:10.1088/1748-9326/abe82c

Ala-aho, P., J.M. Welker, H. Bailey, S. Højlund Pedersen, B. Kopec, E. Klein, M. Mellat, K.-R. Mustonen, K. Noor and H. Marttila, 2021b. Arctic snow isotope hydrology: a comparative snow-water vapor study. Atmosphere, 12:150. doi:10.3390/atmos12020150

AMAP, 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2021. AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

An, J., P. Deng, B. Zhang, J. Liu, S. Ai, Z. Wang and Q. Yu, 2020. Snow depth variations in Svalbard derived from GNSS interferometric reflectometry. Remote Sensing, 12:3352. doi:10.3390/rs12203352

Andresen, C.G., D.M. Lawrence, C.J. Wilson, A.D. McGuire, C. Koven, K. Schaefer, E. Jafarov, S. Peng, X. Chen, I. Gouttevin, E. Burke, S. Chadburn, D. Ji, G. Chen, D. Hayes and W. Zhang, 2020. Soil moisture and hydrology projections of the permafrost region – a model intercomparison. The Cryosphere, 14:445-459. doi:10.5194/tc-14-445-2020

Antwerpen, R.M., M. Tedesco, X. Fettweis, P. Alexander and W.J. Van De Berg, 2022. Assessing bare-ice albedo simulated by MAR over the Greenland ice sheet (2000–2021) and implications for meltwater production estimates. The Cryosphere, 16:4185-4199. doi:10.5194/tc-16-4185-2022

Arctic-HYDRA, 2010. Science Implementation Plan. The Arctic Hydrological Cycle Monitoring, Modelling and Assessment Programme. Oslo, Norway. https://library.arcticportal.org/687/1/Arctic-HYDRA.pdf

Arheimer, B., C. Donnelly and G. Lindström, 2017. Regulation of snow-fed rivers affects flow regimes more than climate change. Nature Communications, 8:62. doi:10.1038/s41467-017-00092-8

Arp, C.D., J.E. Cherry, D.R.N. Brown, A.C. Bondurant and K.L. Endres, 2020a. Observation-derived ice growth curves show patterns and trends in maximum ice thickness and safe travel duration of Alaskan lakes and rivers. The Cryosphere, 14:3595-3609. doi:10.5194/tc-14-3595-2020

Arp, C.D., M.S. Whitman, R. Kemnitz and S.L. Stuefer, 2020b. Evidence of hydrological intensification and regime change from northern Alaskan watershed runoff. Geophysical Research Letters, 47:e2020GL089186. doi:10.1029/2020GL089186

Atchley, A.L., E.T. Coon, S.L. Painter, D.R. Harp and C.J. Wilson, 2016. Influences and interactions of inundation, peat, and snow on active layer thickness. Geophysical Research Letters, 43:5116-5123. doi:10.1002/2016GL068550

Auger, J.D., S.D. Birkel, K.A. Maasch, P.A. Mayewski and K.C. Schuenemann, 2017. Examination of precipitation variability in southern Greenland. Journal of Geophysical Research: Atmospheres, 122:6202-6216. doi:10.1002/2016JD026377

Ballinger, T.J., J.E. Overland, M. Wang, U.S. Bhatt, B. Brettschneider, E. Hanna, I. Hanssen-Bauer, S.-J. Kim, R.L. Thoman and J.E. Walsh, 2021. Surface Air Temperature. NOAA Arctic Report Card 2021. NOAA technical report OAR ARC; 21-02. doi:10.25923/53XD-9K68

Bartosiewicz, M., M. Ptak, R.I. Woolway and M. Sojka, 2021. On thinning ice: Effects of atmospheric warming, changes in wind speed and rainfall on ice conditions in temperate lakes (Northern Poland). Journal of Hydrology, 597:125724. doi:10.1016/j.jhydrol.2020.125724

Bawden, A.J., D.H. Burn and T.D. Prowse, 2015. Recent changes in patterns of western Canadian river flow and association with climatic drivers. Hydrology Research, 46:551-565. doi:10.2166/nh.2014.032

Beltaos, S. and B. Bonsal, 2021. Climate change impacts on Peace River ice thickness and implications to ice-jam flooding of Peace-Athabasca Delta, Canada. Cold Regions Science and Technology, 186:103279. doi:10.1016/j.coldregions.2021.103279

Bennett, K.E., A.J. Cannon and L. Hinzman, 2015. Historical trends and extremes in boreal Alaska river basins. Journal of Hydrology, 527:590-607. doi:10.1016/j.jhydrol.2015.04.065

Benson, B.J., J.J. Magnuson, O.P. Jensen, V.M. Card, G. Hodgkins, J. Korhonen, D.M. Livingstone, K.M. Stewart, G.A. Weyhenmeyer and N.G. Granin, 2012. Extreme events, trends, and variability in Northern Hemisphere lake-ice phenology (1855–2005). Climatic Change, 112:299-323. doi:10.1007/s10584-011-0212-8

Berkes, F. and D. Jolly, 2001. Adapting to climate change: social-ecological resilience in a Canadian western Arctic community. Conservation Ecology, 5:18. doi:10.5751/ES-00342-050218

Bertilsson, S., A. Burgin, C.C. Carey, S.B. Fey, H.-P. Grossart, L.M. Grubisic, I.D. Jones, G. Kirillin, J.T. Lennon, A. Shade and R.L. Smyth, 2013. The under-ice microbiome of seasonally frozen lakes. Limnology and Oceanography, 58:1998-2012. doi:10.4319/lo.2013.58.6.1998

Bhatia, M.P., S. Waterman, D.O. Burgess, P.L. Williams, R.M. Bundy, T. Mellett, M. Roberts and E.M. Bertrand, 2021. Glaciers and nutrients in the Canadian Arctic Archipelago marine system. Global Biogeochemical Cycles, 35:e2021GB006976. doi:10.1029/2021GB006976

Biancamaria, S., D.P. Lettenmaier and T.M. Pavelsky, 2016. The SWOT mission and its capabilities for land hydrology. Surveys in Geophysics, 37:307-337. doi:10.1007/s10712-015-9346-y

Bieniek, P.A., U.S. Bhatt, J.E. Walsh, R. Lader, B. Griffith, J.K. Roach and R.L. Thoman, 2018. Assessment of Alaska rain-on-snow events using dynamical downscaling. Journal of Applied Meteorology and Climatology, 57:1847-1863. doi:10.1175/JAMC-D-17-0276.1

Bigalke, S. and J.E. Walsh, 2022. Future changes of snow in Alaska and the Arctic under stabilized global warming scenarios. Atmosphere, 13:541. doi:10.3390/atmos13040541

Bintanja, R., 2018. The impact of Arctic warming on increased rainfall. Scientific Reports, 8:16001. doi:10.1038/s41598-018-34450-3

Bintanja, R. and O. Andry, 2017. Towards a rain-dominated Arctic. Nature Climate Change, 7:263-267. doi:10.1038/nclimate3240

Bintanja, R. and F.M. Selten, 2014. Future increases in Arctic precipitation linked to local evaporation and sea-ice retreat. Nature, 509:479-482. doi:10.1038/nature13259

Bintanja, R., K. Van Der Wiel, E.C. Van Der Linden, J. Reusen, L. Bogerd, F. Krikken and F.M. Selten, 2020. Strong future increases in Arctic precipitation variability linked to poleward moisture transport. Science Advances, 6:eaax6869. doi:10.1126/sciadv.aax6869

Boisvert, L.N., M.A. Webster, A.A. Petty, T. Markus, D.H. Bromwich and R.I. Cullather, 2018. Intercomparison of precipitation estimates over the Arctic Ocean and its peripheral seas from reanalyses. Journal of Climate, 31:8441-8462. doi:10.1175/JCLI-D-18-0125.1

Bokhorst, S., S.H. Pedersen, L. Brucker, O. Anisimov, J.W. Bjerke, R.D. Brown, D. Ehrich, R.L.H. Essery, A. Heilig, S. Ingvander, C. Johansson, M. Johansson, I.S. Jónsdóttir, N. Inga, K. Luojus, G. Macelloni, H. Mariash, D. McLennan, G.N. Rosqvist, A. Sato, H. Savela, M. Schneebeli, A. Sokolov, S.A. Sokratov, S. Terzago, D. Vikhamar-Schuler, S. Williamson, Y. Qiu and T.V. Callaghan, 2016. Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts. Ambio, 45:516-537. doi:10.1007/s13280-016-0770-0

Bonsal, B.R., D.L. Peters, F. Seglenieks, A. Rivera and A. Berg, 2019. Changes in freshwater availability across Canada. In: Bush, E. and D.S. Lemmen (Eds.), Canada's Changing Climate Report. Government of Canada, Ottawa, Ontario, pp. 261-342.

Bormann, K.J., R.D. Brown, C. Derksen and T.H. Painter, 2018. Estimating snow-cover trends from space. Nature Climate Change, 8:924-928. doi:10.1038/s41558-018-0318-3

Bouchard, F., K.W. Turner, L.A. MacDonald, C. Deakin, H. White, N. Farquharson, A.S. Medeiros, B.B. Wolfe, R.I. Hall, R. Pienitz and T.W.D. Edwards, 2013. Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low. Geophysical Research Letters, 40:6112-6117. doi:10.1002/2013GL058635

Bouchard, F., D. Fortier, M. Paquette, V. Boucher, R. Pienitz and I. Laurion, 2020. Thermokarst lake inception and development in syngenetic ice-wedge polygon terrain during a cooling climatic trend, Bylot Island (Nunavut), eastern Canadian Arctic. The Cryosphere, 14:2607-2627. doi:10.5194/tc-14-2607-2020

Box, J.E., W.T. Colgan, T.R. Christensen, N.M. Schmidt, M. Lund, F.-J.W. Parmentier, R. Brown, U.S. Bhatt, E.S. Euskirchen, V.E. Romanovsky, J.E. Walsh, J.E. Overland, M. Wang, R.W. Corell, W.N. Meier, B. Wouters, S. Mernild, J. Mård, J. Pawlak and M.S. Olsen, 2019. Key indicators of Arctic climate change: 1971–2017. Environmental Research Letters, 14:045010. doi:10.1088/1748-9326/aafc1b

Box, J.E., A. Hubbard, D.B. Bahr, W.T. Colgan, X. Fettweis, K.D. Mankoff, A. Wehrlé, B. Noël, M.R. Van Den Broeke, B. Wouters, A.A. Bjørk and R.S. Fausto, 2022. Greenland ice sheet climate disequilibrium and committed sea-level rise. Nature Climate Change, 12:808-813. doi:10.1038/s41558-022-01441-2

Brewer, M., 1958. The thermal regime of an Arctic lake. Eos, Transactions American Geophysical Union, 39:278-284. doi:10.1029/TR039i002p00278

Bring, A., I. Fedorova, Y. Dibike, L. Hinzman, J. Mård, S.H. Mernild, T. Prowse, O. Semenova, S.L. Stuefer and M.-K. Woo, 2016. Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. Journal of Geophysical Research: Biogeosciences, 121:621-649. doi:10.1002/2015JG003131

Bring, A., A. Shiklomanov and R.B. Lammers, 2017. Pan-Arctic river discharge: Prioritizing monitoring of future climate change hot spots. Earth's Future, 5:72-92. doi:10.1002/2016EF000434

Brooks, R.N., T.D. Prowse and I.J. O'Connell, 2013. Quantifying Northern Hemisphere freshwater ice. Geophysical Research Letters, 40:1128-1131. doi:10.1002/grl.50238

Brosius, L.S., K.M.W. Anthony, C.C. Treat, J. Lenz, M.C. Jones, M.S. Bret-Harte and G. Grosse, 2021. Spatiotemporal patterns of northern lake formation since the Last Glacial Maximum. Quaternary Science Reviews, 253:106773. doi:10.1016/j.quascirev.2020.106773

Brown, L.C. and C.R. Duguay, 2010. The response and role of ice cover in lake-climate interactions. Progress in Physical Geography: Earth and Environment, 34:671-704. doi:10.1177/0309133310375653

Brown, J., O.J. Ferrians, Jr., J.A. Heginbottom and E.S. Melnikov (Eds.), 1997. Circum-Arctic map of permafrost and ground-ice conditions. U.S. Geological Survey in Cooperation with the Circum-Pacific Council for Energy and Mineral Resources. Circum-Pacific Map Series CP-45, scale 1:10,000,000, 1 sheet.

Buchan, J., J.J.-M. Hirschi, A.T. Blaker and B. Sinha, 2014. North Atlantic SST anomalies and the cold north European weather events of winter 2009/10 and December 2010. Monthly Weather Review, 142:922-932. doi:10.1175/MWR-D-13-00104.1

Burenina, T.A., D.A. Prysov and A.V. Musokhranova, 2021. The effects of climate change on the hydrological regime of northern rivers in Krasnoyarsk Krai. Geography and Natural Resources, 42:282-289. doi:10.1134/S1875372821030070

Burn, C.R., 1992. Thermokarst lakes. Canadian Geographies, 36:81-85. doi:10.1111/j.1541-0064.1992.tb01121.x

Burrell, B.C., S. Beltaos and B. Turcotte, 2023. Effects of climate change on river-ice processes and ice jams. International Journal of River Basin Management, 21:421-441. doi:10.1080/15715124.2021.2007936

Cai, L., H. Lee, K.S. Aas and S. Westermann, 2020. Projecting circum-Arctic excess-ground-ice melt with a sub-grid representation in the Community Land Model. The Cryosphere, 14:4611-4626. doi:10.5194/tc-14-4611-2020

Cai, Z., Q. You, H.W. Chen, R. Zhang, Z. Zuo, D. Chen, J. Cohen and J.A. Screen, 2024. Assessing Arctic wetting: Performances of CMIP6 models and projections of precipitation changes. Atmospheric Research, 297:107124. doi:10.1016/j.atmosres.2023.107124

Campbell, T., T. Lantz and R. Fraser, 2018. Impacts of climate change and intensive lesser snow goose (*Chen caerulescens caerulescens*) activity on surface water in High Arctic pond complexes. Remote Sensing, 10:1892. doi:10.3390/rs10121892

Carmack, E.C., M. Yamamoto-Kawai, T.W.N. Haine, S. Bacon, B.A. Bluhm, C. Lique, H. Melling, I.V. Polyakov, F. Straneo, M.-L. Timmermans and W.J. Williams, 2016. Freshwater and its role in the Arctic marine system: Sources, disposition, storage, export, and physical and biogeochemical consequences in the Arctic and global oceans. Journal of Geophysical Research: Biogeosciences, 121:675-717. doi:10.1002/2015JG003140

Carpino, O., K. Haynes, R. Connon, J. Craig, É. Devoie and W. Quinton, 2021. Long-term climate-influenced land cover change in discontinuous permafrost peatland complexes. Hydrology and Earth System Sciences, 25:3301-3317. doi:10.5194/hess-25-3301-2021

Carrivick, J.L. and D.J. Quincey, 2014. Progressive increase in number and volume of ice-marginal lakes on the western margin of the Greenland Ice Sheet. Global and Planetary Change, 116:156-163. doi:10.1016/j.gloplacha.2014.02.009

Carroll, M.L. and T.V. Loboda, 2018. The sign, magnitude and potential drivers of change in surface water extent in Canadian tundra. Environmental Research Letters, 13:045009. doi:10.1088/1748-9326/aab794

Chen, Y. and Y. She, 2020. Long-term variations of river ice breakup timing across Canada and its response to climate change. Cold Regions Science and Technology, 176:103091. doi:10.1016/j.coldregions.2020.103091

Chen, L., D. Fortier, J.M. McKenzie, C.I. Voss and P. Lamontagne-Hallé, 2023. Subsurface porewater flow accelerates talik development under the Alaska Highway, Yukon: a prelude to road collapse and final permafrost thaw? Water Resources Research, 59:e2022WR032578. doi:10.1029/2022WR032578

Cheţan, M.-A., A. Dornik, F. Ardelean, G. Georgievski, S. Hagemann, V.E. Romanovsky, A. Onaca and D.S. Drozdov, 2020. 35 Years of vegetation and lake dynamics in the Pechora catchment, Russian European Arctic. Remote Sensing, 12:1863. doi:10.3390/rs12111863

Chiasson-Poirier, G., J. Franssen, M.J. Lafrenière, D. Fortier and S.F. Lamoureux, 2020. Seasonal evolution of active layer thaw depth and hillslope-stream connectivity in a permafrost watershed. Water Resources Research, 56:e2019WR025828. doi:10.1029/2019WR025828

Christensen, T.R., M. Lund, K. Skov, J. Abermann, E. López-Blanco, J. Scheller, M. Scheel, M. Jackowicz-Korczynski, K. Langley, M.J. Murphy and M. Mastepanov, 2021. Multiple ecosystem effects of extreme weather events in the Arctic. Ecosystems, 24:122-136. doi:10.1007/s10021-020-00507-6

CliC/AMAP/IASC, 2016. The Arctic Freshwater System in a Changing Climate. WCRP Climate and Cryosphere (CliC) Project, Arctic Monitoring and Assessment Programme (AMAP), International Arctic Science Committee (IASC). www.amap.no/documents/doc/the-arctic-freshwater-system-in-a-changing-climate/1375

Cochand, M., J. Molson and J. Lemieux, 2019. Groundwater hydrogeochemistry in permafrost regions. Permafrost and Periglacial Processes, 30:90-103. doi:10.1002/ppp.1998

Connon, R.F., W.L. Quinton, J.R. Craig and M. Hayashi, 2014. Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. Hydrological Processes, 28:4163-4178. doi:10.1002/hyp.10206

Connon, R., É. Devoie, M. Hayashi, T. Veness and W. Quinton, 2018. The influence of shallow taliks on permafrost thaw and active layer dynamics in subarctic Canada. Journal of Geophysical Research: Earth Surface, 123:281-297. doi:10.1002/2017JF004469

Cooley, S.W. and T.M. Pavelsky, 2016. Spatial and temporal patterns in Arctic river ice breakup revealed by automated ice detection from MODIS imagery. Remote Sensing of Environment, 175:310-322. doi:10.1016/j.rse.2016.01.004

Cooper, M.G., T. Zhou, K.E. Bennett, W.R. Bolton, E.T. Coon, S.W. Fleming, J.C. Rowland and J. Schwenk, 2023. Detecting permafrost active layer thickness change from nonlinear baseflow recession. Water Resources Research, 59:e2022WR033154. doi:10.1029/2022WR033154

Corson-Dosch, H.R., C.S. Nell, R.E. Volentine, A.A. Archer, E. Bechtel, J.L. Bruce, N. Felts, T.A. Gross, D. Lopez-Trujillo, C.E. Riggs and E.K. Read, 2023. The water cycle: U.S. Geological Survey General Information Product 221, 1 sheet. doi:10.3133/gip221

Cott, P.A., P.K. Sibley, W.M. Somers, M.R. Lilly and A.M. Gordon, 2008. A review of water level fluctuations on aquatic biota with an emphasis on fishes in ice-covered lakes. Journal of the American Water Resources Association, 44:343-359. doi:10.1111/j.1752-1688.2007.00166.x

Coulombe, S., D. Fortier, F. Bouchard, M. Paquette, S. Charbonneau, D. Lacelle, I. Laurion and R. Pienitz, 2022. Contrasted geomorphological and limnological properties of thermokarst lakes formed in buried glacier ice and ice-wedge polygon terrain. The Cryosphere, 16:2837-2857. doi:10.5194/tc-16-2837-2022

Crites, H., S.V. Kokelj and D. Lacelle, 2020. Icings and groundwater conditions in permafrost catchments of northwestern Canada. Scientific Reports, 10:3283. doi:10.1038/s41598-020-60322-w

Czudek, T. and J. Demek, 1970. Thermokarst in Siberia and its influence on the development of lowland relief. Quaternary Research, 1:103-120. doi:10.1016/0033-5894(70)90013-X

Dagenais, S., J. Molson, J.-M. Lemieux, R. Fortier and R. Therrien, 2020. Coupled cryo-hydrogeological modelling of permafrost dynamics near Umiujaq (Nunavik, Canada). Hydrogeology Journal, 28:887-904. doi:10.1007/s10040-020-02111-3

Dauginis, A.A. and L.C. Brown, 2021. Recent changes in pan-Arctic sea ice, lake ice, and snow-on/off timing. The Cryosphere, 15:4781-4805. doi:10.5194/tc-15-4781-2021

De Rham, L., Y. Dibike, S. Beltaos, D. Peters, B. Bonsal and T. Prowse, 2020. A Canadian river ice database from the national hydrometric program archives. Earth System Science Data, 12:1835-1860. doi:10.5194/essd-12-1835-2020

DeBeer, C.M., H.S. Wheater, J.W. Pomeroy, A.G. Barr, J.L. Baltzer, J.F. Johnstone and 25 others, 2021. Summary and synthesis of Changing Cold Regions Network (CCRN) research in the interior of western Canada – Part 2: Future change in cryosphere, vegetation, and hydrology. Hydrology and Earth System Sciences, 25:1849-1882. doi:10.5194/hess-25-1849-2021

Debolskiy, M.V., V.A. Alexeev, R. Hock, R.B. Lammers, A. Shiklomanov, J. Schulla, D. Nicolsky, V.E. Romanovsky and A. Prusevich, 2021. Water balance response of permafrost-affected watersheds to changes in air temperatures. Environmental Research Letters, 16:084054. doi:10.1088/1748-9326/ac12f3

Déry, S.J., T.A. Stadnyk, M.K. MacDonald and B. Gauli-Sharma, 2016. Recent trends and variability in river discharge across northern Canada. Hydrology and Earth System Sciences, 20:4801-4818. doi:10.5194/hess-20-4801-2016

Déry, S.J., T.A. Stadnyk, M.K. MacDonald, K.A. Koenig and C. Guay, 2018. Flow alteration impacts on Hudson Bay river discharge. Hydrological Processes, 32:3576-3587. doi:10.1002/hyp.13285

Devilliers, M., D. Swingedouw, J. Mignot, J. Deshayes, G. Garric and M. Ayache, 2021. A realistic Greenland ice sheet and surrounding glaciers and ice caps melting in a coupled climate model. Climate Dynamics, 57:2467-2489. doi:10.1007/s00382-021-05816-7

Devoie, É.G., J.R. Craig, R.F. Connon and W.L. Quinton, 2019. Taliks: A tipping point in discontinuous permafrost degradation in peatlands. Water Resources Research, 55:9838-9857. doi:10.1029/2018WR024488

Ditlevsen, P. and S. Ditlevsen, 2023. Warning of a forthcoming collapse of the Atlantic meridional overturning circulation. Nature Communications, 14:4254. doi:10.1038/s41467-023-39810-w

Dou, T.F., S.F. Pan, R. Bintanja and C.D. Xiao, 2022. More frequent, intense, and extensive rainfall events in a strongly warming Arctic. Earth's Future, 10:e2021EF002378. doi:10.1029/2021EF002378

Douglas, T.A., M.R. Turetsky and C.D. Koven, 2020. Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. npj Climate and Atmospheric Science, 3:28. doi:10.1038/s41612-020-0130-4

Doyle, S.H., A. Hubbard, R.S.W. Van De Wal, J.E. Box, D. Van As, K. Scharrer, T.W. Meierbachtol, P.C.J.P. Smeets, J.T. Harper, E. Johansson, R.H. Mottram, A.B. Mikkelsen, F. Wilhelms, H. Patton, P. Christoffersen and B. Hubbard, 2015. Amplified melt and flow of the Greenland ice sheet driven by late-summer cyclonic rainfall. Nature Geoscience, 8:647-653. doi:10.1038/ngeo2482

Duguay, C.R., T.D. Prowse, B.R. Bonsal, R.D. Brown, M.P. Lacroix and P. Ménard, 2006. Recent trends in Canadian lake ice cover. Hydrological Processes, 20:781-801. doi:10.1002/hyp.6131

Durand, M., C.J. Gleason, P.A. Garambois, D. Bjerklie, L.C. Smith, H. Roux, E. Rodriguez and 20 others, 2016. An intercomparison of remote sensing river discharge estimation algorithms from measurements of river height, width, and slope. Water Resources Research, 52:4527-4549. doi:10.1002/2015WR018434

Durocher, M., A.I. Requena, D.H. Burn and J. Pellerin, 2019. Analysis of trends in annual streamflow to the Arctic Ocean. Hydrological Processes, 33:1143-1151. doi:10.1002/hyp.13392

Dye, A., R. Bryant and D. Rippin, 2022. Proglacial lake expansion and glacier retreat in Arctic Sweden. Geografiska Annaler: Series A, Physical Geography, 104:268-287. doi:10.1080/04353676.2022.2121999

Edwards, T.L., S. Nowicki, B. Marzeion, R. Hock, H. Goelzer, H. Seroussi, N.C. Jourdain and 77 others, 2021. Projected land ice contributions to twenty-first-century sea level rise. Nature, 593:74-82. doi:10.1038/s41586-021-03302-y

Eira, I.M.G., A. Oskal, I. Hanssen-Bauer and S.D. Mathiesen, 2018. Snow cover and the loss of traditional indigenous knowledge. Nature Climate Change, 8:928-931. doi:10.1038/s41558-018-0319-2

Eira, I.M.G., E.I. Turi and J.M. Turi, 2023. Sámi traditional reindeer herding knowledge throughout a year: herding periods on snow-covered ground. In: Mathiesen, S.D., I.M.G. Eira, E.I. Turi, A. Oskal, M. Pogodaev and M. Tonkopeeva (Eds.), Reindeer Husbandry, Springer Polar Sciences. Springer International Publishing, pp. 67-97. doi:10.1007/978-3-031-17625-8_4

Ekici, A., H. Lee, D.M. Lawrence, S.C. Swenson and C. Prigent, 2019. Ground subsidence effects on simulating dynamic high-latitude surface inundation under permafrost thaw using CLM5. Geoscientific Model Development, 12:5291-5300. doi:10.5194/gmd-12-5291-2019

Ensom, T., O. Makarieva, P. Morse, D. Kane, V. Alekseev and P. Marsh, 2020. The distribution and dynamics of aufeis in permafrost regions. Permafrost and Periglacial Processes, 31:383-395. doi:10.1002/ppp.2051

Evans, S.G. and S. Ge, 2017. Contrasting hydrogeologic responses to warming in permafrost and seasonally frozen ground hillslopes. Geophysical Research Letters, 44:1803-1813. doi:10.1002/2016GL072009

Evans, S.G., B. Yokeley, C. Stephens and B. Brewer, 2020. Potential mechanistic causes of increased baseflow across northern Eurasia catchments underlain by permafrost. Hydrological Processes, 34:2676-2690. doi:10.1002/hyp.13759

Feng, D., C.J. Gleason, P. Lin, X. Yang, M. Pan and Y. Ishitsuka, 2021. Recent changes to Arctic river discharge. Nature Communications, 12:6917. doi:10.1038/s41467-021-27228-1

Ferguson, C.R., M. Pan and T. Oki, 2018. The effect of global warming on future water availability: CMIP5 synthesis. Water Resources Research, 54:7791-7819. doi:10.1029/2018WR022792

Field, H.R., W.H. Armstrong and M. Huss, 2021. Gulf of Alaska ice-marginal lake area change over the Landsat record and potential physical controls. The Cryosphere, 15:3255-3278. doi:10.5194/tc-15-3255-2021

Fontrodona Bach, A., G. Van Der Schrier, L.A. Melsen, A.M.G. Klein Tank and A.J. Teuling, 2018. Widespread and accelerated decrease of observed mean and extreme snow depth over Europe. Geophysical Research Letters, 45:12,312-12,319. doi:10.1029/2018GL079799

Forbes, B.C., T. Kumpula, N. Meschtyb, R. Laptander, M. Macias-Fauria, P. Zetterberg, M. Verdonen, A. Skarin, K.-Y. Kim, L.N. Boisvert, J.C. Stroeve and A. Bartsch, 2016. Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. Biology Letters, 12:20160466. doi:10.1098/rsbl.2016.0466

Ford, V.L. and O.W. Frauenfeld, 2022. Arctic precipitation recycling and hydrologic budget changes in response to sea ice loss. Global and Planetary Change, 209:103752. doi:10.1016/j.gloplacha.2022.103752

Fortier, D., M. Allard and Y. Shur, 2007. Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago. Permafrost and Periglacial Processes, 18:229-243. doi:10.1002/ppp.595

Fortier, P., N.L. Young, J. Lemieux, M.A. Walvoord and R. Fortier, 2023. Long-term, high-resolution permafrost monitoring reveals coupled energy balance and hydrogeologic controls on talik dynamics near Umiujaq (Nunavik, Québec, Canada). Water Resources Research, 59:e2022WR032456. doi:10.1029/2022WR032456

Francis, J.A., D.M. White, J.J. Cassano, W.J. Gutowski, L.D. Hinzman, M.M. Holland, M.A. Steele and C.J. Vörösmarty, 2009. An arctic hydrologic system in transition: Feedbacks and impacts on terrestrial, marine, and human life. Journal of Geophysical Research: Biogeosciences, 114:2008JG000902. doi:10.1029/2008JG000902

Frolova, N.L., P.A. Belyakova, V.Yu. Grigoriev, A.A. Sazonov, L.V. Zotov and J. Jarsjö, 2017. Runoff fluctuations in the Selenga River Basin. Regional Environmental Change, 17:1965-1976. doi:10.1007/s10113-017-1199-0

Frolova, N.L., D.V. Magritskii, M.B. Kireeva, V.Yu. Grigor'ev, A.N. Gelfan, A.A. Sazonov and A.I. Shevchenko, 2022. Streamflow of Russian rivers under current and forecasted climate changes: a review of publications. 1. Assessment of changes in the water regime of Russian rivers by observation data. Water Resources, 49:333-350. doi:10.1134/S0097807822030046

Fukś, M., 2023. Changes in river ice cover in the context of climate change and dam impacts: a review. Aquatic Sciences, 85:113. doi:10.1007/s00027-023-01011-4

Gädeke, A., V. Krysanova, A. Aryal, J. Chang, M. Grillakis, N. Hanasaki, A. Koutroulis, Y. Pokhrel, Y. Satoh, S. Schaphoff, H. Müller Schmied, T. Stacke, Q. Tang, Y. Wada and K. Thonicke, 2020. Performance evaluation of global hydrological models in six large pan-Arctic watersheds. Climatic Change, 163:1329-1351. doi:10.1007/s10584-020-02892-2

Gagnon, C.A., S. Hamel, D.E. Russell, T. Powell, J. Andre, M.Y. Svoboda and D. Berteaux, 2020. Merging indigenous and scientific knowledge links climate with the growth of a large migratory caribou population. Journal of Applied Ecology, 57:1644-1655. doi:10.1111/1365-2664.13558

Gao, B. and E.T. Coon, 2022. Evaluating simplifications of subsurface process representations for field-scale permafrost hydrology models. The Cryosphere, 16:4141-4162. doi:10.5194/tc-16-4141-2022

Gelfan, A.N., E.M. Gusev, A.S. Kalugin, I.N. Krylenko, Yu.G. Motovilov, O.N. Nasonova, T.D. Millionshchikova and N.L. Frolova, 2022. Runoff of Russian rivers under current and projected climate change: a review 2. Climate change impact on the water regime of Russian Rivers in the XXI century. Water Resources, 49:351-365. doi:10.1134/S0097807822030058

Gelfan, A.N., N.L. Frolova, D.V. Magritsky, M.B. Kireeva, V.Yu. Grigoriev, Yu.G. Motovilov and E.M. Gusev, 2023. Climate change impact on the annual and maximum runoff of Russian rivers: diagnosis and projections. Izvestiya Atmospheric and Oceanic Physics, 59:S153-S169. doi:10.1134/S0001433823140074

Georgiadi, A.G. and I.P. Milyukova, 2023. Peculiarities of long-term phases of the increased and decreased Don and Lena runoff in the 19th–21st centuries. Russian Meteorology and Hydrology, 48:1066-1075. doi:10.3103/S1068373923120075

Georgiadi, A.G., N.I. Koronkevich, E.A. Barabanova, E.A. Kashutina and I.P. Milyukova, 2019. Assessing the effect of climatic and anthropogenic factors on the annual runoff of large rivers in European Russia and Siberia. IOP Conference Series: Earth and Environmental Science, 381:012027. doi:10.1088/1755-1315/381/1/012027

Georgievskii, V.Yu., E.A. Grek, E.N. Grek, A.G. Lobanova and T.G. Molchanova, 2019a. Assessment of modern changes in maximum river flow in Russia. Russian Meteorology and Hydrology, 44:739-745. doi:10.3103/S1068373919110037

Georgievskii, V.Yu., E.A. Grek, M.L. Markov and T.G. Molchanova, 2019b. Hydrological hazards on Russian Arctic rivers. Russian Meteorology and Hydrology, 44:276-282. doi:10.3103/S1068373919040071

Georgievsky, M., O. Golovanov, Z. Balonishnikova and L. Timofeeva, 2021. Changes in river water resources of the Russian Federation's economic regions forecasted based on the CMIP5 runoff data. Ecohydrology and Hydrobiology, 21:669-682. doi:10.1016/j.ecohyd.2021.06.004

Ghanbari, R.N., H.R. Bravo, J.J. Magnuson, W.G. Hyzer and B.J. Benson, 2009. Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin). Journal of Hydrology, 374:282-293. doi:10.1016/j.jhydrol.2009.06.024

Ghias, M., R. Therrien, J. Molson and J.-M. Lemieux, 2019. Numerical simulations of shallow groundwater flow and heat transport in continuous permafrost setting under impact of climate warming. Canadian Geotechnical Journal, 56:436-448. doi:10.1139/cgj-2017-0182

Gimeno-Sotelo, L., R. Nieto, M. Vázquez and L. Gimeno, 2018. A new pattern of the moisture transport for precipitation related to the drastic decline in Arctic sea ice extent. Earth System Dynamics, 9:611-625. doi:10.5194/esd-9-611-2018

Gleason, K.E., J.R. McConnell, M.M. Arienzo, N. Chellman and W.M. Calvin, 2019. Four-fold increase in solar forcing on snow in western U.S. burned forests since 1999. Nature Communications, 10:2026. doi:10.1038/s41467-019-09935-y

Goelzer, H., S. Nowicki, A. Payne, E. Larour, H. Seroussi, W.H. Lipscomb, J. Gregory and 35 others, 2020. The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6. The Cryosphere, 14:3071-3096. doi:10.5194/tc-14-3071-2020

Gohari, A., A. Jalali Shahrood, S. Ghadimi, M. Alborz, E.R. Patro, B. Klöve and A. Torabi Haghighi, 2022. A century of variations in extreme flow across Finnish rivers. Environmental Research Letters, 17:124027. doi:10.1088/1748-9326/aca554

Grant, L., I. Vanderkelen, L. Gudmundsson, Z. Tan, M. Perroud, V.M. Stepanenko, A.V. Debolskiy, B. Droppers, A.B.G. Janssen, R.I. Woolway,

M. Choulga, G. Balsamo, G. Kirillin, J. Schewe, F. Zhao, I.V. Del Valle, M. Golub, D. Pierson, R. Marcé, S.I. Seneviratne and W. Thiery, 2021. Attribution of global lake systems change to anthropogenic forcing. Nature Geoscience, 14:849-854. doi:10.1038/s41561-021-00833-x

Grenier, C., H. Anbergen, V. Bense, Q. Chanzy, E. Coon, N. Collier, F. Costard, M. Ferry, A. Frampton, J. Frederick, J. Gonçalvès, J. Holmén, A. Jost, S. Kokh, B. Kurylyk, J. McKenzie, J. Molson, E. Mouche, L. Orgogozo, R. Pannetier, A. Rivière, N. Roux, W. Rühaak, J. Scheidegger, J.-O. Selroos, R. Therrien, P. Vidstrand and C. Voss, 2018. Groundwater flow and heat transport for systems undergoing freeze-thaw: Intercomparison of numerical simulators for 2D test cases. Advances in Water Resources, 114:196-218. doi:10.1016/j.advwatres.2018.02.001

Groisman, P.Y., O.N. Bulygina, X. Yin, R.S. Vose, S.K. Gulev, I. Hanssen-Bauer and E. Førland, 2016. Recent changes in the frequency of freezing precipitation in North America and Northern Eurasia. Environmental Research Letters, 11:045007. doi:10.1088/1748-9326/11/4/045007

Grosse, G., B. Jones and C. Arp, 2013. Thermokarst lakes, drainage, and drained basins. In: Treatise on Geomorphology. Elsevier, pp. 325-353. doi:10.1016/B978-0-12-374739-6.00216-5

Guimond, J.A., A.A. Mohammed, M.A. Walvoord, V.F. Bense and B.L. Kurylyk, 2022. Sea-level rise and warming mediate coastal groundwater discharge in the Arctic. Environmental Research Letters, 17:045027. doi:10.1088/1748-9326/ac6085

Gurevich, E.V., 2009. Influence of air temperature on the river runoff in winter (the Aldan river catchment case study). Russian Meteorology and Hydrology, 34:628-633. doi:10.3103/S1068373909090088

Hampton, S.E., A.W.E. Galloway, S.M. Powers, T. Ozersky, K.H. Woo, R.D. Batt, S.G. Labou, C.M. O'Reilly and 54 others, 2017. Ecology under lake ice. Ecology Letters, 20:98-111. doi:10.1111/ele.12699

Han, L. and L. Menzel, 2022. Hydrological variability in southern Siberia and the role of permafrost degradation. Journal of Hydrology, 604:127203. doi:10.1016/j.jhydrol.2021.127203

Hancock, H., A. Prokop, M. Eckerstorfer and J. Hendrikx, 2018. Combining high spatial resolution snow mapping and meteorological analyses to improve forecasting of destructive avalanches in Longyearbyen, Svalbard. Cold Regions Science and Technology, 154:120-132. doi:10.1016/j.coldregions.2018.05.011

Hanna, E., D. Topál, J.E. Box, S. Buzzard, F.D.W. Christie, C. Hvidberg, M. Morlighem, L. De Santis, A. Silvano, F. Colleoni, I. Sasgen, A.F. Banwell, M.R. Van Den Broeke, R. DeConto, J. De Rydt, H. Goelzer, A. Gossart, G.H. Gudmundsson, K. Lindbäck, B. Miles, R. Mottram, F. Pattyn, R. Reese, E. Rignot, A. Srivastava, S. Sun, J. Toller, P.A. Tuckett and L. Ultee, 2024. Short- and long-term variability of the Antarctic and Greenland ice sheets. Nature Reviews Earth & Environment, 5:193-210. doi:10.1038/s43017-023-00509-7

Haynes, T.B., A.E. Rosenberger, M.S. Lindberg, M. Whitman and J.A. Schmutz, 2014. Patterns of lake occupancy by fish indicate different adaptations to life in a harsh Arctic environment. Freshwater Biology, 59:1884-1896. doi:10.1111/fwb.12391

Haynes, K.M., R.F. Connon and W.L. Quinton, 2018. Permafrost thaw induced drying of wetlands at Scotty Creek, NWT, Canada. Environmental Research Letters, 13:114001. doi:10.1088/1748-9326/aae46c

Helbig, M., J.M. Waddington, P. Alekseychik, B.D. Amiro, M. Aurela, A.G. Barr, T.A. Black, P.D. Blanken and 51 others, 2020. Increasing contribution of peatlands to boreal evapotranspiration in a warming climate. Nature Climate Change, 10:555-560. doi:10.1038/s41558-020-0763-7

Higgins, S.N., C.M. Desjardins, H. Drouin, L.E. Hrenchuk and J.J. Van Der Sanden, 2021. The role of climate and lake size in regulating the ice phenology of boreal lakes. Journal of Geophysical Research: Biogeosciences, 126:e2020JG005898. doi:10.1029/2020JG005898

Hindshaw, R.S., S.M. Aciego and E.T. Tipper, 2018. Li and U isotopes as a potential tool for monitoring active layer deepening in permafrost dominated catchments. Frontiers in Earth Science, 6:102. doi:10.3389/feart.2018.00102

Hinzman, A.M., Y. Sjöberg, S.W. Lyon, S.W. Ploum and Y. Van Der Velde, 2020. Increasing non-linearity of the storage-discharge relationship in sub-arctic catchments. Hydrological Processes, 34:3894-3909. doi:10.1002/hyp.13860

Hinzman, A., Y. Sjöberg, S. Lyon, P. Schaap and Y. Van Der Velde, 2022. Using a mechanistic model to explain the rising non-linearity in storage discharge relationships as the extent of permafrost decreases in Arctic catchments. Journal of Hydrology, 612:128162. doi:10.1016/j.jhydrol.2022.128162

Hiyama, T., H. Park, K. Kobayashi, L. Lebedeva and D. Gustafsson, 2023. Contribution of summer net precipitation to winter river discharge in permafrost zone of the Lena River basin. Journal of Hydrology, 616:128797. doi:10.1016/j.jhydrol.2022.128797

Hock, R., A. Bliss, B. Marzeion, R.H. Giesen, Y. Hirabayashi, M. Huss, V. Radić and A.B.A. Slangen, 2019. GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections. Journal of Glaciology, 65:453-467. doi:10.1017/jog.2019.22

Holland, M.M., J. Finnis, A.P. Barrett and M.C. Serreze, 2007. Projected changes in Arctic Ocean freshwater budgets. Journal of Geophysical Research: Biogeosciences, 112:2006JG000354. doi:10.1029/2006JG000354

Holmes, R.M., A.I. Shiklomanov, A. Suslova, M. Tretiakov, J.M. McClelland, L. Scott, R.G.M. Spencer and S.E. Tank, 2021. River discharge. In: State of the Climate in 2020. Bulletin of the American Meteorological Society, 102:S290-S293. doi:10.1175/2021BAMSStateoftheClimate.1

Holmes, F.A., E. van Dongen and N. Kirchner, 2024. Modelled frontal ablation and velocities at Kronebreen, Svalbard, are sensitive to the choice of submarine melt rate scenario. Journal of Glaciology, 70:e39. doi:10.1017/jog.2023.94

Hopkins, D.M., 1949. Thaw lakes and thaw sinks in the Imuruk Lake area, Seward Peninsula, Alaska. The Journal of Geology, 57:119-131. doi:10.1086/625591

Hori, Y., V.Y.S. Cheng, W.A. Gough, J.Y. Jien and L.J.S. Tsuji, 2018. Implications of projected climate change on winter road systems in Ontario's Far North, Canada. Climatic Change, 148:109-122. doi:10.1007/s10584-018-2178-2

Hu, D., M. Xu, S. Kang and H. Wu, 2022. Impacts of climate change and human activities on runoff changes in the Ob River Basin of the Arctic region from 1980 to 2017. Theoretical and Applied Climatology, 148:1663-1674. doi:10.1007/s00704-022-04021-8

Huang, L., A. Timmermann, S.-S. Lee, K.B. Rodgers, R. Yamaguchi and E.-S. Chung, 2022. Emerging unprecedented lake ice loss in climate change projections. Nature Communications, 13:5798. doi:10.1038/s41467-022-33495-3

Iijima, Y., A.N. Fedorov, H. Park, K. Suzuki, H. Yabuki, T.C. Maximov and T. Ohata, 2010. Abrupt increases in soil temperatures following increased precipitation in a permafrost region, central Lena River basin, Russia. Permafrost and Periglacial Processes, 21:30-41. doi:10.1002/ppp.662

Imrit, M.A. and S. Sharma, 2021. Climate change is contributing to faster rates of lake ice loss in lakes around the northern hemisphere. Journal of Geophysical Research: Biogeosciences, 126:e2020JG006134. doi:10.1029/2020JG006134

Imrit, M.A., Z. Yousaf and S. Sharma, 2022. Quantifying the trends and drivers of ice thickness in lakes and rivers across North America. Water, 14:1841. doi:10.3390/w14121841

Instanes, A., V. Kokorev, R. Janowicz, O. Bruland, K. Sand and T. Prowse, 2016. Changes to freshwater systems affecting Arctic infrastructure and natural resources. Journal of Geophysical Research: Biogeosciences, 121:567-585. doi:10.1002/2015JG003125

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V.P., A. Zhai, S.L. Pirani, C. Connors, S. Péan, N. Berger, Y. Caud, L. Chen, M.I. Goldfarb, M. Gomis, K. Huang, E. Leitzell, J.B.R. Lonnoy, T.K. Matthews, T. Maycock, O. Waterfield, R.Yu. Yelekçi and B. Zhou (eds.)]. Cambridge University Press. 2391 pp. doi:10.1017/9781009157896

Irannezhad, M., A.-K. Ronkanen and B. Kløve, 2016. Wintertime climate factors controlling snow resource decline in Finland. International Journal of Climatology, 36:110-131. doi:10.1002/joc.4332

Ishitsuka, Y., C.J. Gleason, M.W. Hagemann, E. Beighley, G.H. Allen, D. Feng, P. Lin, M. Pan, K. Andreadis and T.M. Pavelsky, 2021. Combining optical remote sensing, McFLI discharge estimation, global hydrologic modeling, and data assimilation to improve daily discharge estimates across an entire large watershed. Water Resources Research, 57:e2020WR027794. doi:10.1029/2020WR027794

Jaakkola, J.J.K., S. Juntunen and K. Näkkäläjärvi, 2018. The holistic effects of climate change on the culture, well-being, and health of the Saami, the only indigenous people in the European Union. Current Environmental Health Reports, 5:401-417. doi:10.1007/s40572-018-0211-2

Jafarov, E.E., E.T. Coon, D.R. Harp, C.J. Wilson, S.L. Painter, A.L. Atchley and V.E. Romanovsky, 2018. Modeling the role of preferential snow accumulation through talik development and hillslope groundwater flow in a transitional permafrost landscape. Environmental Research Letters, 13:105006. doi:10.1088/1748-9326/aadd30

Jakob, L., N. Gourmelen, M. Ewart and S. Plummer, 2021. Spatially and temporally resolved ice loss in High Mountain Asia and the Gulf of Alaska observed by CryoSat-2 swath altimetry between 2010 and 2019. The Cryosphere, 15:1845-1862. doi:10.5194/tc-15-1845-2021

Jan, A., 2022. Modeling the role of lateral surface flow in low-relief polygonal tundra. Permafrost and Periglacial Processes, 33:214-225. doi:10.1002/ppp.2145

Jan, A., E.T. Coon, J.D. Graham and S.L. Painter, 2018a. A subgrid approach for modeling microtopography effects on overland flow. Water Resources Research, 54:6153-6167. doi:10.1029/2017WR021898

Jan, A., E.T. Coon, S.L. Painter, R. Garimella and J.D. Moulton, 2018b. An intermediate-scale model for thermal hydrology in low-relief permafrost-affected landscapes. Computational Geosciences, 22:163-177. doi:10.1007/s10596-017-9679-3

Jane, S.F., G.J.A. Hansen, B.M. Kraemer, P.R. Leavitt, J.L. Mincer, R.L. North, R.M. Pilla, J.T. Stetler, C.E. Williamson and 35 others, 2021. Widespread deoxygenation of temperate lakes. Nature, 594:66-70. doi:10.1038/s41586-021-03550-y

Jin, X.-Y., H.-J. Jin, G. Iwahana, S.S. Marchenko, D.-L. Luo, X.-Y. Li and S.-H. Liang, 2021. Impacts of climate-induced permafrost degradation on vegetation: A review. Advances in Climate Change Research, 12:29-47. doi:10.1016/j.accre.2020.07.002

Johnsen, K.I., I.M.G. Eira, S.D. Mathiesen and A. Oskal, 2023. 'Leaving No One Behind' – Sustainable Development of Sámi Reindeer Husbandry in Norway. In: Mathiesen, S.D., I.M.G. Eira, E.I. Turi, A. Oskal, M. Pogodaev and M. Tonkopeeva (Eds.), Reindeer Husbandry. Springer Polar Sciences. pp. 37-66. doi:10.1007/978-3-031-17625-8_3

Jones, B.M. and C.D. Arp, 2015. Observing a catastrophic thermokarst lake drainage in Northern Alaska. Permafrost and Periglacial Processes, 26:119-128. doi:10.1002/ppp.1842

Jones, B.M., C.D. Arp, K.M. Hinkel, R.A. Beck, J.A. Schmutz and B. Winston, 2009. Arctic lake physical processes and regimes with implications for winter water availability and management in the National Petroleum Reserve Alaska. Environmental Management, 43:1071-1084. doi:10.1007/s00267-008-9241-0

Jones, B.M., G. Grosse, C.D. Arp, M.C. Jones, K.M. Walter Anthony and V.E. Romanovsky, 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. Journal of Geophysical Research: Biogeosciences, 116:G00M03. doi:10.1029/2011JG001666

Jones, M.C., G. Grosse, B.M. Jones and K. Walter Anthony, 2012. Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska. Journal of Geophysical Research: Biogeosciences, 117:G00M07. doi:10.1029/2011JG001766

Jones, B.M., G. Grosse, L.M. Farquharson, P. Roy-Léveillée, A. Veremeeva, M.Z. Kanevskiy, B.V. Gaglioti, A.L. Breen, A.D. Parsekian, M. Ulrich and K.M. Hinkel, 2022. Lake and drained lake basin systems in lowland permafrost regions. Nature Reviews Earth & Environment, 3:85-98. doi:10.1038/s43017-021-00238-9

Jones, B.M., S. Schaeffer Tessier, T. Tessier, M. Brubaker, M. Brook, J. Schaeffer, M.K. Ward Jones, G. Grosse, I. Nitze, T. Rettelbach, S. Zavoico, J.A. Clark and K.D. Tape, 2023. Integrating local environmental observations and remote sensing to better understand the life cycle of a thermokarst lake in Arctic Alaska. Arctic, Antarctic, and Alpine Research, 55:2195518. doi:10.1080/15230430.2023.2195518

Kalyuzhny, I.L. and S.A. Lavrov, 2016. Effect of climate changes on the soil freezing depth in the Volga River basin. Ice and Snow, 56:207-220 (In Russian). doi:10.15356/2076-6734-2016-2-207-220

Katsov, V.M. (Ed.), 2022. Roshydromet: Third Assessment Report on Climate Change and their consequences on the territory of the Russian Federation. Naukoemkie Technolgii, Moscow, Russia. 679p. https://cc.voeikovmgo.ru/images/dokumenty/2022/od3.pdf

Khazendar, A., I.G. Fenty, D. Carroll, A. Gardner, C.M. Lee, I. Fukumori, O. Wang, H. Zhang, H. Seroussi, D. Moller, B.P.Y. Noël, M.R. Van Den Broeke, S. Dinardo and J. Willis, 2019. Author Correction: Interruption of two decades of Jakobshavn Isbrae acceleration and thinning as regional ocean cools. Nature Geoscience, 12:493-493. doi:10.1038/s41561-019-0382-y

Kirchner, N., J. Kuttenkeuler, G. Rosqvist, M. Hancke, A. Granebeck, J. Weckström, K. Weckström, F. Schenk, A. Korhola and P. Eriksson, 2021. A first continuous three-year temperature record from the dimictic arctic–alpine Lake Tarfala, northern Sweden. Arctic, Antarctic, and Alpine Research, 53:69-79. doi:10.1080/15230430.2021.1886577

Kirchner, N., J. Weckström, J. Jansen, F. Schenk, J. Barnett, A. Granebeck, M. Leppäranta and A. Korhola, 2024. Water temperature, mixing, and ice phenology in the arctic–alpine Lake Darfáljávri (Lake Tarfala), northern Sweden. Arctic, Antarctic, and Alpine Research, 56:2287704. doi:10.1080/15230430.2023.2287704

Kirillin, G., M. Leppäranta, A. Terzhevik, N. Granin, J. Bernhardt, C. Engelhardt, T. Efremova, S. Golosov, N. Palshin, P. Sherstyankin, G. Zdorovennova and R. Zdorovennov, 2012. Physics of seasonally ice-covered lakes: a review. Aquatic Sciences, 74:659-682. doi:10.1007/s00027-012-0279-y

Knoll, L.B., S. Sharma, B.A. Denfeld, G. Flaim, Y. Hori, J.J. Magnuson, D. Straile and G.A. Weyhenmeyer, 2019. Consequences of lake and river ice loss on cultural ecosystem services. Limnology and Oceanography Letters, 4:119-131. doi:10.1002/lol2.10116

Knopp, J.A., B. Levenstein, A. Watson, I. Ivanova and J. Lento, 2022. Systematic review of documented Indigenous Knowledge of freshwater biodiversity in the circumpolar Arctic. Freshwater Biology, 67:194-209. doi:10.1111/fwb.13570

Koch, J.C., Y. Sjöberg, J.A. O'Donnell, M.P. Carey, P.F. Sullivan and A. Terskaia, 2022. Sensitivity of headwater streamflow to thawing permafrost and vegetation change in a warming Arctic. Environmental Research Letters, 17:044074. doi:10.1088/1748-9326/ac5f2d

Kochtubajda, B., C. Mooney and R. Stewart, 2017. Characteristics, atmospheric drivers and occurrence patterns of freezing precipitation and ice pellets over the Prairie Provinces and Arctic Territories of Canada: 1964–2005. Atmospheric Research, 191:115-127. doi:10.1016/j.atmosres.2017.03.005

Kokelj, S.V., J. Tunnicliffe, D. Lacelle, T.C. Lantz, K.S. Chin and R. Fraser, 2015. Increased precipitation drives mega slump development and destabilization of ice-rich permafrost terrain, northwestern Canada. Global and Planetary Change, 129:56-68. doi:10.1016/j.gloplacha.2015.02.008

Koronkevich, N.I., E.A. Barabanova, A.G. Georgiadi, I.S. Zaitseva and S.I. Shaporenko, 2019. Anthropogenic impacts on the water resources of the Russian Arctic Basin rivers. Geography and Natural Resources, 40:22-29. doi:10.1134/S1875372819010049

Koyama, T. and J. Stroeve, 2019. Greenland monthly precipitation analysis from the Arctic System Reanalysis (ASR): 2000–2012. Polar Science, 19:1-12. doi:10.1016/j.polar.2018.09.001

Kraemer, B.M., R.M. Pilla, R.I. Woolway, O. Anneville, S. Ban, W. Colom-Montero, S.P. Devlin, M.T. Dokulil and 29 others, 2021. Climate change drives widespread shifts in lake thermal habitat. Nature Climate Change, 11:521-529. doi:10.1038/s41558-021-01060-3

Krogh, S.A. and J.W. Pomeroy, 2018. Recent changes to the hydrological cycle of an Arctic basin at the tundra–taiga transition. Hydrology and Earth System Sciences, 22:3993-4014. doi:10.5194/hess-22-3993-2018

Krysanova, V., C. Donnelly, A. Gelfan, D. Gerten, B. Arheimer, F. Hattermann and Z.W. Kundzewicz, 2018. How the performance of hydrological models relates to credibility of projections under climate change. Hydrological Sciences Journal, 63:696-720. doi:10.1080/02626667.2018.1446214

Kuhn, C. and D. Butman, 2021. Declining greenness in Arctic-boreal lakes. Proceedings of the National Academy of Sciences U.S.A., 118:e2021219118. doi:10.1073/pnas.2021219118

Kurylyk, B.L., M. Hayashi, W.L. Quinton, J.M. McKenzie and C.I. Voss, 2016. Influence of vertical and lateral heat transfer on permafrost thaw, peatland landscape transition, and groundwater flow. Water Resources Research, 52:1286-1305. doi:10.1002/2015WR018057

Labrecque, S., D. Lacelle, C.R. Duguay, B. Lauriol and J. Hawkings, 2009. Contemporary (1951–2001) evolution of lakes in the Old Crow Basin, Northern Yukon, Canada: remote sensing, numerical modeling, and stable isotope analysis. ARCTIC, 62:225-238. doi:10.14430/arctic134

Lafrenière, M.J. and S.F. Lamoureux, 2019. Effects of changing permafrost conditions on hydrological processes and fluvial fluxes. Earth-Science Reviews, 191:212-223. doi:10.1016/j.earscirev.2019.02.018

Lamontagne-Hallé, P., J.M. McKenzie, B.L. Kurylyk and S.C. Zipper, 2018. Changing groundwater discharge dynamics in permafrost regions. Environmental Research Letters, 13:084017. doi:10.1088/1748-9326/aad404

Lamontagne-Hallé, P., J.M. McKenzie, B.L. Kurylyk, J. Molson and L.N. Lyon, 2020. Guidelines for cold-regions groundwater numerical modeling. WIREs Water, 7:e1467. doi:10.1002/wat2.1467

Landrum, L. and M.M. Holland, 2020. Extremes become routine in an emerging new Arctic. Nature Climate Change, 10:1108-1115. doi:10.1038/s41558-020-0892-z

Lantz, T.C. and S.V. Kokelj, 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T., Canada. Geophysical Research Letters, 35:2007GL032433. doi:10.1029/2007GL032433

Lantz, T.C. and K.W. Turner, 2015. Changes in lake area in response to thermokarst processes and climate in Old Crow Flats, Yukon. Journal of Geophysical Research: Biogeosciences, 120:513-524. doi:10.1002/2014JG002744

Laptander, R., T. Horstkotte, J.O. Habeck, S. Rasmus, T. Komu, H. Matthes, H. Tømmervik, K. Istomin, J.T. Eronen and B.C. Forbes, 2024. Critical seasonal conditions in the reindeer-herding year: A synopsis of factors and events in Fennoscandia and northwestern Russia. Polar Science, 39:101016. doi:10.1016/j.polar.2023.101016

Lara, M.J., Y. Chen and B.M. Jones, 2021. Recent warming reverses forty-year decline in catastrophic lake drainage and hastens gradual lake drainage across northern Alaska. Environmental Research Letters, 16:124019. doi:10.1088/1748-9326/ac3602

Lebedeva, L. and D. Gustafsson, 2021. Streamflow changes of small and large rivers in the Aldan River basin, eastern Siberia. Water, 13:2747. doi:10.3390/w13192747

Lebedeva, L., O. Makarieva and T. Vinogradova, 2019. Analysis of spatial variability of river streamflow at the catchment area of the Kolyma reservoir. IOP Conference Series: Earth and Environmental Science, 321:012022. doi:10.1088/1755-1315/321/1/012022

Lemieux, J.-M., R. Fortier, J. Molson, R. Therrien and M. Ouellet, 2020. Topical Collection: Hydrogeology of a cold-region watershed near Umiujaq (Nunavik, Canada). Hydrogeology Journal, 28:809-812. doi:10.1007/s10040-020-02131-z

Leppäranta, M., A. Terzhevik and K. Shirasawa, 2010. Solar radiation and ice melting in Lake Vendyurskoe, Russian Karelia. Hydrology Research, 41:50-62. doi:10.2166/nh.2010.122

Letterly, A., J. Key and Y. Liu, 2018. Arctic climate: changes in sea ice extent outweigh changes in snow cover. The Cryosphere, 12:3373-3382. doi:10.5194/tc-12-3373-2018

Lewis, E.L., E.P. Jones, P. Lemke, T.D. Prowse and P. Wadhams (Eds.), 2000. The Freshwater Budget of the Arctic Ocean. Springer Netherlands, Dordrecht. doi:10.1007/978-94-011-4132-1

Lewkowicz, A.G. and R.G. Way, 2019. Extremes of summer climate trigger thousands of thermokarst landslides in a High Arctic environment. Nature Communications, 10:1329. doi:10.1038/s41467-019-09314-7

Li, S., G. Wang, C. Zhu, J. Lu, W. Ullah, D.F.T. Hagan, G. Kattel and J. Peng, 2022. Attribution of global evapotranspiration trends based on the Budyko framework. Hydrology and Earth System Sciences, 26:3691-3707. doi:10.5194/hess-26-3691-2022

Li, X., D. Long, Q. Huang and F. Zhao, 2022. The state and fate of lake ice thickness in the Northern Hemisphere. Science Bulletin, 67:537-546. doi:10.1016/j.scib.2021.10.015

Lin, H., X. Cheng, L. Zheng, X. Peng, W. Feng and F. Peng, 2022. Recent changes in groundwater and surface water in large pan-Arctic river basins. Remote Sensing, 14:607. doi:10.3390/rs14030607

Lindgren, P.R., L.M. Farquharson, V.E. Romanovsky and G. Grosse, 2021. Landsat-based lake distribution and changes in western Alaska permafrost regions between the 1970s and 2010s. Environmental Research Letters, 16:025006. doi:10.1088/1748-9326/abd270

Lique, C., M.M. Holland, Y.B. Dibike, D.M. Lawrence and J.A. Screen, 2016. Modeling the Arctic freshwater system and its integration in the global system: Lessons learned and future challenges. Journal of Geophysical Research: Biogeosciences, 121:540-566. doi:10.1002/2015JG003120

Littell, J.S., S.A. McAfee and G.D. Hayward, 2018. Alaska snowpack response to climate change: statewide snowfall equivalent and snowpack water scenarios. Water, 10:668. doi:10.3390/w10050668

Liu, J., D. Wu, X. Xu, M. Ji, Q. Chen and X. Wang, 2021. Projection of extreme precipitation induced by Arctic amplification over the Northern Hemisphere. Environmental Research Letters, 16:074012. doi:10.1088/1748-9326/ac0acc

Liu, S., P. Wang, J. Yu, T. Wang, H. Cai, Q. Huang, S.P. Pozdniakov, Y. Zhang and E.S. Kazak, 2022. Mechanisms behind the uneven increases in early, mid- and late winter streamflow across four Arctic river basins. Journal of Hydrology, 606:127425. doi:10.1016/j.jhydrol.2021.127425

Livingstone, D.M., 2000. Large-scale climatic forcing detected in historical observations of lake ice break-up. SIL Proceedings, 1922-2010, 27:2775-2783. doi:10.1080/03680770.1998.11898171

Loeb, N.A., A. Crawford, J.C. Stroeve and J. Hanesiak, 2022. Extreme precipitation in the eastern Canadian Arctic and Greenland: An evaluation of atmospheric reanalyses. Frontiers in Environmental Science, 10:866929. doi:10.3389/fenvs.2022.866929

Löf, A., 2013. Examining limits and barriers to climate change adaptation in an Indigenous reindeer herding community. Climate and Development, 5:328-339. doi:10.1080/17565529.2013.831338

Lopez, L.S., B.A. Hewitt and S. Sharma, 2019. Reaching a breaking point: How is climate change influencing the timing of ice breakup in lakes across the northern hemisphere? Limnology and Oceanography, 64:2621-2631. doi:10.1002/lno.11239

Lundquist, J.D., J. Vano, E. Gutmann, D. Hogan, E. Schwat, M. Haugeneder, M. Mateo, S. Oncley, C. Roden, E. Osenga and L. Carver, 2024. Sublimation of snow. Bulletin of the American Meteorological Society, 105:E975-E990. doi:10.1175/BAMS-D-23-0191.1

Luomaranta, A., J. Aalto and K. Jylhä, 2019. Snow cover trends in Finland over 1961–2014 based on gridded snow depth observations. International Journal of Climatology, 39:3147-3159. doi:10.1002/joc.6007

Lyon, S.W., G. Destouni, R. Giesler, C. Humborg, M. Mörth, J. Seibert, J. Karlsson and P.A. Troch, 2009. Estimation of permafrost thawing rates in a sub-arctic catchment using recession flow analysis. Hydrology and Earth System Sciences, 13:595-604. doi:10.5194/hess-13-595-2009

MacDonald, L.A., B.B. Wolfe, K.W. Turner, L. Anderson, C.D. Arp, S.J. Birks, F. Bouchard, T.W.D. Edwards, N. Farquharson, R.I. Hall, I. McDonald, B. Narancic, C. Ouimet, R. Pienitz, J. Tondu and H. White, 2017. A synthesis of thermokarst lake water balance in high-latitude regions of North America from isotope tracers. Arctic Science, 3:118-149. doi:10.1139/as-2016-0019

MacDonald, M.K., T.A. Stadnyk, S.J. Déry, M. Braun, D. Gustafsson, K. Isberg and B. Arheimer, 2018. Impacts of 1.5 and 2.0 °C warming on pan-arctic river discharge into the Hudson Bay complex through 2070. Geophysical Research Letters, 45:7561-7570. doi:10.1029/2018GL079147

MacFerrin, M., H. Machguth, D.V. As, C. Charalampidis, C.M. Stevens, A. Heilig, B. Vandecrux, P.L. Langen, R. Mottram, X. Fettweis, M.R.Van Den Broeke, W.T. Pfeffer, M.S. Moussavi and W. Abdalati, 2019. Rapid expansion of Greenland's low-permeability ice slabs. Nature, 573:403-407. doi:10.1038/s41586-019-1550-3

Mack, M., R. Connon, O. Makarieva, J. McLaughlin, N. Nesterova and W. Quinton, 2021. Heterogenous runoff trends in peatland-dominated basins throughout the circumpolar North. Environmental Research Communications, 3:075006. doi:10.1088/2515-7620/ac11ed

Mackay, J.R., 1988. Catastrophic lake drainage, Tuktoyaktuk Peninsula area, District of Mackenzie. Geological Survey of Canada, No. 88–1D, 83-90. doi:10.4095/122663

Magnuson, J. and R. Lathrop, 2014. Lake ice: Winter, beauty, value, changes, and a threatened future. Lakeline, 34:18-27. www.nalms.org/wp-content/uploads/LakeLine/34-4/Articles/34-4-7.pdf

Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart and V.S. Vuglinski, 2000. Historical trends in lake and river ice cover in the northern hemisphere. Science, 289:1743-1746. doi:10.1126/science.289.5485.1743

Magritsky, D.V., N.L. Frolova, V.M. Evstigneev, E.S. Povalishnikova, M.B. Kireeva and O.M. Pakhomova, 2018. Long-term changes of river water inflow into the seas of the Russian Arctic sector. Polarforschung, 87:177-194. doi:10.2312/POLARFORSCHUNG.87.2.177

Makarieva, O., N. Nesterova, D.A. Post, A. Sherstyukov and L. Lebedeva, 2019. Warming temperatures are impacting the hydrometeorological regime of Russian rivers in the zone of continuous permafrost. The Cryosphere, 13:1635-1659. doi:10.5194/tc-13-1635-2019

Mallalieu, J., J.L. Carrivick, D.J. Quincey and C.L. Raby, 2021. Ice-marginal lakes associated with enhanced recession of the Greenland Ice Sheet. Global and Planetary Change, 202:103503. doi:10.1016/j.gloplacha.2021.103503

Markkula, I., M. Turunen and S. Rasmus, 2019. A review of climate change impacts on the ecosystem services in the Saami Homeland in Finland. Science of the Total Environment, 692:1070-1085. doi:10.1016/j.scitotenv.2019.07.272

Marshall, G.J., K. Jylhä, S. Kivinen, M. Laapas and A.V. Dyrrdal, 2020. The role of atmospheric circulation patterns in driving recent changes in indices of extreme seasonal precipitation across Arctic Fennoscandia. Climatic Change, 162:741-759. doi:10.1007/s10584-020-02747-w

Martin, T. and A. Biastoch, 2023. On the ocean's response to enhanced Greenland runoff in model experiments: relevance of mesoscale dynamics and atmospheric coupling. Ocean Science, 19:141-167. doi:10.5194/os-19-141-2023

McClelland, J.W., S.E. Tank, R.G.M. Spencer and A.I. Shiklomanov, 2015. Coordination and sustainability of river observing activities in the Arctic. ARCTIC, 68:59. doi:10.14430/arctic4448

McClelland, J.W., A.I. Shiklomanov, A. Suslova, M. Tretiakov, R.M. Holmes, R.G.M. Spencer, S.E. Tank and S. Zolkos, 2023. Arctic river discharge. In: State of the Climate in 2022. Bulletin of the American Meteorological Society, 104:S281-S284. doi:10.1175/10.1175/BAMS-D-23-0079.1

McCrystall, M.R., J. Stroeve, M. Serreze, B.C. Forbes and J.A. Screen, 2021. New climate models reveal faster and larger increases in Arctic precipitation than previously projected. Nature Communications, 12:6765. doi:10.1038/s41467-021-27031-y

McKenzie, J.M., B.L. Kurylyk, M.A. Walvoord, V.F. Bense, D. Fortier, C. Spence and C. Grenier, 2021. Invited perspective: What lies beneath a changing Arctic? The Cryosphere, 15:479-484. doi:10.5194/tc-15-479-2021

McMahon, R., Z. Taveras, P. Neubert and H.R. Harvey, 2021. Organic biomarkers and Meiofauna diversity reflect distinct carbon sources to sediments transecting the Mackenzie continental shelf. Continental Shelf Research, 220:104406. doi:10.1016/j.csr.2021.104406

Medeiros, A.S., P. Wood, S.D. Wesche, M. Bakaic and J.F. Peters, 2017. Water security for northern peoples: review of threats to Arctic freshwater systems in Nunavut, Canada. Regional Environmental Change, 17:635-647. doi:10.1007/s10113-016-1084-2

Mohammadzadeh Khani, H., C. Kinnard and E. Lévesque, 2022. Historical trends and projections of snow cover over the High Arctic: a review. Water, 14:587. doi:10.3390/w14040587

Mohammed, A.A., J.A. Guimond, V.F. Bense, R.C. Jamieson, J.M. McKenzie and B.L. Kurylyk, 2022. Mobilization of subsurface carbon pools driven by permafrost thaw and reactivation of groundwater flow: a virtual experiment. Environmental Research Letters, 17:124036. doi:10.1088/1748-9326/aca701

Moon, T.A., M.L. Druckenmiller and R.L. Thoman, 2021. NOAA Arctic Report Card 2021: Executive Summary. NOAA Technical Report OAR ARC; 21-01. doi:10.25923/5S0F-5163

Morse, P.D. and S.A. Wolfe, 2015. Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. Journal of Geophysical Research: Earth Surface, 120:1670-1686. doi:10.1002/2015JF003534

Morse, P.D. and S.A. Wolfe, 2017. Long-term river icing dynamics in discontinuous permafrost, subarctic Canadian Shield. Permafrost and Periglacial Processes, 28:580-586. doi:10.1002/ppp.1907

Mouginot, J., E. Rignot, B. Scheuchl, I. Fenty, A. Khazendar, M. Morlighem, A. Buzzi and J. Paden, 2015. Fast retreat of Zachariæ Isstrøm, northeast Greenland. Science, 350:1357-1361. doi:10.1126/science.aac7111

Musselman, K.N., N. Addor, J.A. Vano and N.P. Molotch, 2021. Winter melt trends portend widespread declines in snow water resources. Nature Climate Change, 11:418-424. doi:10.1038/s41558-021-01014-9

Nasonova, O.N., Ye.M. Gusev, E.E. Kovalev, G.V. Ayzel and K.M. Panysheva, 2019. Projecting changes in Russian northern river runoff due to possible climate change during the 21st century: A case study of the Northern Dvina, Taz and Indigirka rivers. Water Resources, 46:S145-S154. doi:10.1134/S0097807819070145

Nasonova, O.N., Ye.M. Gusev, E.E. Kovalev, G.V. Ayzel and M.K. Chebanova, 2021. Projected changes in water balance components of 11 large river basins during the 21st century and their uncertainties. Water Resources, 48:666-675. doi:10.1134/S0097807821050158

Nasonova, O.N., Y.M. Gusev and E. Kovalev, 2022. Climate change impact on water balance components in Arctic river basins. Geography Environment Sustainability, 15:148-157. doi:10.24057/2071-9388-2021-144

Natali, S.M., E.A.G. Schuur, C. Trucco, C.E. Hicks Pries, K.G. Crummer and A.F. Baron Lopez, 2011. Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra: warming of Alaskan tundra. Global Change Biology, 17:1394-1407. doi:10.1111/j.1365-2486.2010.02303.x

Nesterova, N., O. Makarieva and A. Zemlyanskova, 2020. Hydrometeorological changes in the north-east of Russia. E3S Web of Conferences, 163:05010. doi:10.1051/e3sconf/202016305010

Newton, A.M.W. and D. Mullan, 2021. Climate change and Northern Hemisphere lake and river ice phenology from 1931-2005. The Cryosphere, 15:2211-2234. doi:10.5194/tc-2020-172

Nitzbon, J., S. Westermann, M. Langer, L.C.P. Martin, J. Strauss, S. Laboor and J. Boike, 2020. Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate. Nature Communications, 11:2201. doi:10.1038/s41467-020-15725-8

Nitze, I., S.W. Cooley, C.R. Duguay, B.M. Jones and G. Grosse, 2020. The catastrophic thermokarst lake drainage events of 2018 in northwestern Alaska: fast-forward into the future. The Cryosphere, 14:4279-4297. doi:10.5194/tc-14-4279-2020

Nummelin, A., M. Ilicak, C. Li and L.H. Smedsrud, 2016. Consequences of future increased Arctic runoff on Arctic Ocean stratification, circulation, and sea ice cover. Journal of Geophysical Research: Oceans, 121:617-637. doi:10.1002/2015JC011156

Nygård, T., T. Naakka and T. Vihma, 2020. Horizontal moisture transport dominates the regional moistening patterns in the Arctic. Journal of Climate, 33:6793-6807. doi:10.1175/JCLI-D-19-0891.1

Obu, J., 2021. How much of the earth's surface is underlain by permafrost? Journal of Geophysical Research: Earth Surface, 126:e2021JF006123. doi:10.1029/2021JF006123

Obyazov, V.A. and V.K. Smakhtin, 2014. Ice regime of Transbaikalian rivers under changing climate. Water Resources, 41:225-231. doi:10.1134/S0097807814030130

Ocobock, C., M. Turunen, P. Soppela and S. Rasmus, 2022. The impact of winter warming and more frequent icing events on reindeer herder occupational safety, health, and wellbeing. American Journal of Human Biology, 35:e23790. doi:10.1002/ajhb.23790

Oh, S.-G., L. Sushama and B. Teufel, 2020. Arctic precipitation and surface wind speed associated with cyclones in a changing climate. Climate Dynamics, 55:3067-3085. doi:10.1007/s00382-020-05425-w

Olefeldt, D., M. Hovemyr, M.A. Kuhn, D. Bastviken, T.J. Bohn, J. Connolly, P. Crill, E.S. Euskirchen, S.A. Finkelstein, H. Genet, G. Grosse, L.I. Harris, L. Heffernan, M. Helbig, G. Hugelius, R. Hutchins, S. Juutinen, M.J. Lara, A. Malhotra, K. Manies, A.D. McGuire, S.M. Natali, J.A. O'Donnell, F.-J.W. Parmentier, A. Räsänen, C. Schädel, O. Sonnentag, M. Strack, S.E. Tank, C. Treat, R.K. Varner, T. Virtanen, R.K. Warren and J.D. Watts, 2021. The Boreal–Arctic Wetland and Lake Dataset (BAWLD). Earth System Science Data, 13:5127-5149. doi:10.5194/essd-13-5127-2021

Olthof, I. and T. Rainville, 2022. Dynamic surface water maps of Canada from 1984 to 2019 Landsat satellite imagery. Remote Sensing of Environment, 279:113121. doi:10.1016/j.rse.2022.113121

Olthof, I., R.H. Fraser, J. van der Sluijs and H. Travers-Smith, 2023. Detecting long-term Arctic surface water changes. Nature Climate Change, 13:1191-1193. doi:10.1038/s41558-023-01836-9

O'Neel, S., E. Hood, A. Arendt and L. Sass, 2014. Assessing streamflow sensitivity to variations in glacier mass balance. Climatic Change, 123:329-341. doi:10.1007/s10584-013-1042-7

O'Neill, H.B., P. Roy-Leveillee, L. Lebedeva and F. Ling, 2020. Recent advances (2010–2019) in the study of taliks. Permafrost and Periglacial Processes, 31:346-357. doi:10.1002/ppp.2050

Osborne, E., J. Richter-Menge and M. Jeffries (Eds.), 2018. Arctic Report Card 2018. https://arctic.noaa.gov/wp-content/uploads/2023/04/ArcticReportCard_full_report2018.pdf

Overland, J., E. Dunlea, J.E. Box, R. Corell, M. Forsius, V. Kattsov, M.S. Olsen, J. Pawlak, L.-O. Reiersen and M. Wang, 2019. The urgency of Arctic change. Polar Science, 21:6-13. doi:10.1016/j.polar.2018.11.008

Painter, S.L., E.T. Coon, A.J. Khattak and J.D. Jastrow, 2023. Drying of tundra landscapes will limit subsidence-induced acceleration of permafrost thaw. Proceedings of the National Academy of Sciences U.S.A., 120:e2212171120. doi:10.1073/pnas.2212171120

Palecki, M.A. and R.G. Barry, 1986. Freeze-up and break-up of lakes as an index of temperature changes during the transition seasons: a case study for Finland. Journal of Applied Meteorology and Climatology, 25:893-902. doi:10.1175/1520-0450(1986)025<0893:FUABUO>2.0.CO;2

Pan, C.G., P.B. Kirchner, J.S. Kimball, Y. Kim and J. Du, 2018. Rain-on-snow events in Alaska, their frequency and distribution from satellite observations. Environmental Research Letters, 13:075004. doi:10.1088/1748-9326/aac9d3

Pan, S., T. Dou, L. Lin, J. Yang, F. Zhang, M. Duan, C. Zhao, H. Liao and C. Xiao, 2020. Larger sensitivity of Arctic precipitation phase to aerosol than greenhouse gas forcing. Geophysical Research Letters, 47:e2020GL090452. doi:10.1029/2020GL090452

Panyushkina, I.P., D.M. Meko, A. Shiklomanov, R.D. Thaxton, V. Myglan, V.V. Barinov and A.V. Taynik, 2021. Unprecedented acceleration of winter discharge of Upper Yenisei River inferred from tree rings. Environmental Research Letters, 16:125014. doi:10.1088/1748-9326/ac3e20

Park, H., Y. Yoshikawa, K. Oshima, Y. Kim, T. Ngo-Duc, J.S. Kimball and D. Yang, 2016. Quantification of warming climate-induced changes in terrestrial Arctic river ice thickness and phenology. Journal of Climate, 29:1733-1754. doi:10.1175/JCLI-D-15-0569.1

Pattyn, F., C. Ritz, E. Hanna, X. Asay-Davis, R. DeConto, G. Durand, L. Favier, X. Fettweis, H. Goelzer, N.R. Golledge, P. Kuipers Munneke, J.T.M. Lenaerts, S. Nowicki, A.J. Payne, A. Robinson, H. Seroussi, L.D. Trusel and M. Van Den Broeke, 2018. The Greenland and Antarctic ice sheets under 1.5 °C global warming. Nature Climate Change, 8:1053-1061. doi:10.1038/s41558-018-0305-8

Pavlovskii, I., M. Hayashi and D. Itenfisu, 2019. Midwinter melts in the Canadian prairies: energy balance and hydrological effects. Hydrology and Earth System Sciences, 23:1867-1883. doi:10.5194/hess-23-1867-2019

Peeters, B., Å.Ø. Pedersen, L.E. Loe, K. Isaksen, V. Veiberg, A. Stien, J. Kohler, J.-C. Gallet, R. Aanes, and B.B. Hansen, 2019. Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: detection of a climate-cryosphere regime shift. Environmental Research Letters, 14:015002. doi:10.1088/1748-9326/aaefb3

Peterson, B.J., J. McClelland, R. Curry, R.M. Holmes, J.E. Walsh and K. Aagaard, 2006. Trajectory shifts in the Arctic and subarctic freshwater cycle. Science, 313:1061-1066. doi:10.1126/science.1122593

Phillips, T., H. Rajaram and K. Steffen, 2010. Cryo-hydrologic warming: A potential mechanism for rapid thermal response of ice sheets. Geophysical Research Letters, 37:2010GL044397. doi:10.1029/2010GL044397

Podkowa, A., Z. Kugler, S.V. Nghiem and G.R. Brakenridge, 2023. Ice freeze-up and break-up in Arctic rivers observed with satellite L-band passive microwave data from 2010 to 2020. Water Resources Research, 59:e2022WR031939. doi:10.1029/2022WR031939

Prakash, A., Q. Zhou, T. Hattermann, W. Bao, R. Graversen and N. Kirchner, 2022. A nested high-resolution unstructured grid 3-D ocean-sea ice-ice shelf setup for numerical investigations of the Petermann ice shelf and fjord. MethodsX, 9:101668. doi:10.1016/j.mex.2022.101668

Preston, D.L., N. Caine, D.M. McKnight, M.W. Williams, K. Hell, M.P. Miller, S.J. Hart and P.T.J. Johnson, 2016. Climate regulates alpine lake ice cover phenology and aquatic ecosystem structure. Geophysical Research Letters, 43:5353-5360. doi:10.1002/2016GL069036

Prowse, T., A. Bring, J. Mård and E. Carmack, 2015a. Arctic freshwater synthesis: introduction. Journal of Geophysical Research: Biogeosciences, 120:2121-2131. doi:10.1002/2015JG003127

Prowse, T., A. Bring, J. Mård, E. Carmack, M. Holland, A. Instanes, T. Vihma and F.J. Wrona, 2015b. Arctic freshwater synthesis: summary of key emerging issues. Journal of Geophysical Research: Biogeosciences, 120:1887-1893. doi:10.1002/2015JG003128

Pulliainen, J., K. Luojus, C. Derksen, L. Mudryk, J. Lemmetyinen, M. Salminen, J. Ikonen, M. Takala, J. Cohen, T. Smolander and J. Norberg, 2020. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature, 581:294-298. doi:10.1038/s41586-020-2258-0

Rahmstorf, S., 2002. Ocean circulation and climate during the past 120,000 years. Nature, 419:207-214. doi:10.1038/nature01090

Räisänen, J., 2021. Snow conditions in northern Europe: the dynamics of interannual variability versus projected long-term change. The Cryosphere, 15:1677-1696. doi:10.5194/tc-15-1677-2021

Räisänen, J., 2023. Changes in March mean snow water equivalent since the mid-20th century and the contributing factors in reanalyses and CMIP6 climate models. The Cryosphere, 17:1913-1934. doi:10.5194/tc-17-1913-2023

Rawlins, M.A., M. Steele, M.M. Holland, J.C. Adam, J.E. Cherry, J.A. Francis, P.Y. Groisman, L.D. Hinzman and 22 others, 2010. Analysis of the Arctic system for freshwater cycle intensification: observations and expectations. Journal of Climate, 23:5715-5737. doi:10.1175/2010JCLI3421.1

Rawlins, M.A., L. Cai, S.L. Stuefer and D. Nicolsky, 2019. Changing characteristics of runoff and freshwater export from watersheds draining northern Alaska. The Cryosphere, 13:3337-3352. doi:10.5194/tc-13-3337-2019

Richter-Menge, J., J.E. Overland, J. Mathis and E. Osborne (Eds.), 2017. Arctic Report Card 2017. https://arctic.noaa.gov/wp-content/uploads/2023/04/ArcticReportCard_full_report2017.pdf

Rick, B., D. McGrath, W. Armstrong and S.W. McCoy, 2022. Dam type and lake location characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019. The Cryosphere, 16:297-314. doi:10.5194/tc-16-297-2022

Rixen, C., T.T. Høye, P. Macek, R. Aerts, J.M. Alatalo, J.T. Anderson, P.A. Arnold, I.C. Barrio and 60 others, 2022. Winters are changing: snow effects on Arctic and alpine tundra ecosystems. Arctic Science, 8:572-608. doi:10.1139/as-2020-0058

Roach, J.K. and B. Griffith, 2015. Climate-induced lake drying causes heterogeneous reductions in waterfowl species richness. Landscape Ecology, 30:1005-1022. doi:10.1007/s10980-015-0207-3

Robinson, A.L., S.S. Ariano and L.C. Brown, 2021. The influence of snow and ice albedo towards improved lake ice simulations. Hydrology, 8:11. doi:10.3390/hydrology8010011

Rodenhizer, H., F. Belshe, G. Celis, J. Ledman, M. Mauritz, S. Goetz, T. Sankey and E.A.G. Schuur, 2022. Abrupt permafrost thaw accelerates carbon dioxide and methane release at a tussock tundra site. Arctic, Antarctic, and Alpine Research, 54:443-464. doi:10.1080/15230430.2022.2118639

Rokaya, P., L. Morales-Marín, B. Bonsal, H. Wheater and K.-E. Lindenschmidt, 2019. Climatic effects on ice phenology and ice-jam flooding of the Athabasca River in western Canada. Hydrological Sciences Journal, 64:1265-1278. doi:10.1080/02626667.2019.1638927

Rokaya, P., K.-E. Lindenschmidt, A. Pietroniro and M. Clark, 2022. Modelling of ice jam floods under past and future climates: A review. Journal of Hydrology X, 15:100120. doi:10.1016/j.hydroa.2022.100120

Rood, S.B., S. Kaluthota, L.J. Philipsen, N.J. Rood and K.P. Zanewich, 2017. Increasing discharge from the Mackenzie River system to the Arctic Ocean. Hydrological Processes, 31:150-160. doi:10.1002/hyp.10986

Rosqvist, G.C., N. Inga and P. Eriksson, 2022. Impacts of climate warming on reindeer herding require new land-use strategies. Ambio, 51:1247-1262. doi:10.1007/s13280-021-01655-2

Rounce, D.R., R. Hock, F. Maussion, R. Hugonnet, W. Kochtitzky, M. Huss, E. Berthier, D. Brinkerhoff, L. Compagno, L. Copland, D. Farinotti, B. Menounos and R.W. McNabb, 2023. Global glacier change in the 21st century: Every increase in temperature matters. Science, 379:78-83. doi:10.1126/science.abo1324

Saito, K., J.E. Walsh, A. Bring, R. Brown, A. Shiklomanov and D. Yang, 2021. Future trajectory of Arctic system evolution. In: Yang, D. and D.L. Kane (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer International Publishing, pp. 893-914. doi:10.1007/978-3-030-50930-9_30

Santolaria-Otín, M. and O. Zolina, 2020. Evaluation of snow cover and snow water equivalent in the continental Arctic in CMIP5 models. Climate Dynamics, 55:2993-3016. doi:10.1007/s00382-020-05434-9

Saros, J.E., C.D. Arp, F. Bouchard, J. Comte, R.-M. Couture, J.F. Dean, M. Lafrenière, S. MacIntyre, S. McGowan, M. Rautio, C. Prater, S.E. Tank, M. Walvoord, K.P. Wickland, D. Antoniades, P. Ayala-Borda, J. Canario, T.W. Drake, D. Folhas, V. Hazuková, H. Kivilä, Y. Klanten, S. Lamoureux, I. Laurion, R.M. Pilla, J.E. Vonk, S. Zolkos and W.F. Vincent, 2023. Sentinel responses of Arctic freshwater systems to climate: linkages, evidence, and a roadmap for future research. Arctic Science, 9:356-392. doi:10.1139/as-2022-0021

Savichev, O., J. Moiseeva and N. Guseva, 2022. Changes in the groundwater levels and regimes in the taiga zone of Western Siberia as a result of global warming. Theoretical and Applied Climatology, 147:1121-1131. doi:10.1007/s00704-021-03879-4

Scanlon, B.R., Z. Zhang, H. Save, D.N. Wiese, F.W. Landerer, D. Long, L. Longuevergne and J. Chen, 2016. Global evaluation of new GRACE mascon products for hydrologic applications. Water Resources Research, 52:9412-9429. doi:10.1002/2016WR019494

Schmale, J., P. Zieger and A.M.L. Ekman, 2021. Aerosols in current and future Arctic climate. Nature Climate Change, 11:95-105. doi:10.1038/s41558-020-00969-5

Schulz, K., A.T. Nguyen and H.R. Pillar, 2022. An improved and observationally-constrained melt rate parameterization for vertical ice fronts of marine terminating glaciers. Geophysical Research Letters, 49:e2022GL100654. doi:10.1029/2022GL100654

Sergeant, F., R. Therrien, L. Oudin, A. Jost and F. Anctil, 2021. Evolution of Arctic rivers recession flow: Global assessment and data-based attribution analysis. Journal of Hydrology, 601:126577. doi:10.1016/j.jhydrol.2021.126577

Serreze, M.C., A.P. Barrett, A.G. Slater, R.A. Woodgate, K. Aagaard, R.B. Lammers, M. Steele, R. Moritz, M. Meredith and C.M. Lee, 2006. The large-scale freshwater cycle of the Arctic. Journal of Geophysical Research: Oceans, 111:2005JC003424. doi:10.1029/2005JC003424

Sharma, S., J.J. Magnuson, G. Mendoza and S.R. Carpenter, 2013. Influences of local weather, large-scale climatic drivers, and the ca. 11 year solar cycle on lake ice breakup dates; 1905–2004. Climatic Change, 118:857-870. doi:10.1007/s10584-012-0670-7

Sharma, S., J.J. Magnuson, R.D. Batt, L.A. Winslow, J. Korhonen and Y. Aono, 2016. Direct observations of ice seasonality reveal changes in climate over the past 320–570 years. Scientific Reports, 6:25061. doi:10.1038/srep25061

Sharma, S., K. Blagrave, J.J. Magnuson, C.M. O'Reilly, S. Oliver, R.D. Batt, M.R. Magee, D. Straile, G.A. Weyhenmeyer, L. Winslow and R.I. Woolway, 2019. Widespread loss of lake ice around the Northern Hemisphere in a warming world. Nature Climate Change, 9:227-231. doi:10.1038/s41558-018-0393-5

Sharma, S., K. Blagrave, S.R. Watson, C.M. O'Reilly, R. Batt, J.J. Magnuson, T. Clemens, B.A. Denfeld, G. Flaim, L. Grinberga, Y. Hori, A. Laas, L.B. Knoll, D. Straile, N. Takamura and G.A. Weyhenmeyer, 2020a. Increased winter drownings in ice-covered regions with warmer winters. PLoS ONE, 15:e0241222. doi:10.1371/journal.pone.0241222

Sharma, S., M.F. Meyer, J. Culpepper, X. Yang, S. Hampton, S.A. Berger, M.R. Brousil, S.C. Fradkin, S.N. Higgins, K.J. Jankowski, G. Kirillin, A.P. Smits, E.C. Whitaker, F. Yousef and S. Zhang, 2020b. Integrating perspectives to understand lake ice dynamics in a changing world. Journal of Geophysical Research: Biogeosciences, 125:e2020JG005799. doi:10.1029/2020JG005799

Sharma, S., K. Blagrave, A. Filazzola, M.A. Imrit and H. Hendricks Franssen, 2021. Forecasting the permanent loss of lake ice in the Northern Hemisphere within the 21st century. Geophysical Research Letters, 48:e2020GL091108. doi:10.1029/2020GL091108

Sharma, S., A. Filazzola, T. Nguyen, M.A. Imrit, K. Blagrave, D. Bouffard, J. Daly, H. Feldman, N. Feldsine and 27 others, 2022. Long-term ice phenology records spanning up to 578 years for 78 lakes around the Northern Hemisphere. Scientific Data, 9:318. doi:10.1038/s41597-022-01391-6

Shen, H.T., 2016. River ice processes. In: Wang, L.K., C.T. Yang and M.-H.S. Wang (Eds.), Advances in Water Resources Management. Springer, pp. 483-530. doi:10.1007/978-3-319-22924-9_9

Shi, S. and G. Liu, 2021. The latitudinal dependence in the trend of snow event to precipitation event ratio. Scientific Reports, 11:18112. doi:10.1038/s41598-021-97451-9

Shi, S., P. Wang and J. Yu, 2022. Vegetation greening and climate change promote an increase in evapotranspiration across Siberia. Journal of Hydrology, 610:127965. doi:10.1016/j.jhydrol.2022.127965

Shiklomanov, A.I. and R.B. Lammers, 2009. Record Russian river discharge in 2007 and the limits of analysis. Environmental Research Letters, 4:045015. doi:10.1088/1748-9326/4/4/045015

Shiklomanov, A.I. and R.B. Lammers, 2013. Changing discharge patterns of high-latitude rivers. In: Climate Vulnerability. Elsevier, pp. 161-175. doi:10.1016/B978-0-12-384703-4.00526-8

Shiklomanov, A.I. and R.B. Lammers, 2014. River ice responses to a warming Arctic—recent evidence from Russian rivers. Environmental Research Letters, 9:035008. doi:10.1088/1748-9326/9/3/035008

Shiklomanov, I.A., A.I. Shiklomanov, R.B. Lammers, B.J. Peterson and C.J. Vorosmarty, 2000. The dynamics of river water inflow to the Arctic Ocean. In: Lewis, E.L., E.P. Jones, P. Lemke, T.D. Prowse and P. Wadhams, (Eds.), The Freshwater Budget of the Arctic Ocean. Springer, pp. 281-296. doi:10.1007/978-94-011-4132-1_13

Shiklomanov, A.I., T.I. Yakovleva, R.B. Lammers, I.Ph. Karasev, C.J. Vörösmarty and E. Linder, 2006. Cold region river discharge uncertainty - estimates from large Russian rivers. Journal of Hydrology, 326:231-256. doi:10.1016/j.jhydrol.2005.10.037

Shiklomanov, A., S. Déry, M. Tretiakov, D. Yang, D. Magritsky, A. Georgiadi and W. Tang, 2021. River freshwater flux to the Arctic Ocean. In: Yang, D. and D.L. Kane (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer, pp. 703-738. doi:10.1007/978-3-030-50930-9_24

Shrestha, R.R., K.E. Bennett, D.L. Peters and D. Yang, 2021. Hydrologic extremes in Arctic rivers and regions: historical variability and future perspectives. In: Yang, D. and D.L. Kane (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer, pp. 187-218. doi:10.1007/978-3-030-50930-9_7

Shu, Q., F. Qiao, Z. Song and B. Xiao, 2017. Effect of increasing Arctic river runoff on the Atlantic meridional overturning circulation: a model study. Acta Oceanologica Sinica, 36:59-65. doi:10.1007/s13131-017-1009-z

Shugar, D.H., A. Burr, U.K. Haritashya, J.S. Kargel, C.S. Watson, M.C. Kennedy, A.R. Bevington, R.A. Betts, S. Harrison and K. Strattman, 2020. Rapid worldwide growth of glacial lakes since 1990. Nature Climate Change, 10:939-945. doi:10.1038/s41558-020-0855-4

Shuter, B.J., C.K. Minns and S.R. Fung, 2013. Empirical models for forecasting changes in the phenology of ice cover for Canadian lakes. Canadian Journal of Fisheries and Aquatic Sciences, 70:982-991. doi:10.1139/cjfas-2012-0437

Siegert, M., R.B. Alley, E. Rignot, J. Englander and R. Corell, 2020. Twenty-first century sea-level rise could exceed IPCC projections for strong-warming futures. One Earth, 3:691-703. doi:10.1016/j.oneear.2020.11.002

Singh, H.K.A., C.M. Bitz, A. Donohoe and P.J. Rasch, 2017. A source–receptor perspective on the polar hydrologic cycle: sources, seasonality, and Arctic–Antarctic parity in the hydrologic cycle response to CO_2 doubling. Journal of Climate, 30:9999-10017. doi:10.1175/JCLI-D-16-0917.1

Sjöberg, Y., A. Jan, S.L. Painter, E.T. Coon, M.P. Carey, J.A. O'Donnell and J.C. Koch, 2021. Permafrost promotes shallow groundwater flow and warmer headwater streams. Water Resources Research, 57:e2020WR027463. doi:10.1029/2020WR027463

Slater, D.A., F. Straneo, D. Felikson, C.M. Little, H. Goelzer, X. Fettweis and J. Holte, 2019. Estimating Greenland tidewater glacier retreat driven by submarine melting. The Cryosphere, 13:2489-2509. doi:10.5194/tc-13-2489-2019

Slater, D.A., D. Felikson, F. Straneo, H. Goelzer, C.M. Little, M. Morlighem, X. Fettweis and S. Nowicki, 2020. Twenty-first century ocean forcing of the Greenland ice sheet for modelling of sea level contribution. The Cryosphere, 14:985-1008. doi:10.5194/tc-14-985-2020

Šmejkalová, T., M.E. Edwards and J. Dash, 2016. Arctic lakes show strong decadal trend in earlier spring ice-out. Scientific Reports, 6:38449. doi:10.1038/srep38449

Smith, L.C., Y. Sheng, G.M. MacDonald and L.D. Hinzman, 2005. Disappearing Arctic lakes. Science, 308:1429-1429. doi:10.1126/science.1108142

Smits, A.P., S. MacIntyre and S. Sadro, 2020. Snowpack determines relative importance of climate factors driving summer lake warming. Limnology and Oceanography Letters, 5:271-279. doi:10.1002/lol2.10147

Smol, J.P. and M.S.V. Douglas, 2007. Crossing the final ecological threshold in high Arctic ponds. Proceedings of the National Academy of Sciences U.S.A., 104:12395-12397. doi:10.1073/pnas.0702777104

Solomon, A., C. Heuzé, B. Rabe, S. Bacon, L. Bertino, P. Heimbach, J. Inoue, D. Iovino, R. Mottram, X. Zhang, Y. Aksenov, R. McAdam, A. Nguyen, R.P. Raj and H. Tang, 2021. Freshwater in the Arctic Ocean 2010–2019. Ocean Science, 17:1081-1102. doi:10.5194/os-17-1081-2021

Spence, C., M. Norris, G. Bickerton, B.R. Bonsal, R. Brua, J.M. Culp, Y. Dibike, S. Gruber, P.D. Morse, D.L. Peters, R. Shrestha and S.A. Wolfe, 2020. The Canadian water resource vulnerability index to permafrost thaw ($CWRVI_{PT}$). Arctic Science, 6:437-462. doi:10.1139/as-2019-0028

Stadnyk, T.A., A. Tefs, M. Broesky, S.J. Déry, P.G. Myers, N.A. Ridenour, K. Koenig, L. Vonderbank, and D. Gustafsson, 2021. Changing freshwater contributions to the Arctic. Elementa: Science of the Anthropocene, 9:00098. doi:10.1525/elementa.2020.00098

Stenekes, S., B. Parlee and C. Seixas, 2020. Culturally driven monitoring: the importance of traditional ecological knowledge indicators in understanding aquatic ecosystem change in the Northwest Territories' Dehcho Region. Sustainability, 12:7923. doi:10.3390/su12197923

Stibal, M., J.E. Box, K.A. Cameron, P.L. Langen, M.L. Yallop, R.H. Mottram, A.L. Khan, N.P. Molotch, N.A.M. Chrismas, F. Calì Quaglia, D. Remias, C.J.P.P. Smeets, M.R. Van Den Broeke, J.C. Ryan, A. Hubbard, M. Tranter, D. Van As and A.P. Ahlstrøm, 2017. Algae drive enhanced darkening of bare ice on the Greenland Ice Sheet. Geophysical Research Letters, 44:11,463-11,471. doi:10.1002/2017GL075958

Streletskiy, D.A., N.I. Tananaev, T. Opel, N.I. Shiklomanov, K.E. Nyland, I.D. Streletskaya, I. Tokarev and A.I. Shiklomanov, 2015. Permafrost hydrology in changing climatic conditions: seasonal variability of stable isotope composition in rivers in discontinuous permafrost. Environmental Research Letters, 10:095003. doi:10.1088/1748-9326/10/9/095003

Stuefer, S., D. Yang and A. Shiklomanov, 2011. Effect of streamflow regulation on mean annual discharge variability of the Yenisei River. IAHS Publ 346, Cold regions hydrology in a changing climate. https://iahs.info/uploads/dms/16841.09-27-32-346-10-Stuefer-h02-finalCORR.pdf

Sturtevant, C.S. and W.C. Oechel, 2013. Spatial variation in landscape-level CO_2 and CH_4 fluxes from arctic coastal tundra: influence from vegetation, wetness, and the thaw lake cycle. Global Change Biology, 19:2853-2866. doi:10.1111/gcb.12247

Suzuki, K., T. Hiyama, K. Matsuo, K. Ichii, Y. Iijima and D. Yamazaki, 2020. Accelerated continental-scale snowmelt and ecohydrological impacts in the four largest Siberian river basins in response to spring warming. Hydrological Processes, 34:3867-3881. doi:10.1002/hyp.13844

Swanson, D.K., 2019. Thermokarst and precipitation drive changes in the area of lakes and ponds in the National Parks of northwestern Alaska, 1984–2018. Arctic, Antarctic, and Alpine Research, 51:265-279. doi:10.1080/15230430.2019.1629222

Swingedouw, D., M.-N. Houssais, C. Herbaut, A.-C. Blaizot, M. Devilliers and J. Deshayes, 2022. AMOC recent and future trends: a crucial role for oceanic resolution and Greenland melting? Frontiers in Climate, 4:838310. doi:10.3389/fclim.2022.838310

Tang, W., S. Yueh, D. Yang, A. Fore, A. Hayashi, T. Lee, S. Fournier and B. Holt, 2018. The potential and challenges of using soil moisture active passive (SMAP) sea surface salinity to monitor Arctic Ocean freshwater changes. Remote Sensing, 10:869. doi:10.3390/rs10060869

Tank, S.E., R.G. Striegl, J.W. McClelland and S.V. Kokelj, 2016. Multi-decadal increases in dissolved organic carbon and alkalinity flux from the Mackenzie drainage basin to the Arctic Ocean. Environmental Research Letters, 11:054015. doi:10.1088/1748-9326/11/5/054015

Thackeray, C.W., C. Derksen, C.G. Fletcher and A. Hall, 2019. Snow and climate: feedbacks, drivers, and indices of change. Current Climate Change Reports, 5:322-333. doi:10.1007/s40641-019-00143-w

Thoman, R., J. Richter-Menge and M. Druckenmiller (Eds.), 2020. Arctic Report Card 2020. https://arctic.noaa.gov/wp-content/uploads/2023/04/ArcticReportCard_full_report2020.pdf

Toohey, R.C., N.M. Herman-Mercer, P.F. Schuster, E.A. Mutter and J.C. Koch, 2016. Multidecadal increases in the Yukon River Basin of chemical fluxes as indicators of changing flowpaths, groundwater, and permafrost. Geophysical Research Letters, 43:12,120-12,130. doi:10.1002/2016GL070817

Travers-Smith, H., T.C. Lantz, R.H. Fraser and S.V. Kokelj, 2022. Changes in surface water dynamics across northwestern Canada are influenced by wildfire and permafrost thaw. Environmental Research Letters, 17:114021. doi:10.1088/1748-9326/ac97f7

Tretiakov, M.V., O.V. Muzhdaba, A.A. Piskun and R.A. Terekhova, 2022. The State of the Roshydromet Hydrological Observation Network in the Mouth Areas of RFAZ. Water Resources, 49:796-807. doi:10.1134/S0097807822050153

Truffer, M. and M. Fahnestock, 2007. Rethinking ice sheet time scales. Science, 315:1508-1510. doi:10.1126/science.1140469

Turetsky, M.R., B.W. Abbott, M.C. Jones, K.W. Anthony, D. Olefeldt, E.A.G. Schuur, G. Grosse, P. Kuhry, G. Hugelius, C. Koven, D.M. Lawrence, C. Gibson, A.B.K. Sannel and A.D. McGuire, 2020. Carbon release through abrupt permafrost thaw. Nature Geoscience, 13:138-143. doi:10.1038/s41561-019-0526-0

Turner, C.K., T.C. Lantz and Gwich'in Tribal Council Department of Cultural Heritage, 2018. Springtime in the delta: The socio-cultural importance of muskrats to Gwich'in and Inuvialuit trappers through periods of ecological and socioeconomic change. Human Ecology, 46:601-611. doi:10.1007/s10745-018-0014-y

Van Huissteden, J., C. Berrittella, F.-J.W. Parmentier, Y. Mi, T.C. Maximov and A.J. Dolman, 2011. Methane emissions from permafrost thaw lakes limited by lake drainage. Nature Climate Change, 1:119-123. doi:10.1038/nclimate1101

Van Pelt, W.J.J., T.V. Schuler, V.A. Pohjola and R. Pettersson, 2021. Accelerating future mass loss of Svalbard glaciers from a multi-model ensemble. Journal of Glaciology, 67:485-499. doi:10.1017/jog.2021.2

Vavrus, S.J., R.H. Wynne and J.A. Foley, 1996. Measuring the sensitivity of southern Wisconsin lake ice to climate variations and lake depth using a numerical model. Limnology and Oceanography, 41:822-831. doi:10.4319/lo.1996.41.5.0822

Veremeeva, A., I. Nitze, F. Günther, G. Grosse and E. Rivkina, 2021. Geomorphological and climatic drivers of thermokarst lake area increase trend (1999–2018) in the Kolyma Lowland Yedoma Region, north-eastern Siberia. Remote Sensing, 13:178. doi:10.3390/rs13020178

Vihma, T., J. Screen, M. Tjernström, B. Newton, X. Zhang, V. Popova, C. Deser, M. Holland and T. Prowse, 2016. The atmospheric role in the Arctic water cycle: A review on processes, past and future changes, and their impacts. Journal of Geophysical Research: Biogeosciences, 121:586-620. doi:10.1002/2015JG003132

Vuglinsky, V., 2017. Assessment of changes in ice regime characteristics of Russian lakes and rivers under current climate conditions. Natural Resources, 8:416-431. doi:10.4236/nr.2017.86027

Vuglinsky, V. and D. Valatin, 2018. Changes in ice cover duration and maximum ice thickness for rivers and lakes in the Asian Part of Russia. Natural Resources, 9:73-87. doi:10.4236/nr.2018.93006

Vulis, L., A. Tejedor, J. Schwenk, A. Piliouras, J. Rowland and E. Foufoula-Georgiou, 2020. Channel network control on seasonal lake area dynamics in Arctic Deltas. Geophysical Research Letters, 47:e2019GL086710. doi:10.1029/2019GL086710

Vyazilova, A.E., G.V. Alekseev and N.E. Kharlanenkova, 2022. Impact of global warming on river inflow to the Arctic Seas. Russian Meteorology and Hydrology, 47:449-456. doi:10.3103/S1068373922060048

Walsh, J.E., T.J. Ballinger, E.S. Euskirchen, E. Hanna, J. Mård, J.E. Overland, H. Tangen and T. Vihma, 2020. Extreme weather and climate events in northern areas: A review. Earth-Science Reviews, 209:103324. doi:10.1016/j.earscirev.2020.103324

Walsh, J.E., S. Bigalke, S.A. McAfee, R. Lader, M.C. Serreze and T.J. Ballinger, 2023a. NOAA Arctic Report Card 2023: Precipitation. NOAA technical report OAR ARC; 23-04. doi:10.25923/HCM7-AZ41

Walsh, J.E., S. Bigalke, S.A. McAfee, R. Lader, M.C. Serreze and T.J. Ballinger, 2023b. Precipitation. In: State of the Climate in 2022. Bulletin of the American Meteorological Society, 104:S281-S284, doi:10.1175/BAMS-D-23-0079.1

Walter, K.M., S.A. Zimov, J.P. Chanton, D. Verbyla and F.S. Chapin, 2006. Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature, 443:71-75. doi:10.1038/nature05040

Walter Anthony, K., R. Daanen, P. Anthony, T. Schneider Von Deimling, C.-L. Ping, J.P. Chanton and G. Grosse, 2016. Methane emissions proportional to permafrost carbon thawed in Arctic lakes since the 1950s. Nature Geoscience, 9:679-682. doi:10.1038/ngeo2795

Walter Anthony, K., T. Schneider Von Deimling, I. Nitze, S. Frolking, A. Emond, R. Daanen, P. Anthony, P. Lindgren, B. Jones and G. Grosse, 2018. 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. Nature Communications, 9:3262. doi:10.1038/s41467-018-05738-9

Walvoord, M.A. and B.L. Kurylyk, 2016. Hydrologic impacts of thawing permafrost - a review. Vadose Zone Journal, 15:1-20. doi:10.2136/vzj2016.01.0010

Walvoord, M.A., C.I. Voss and T.P. Wellman, 2012. Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: Example from Yukon Flats Basin, Alaska, United States. Water Resources Research, 48:2011WR011595. doi:10.1029/2011WR011595

Walvoord, M.A., C.I. Voss, B.A. Ebel and B.J. Minsley, 2019. Development of perennial thaw zones in boreal hillslopes enhances potential mobilization of permafrost carbon. Environmental Research Letters, 14:015003. doi:10.1088/1748-9326/aaf0cc

Wang, K., T. Zhang and D. Yang, 2021. Permafrost dynamics and their hydrologic impacts over the Russian Arctic drainage basin. Advances in Climate Change Research, 12:482-498. doi:10.1016/j.accre.2021.03.014

Wang, X., L. Feng, W. Qi, X. Cai, Y. Zheng, L. Gibson, J. Tang, X. Song, J. Liu, C. Zheng and B.A. Bryan, 2022. Continuous loss of global lake ice across two centuries revealed by satellite observations and numerical modeling. Geophysical Research Letters, 49:e2022GL099022. doi:10.1029/2022GL099022

Webb, E.E. and A.K. Liljedahl, 2023. Diminishing lake area across the northern permafrost zone. Nature Geoscience, 16:202-209. doi:10.1038/s41561-023-01128-z

Webb, E.E., M.M. Loranty and J.W. Lichstein, 2021. Surface water, vegetation, and fire as drivers of the terrestrial Arctic-boreal albedo feedback. Environmental Research Letters, 16:084046. doi:10.1088/1748-9326/ac14ea

Webb, E.E., A.K. Liljedahl, J.A. Cordeiro, M.M. Loranty, C. Witharana and J.W. Lichstein, 2022. Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. Nature Climate Change, 12:841-846. doi:10.1038/s41558-022-01455-w

Webb, E.E., A.K. Liljedahl, M.M. Loranty, C. Witharana and J.W. Lichstein, 2023. Reply to: Detecting long-term Arctic surface water changes. Nature Climate Change, 13:1194-1196. doi:10.1038/s41558-023-01837-8

Weyhenmeyer, G.A., U. Obertegger, H. Rudebeck, E. Jakobsson, J. Jansen, G. Zdorovennova, S. Bansal, B.D. Block, C.C. Carey, J.P. Doubek, H. Dugan, O. Erina, I. Fedorova, J.M. Fischer, L. Grinberga, H.-P. Grossart, K. Kangur, L.B. Knoll, A. Laas, F. Lepori, J. Meier, N. Palshin, M. Peternell, M. Pulkkanen, J.A. Rusak, S. Sharma, D. Wain and R. Zdorovennov, 2022. Towards critical white ice conditions in lakes under global warming. Nature Communications, 13:4974. doi:10.1038/s41467-022-32633-1

White, D., L. Hinzman, L. Alessa, J. Cassano, M. Chambers, K. Falkner, J. Francis, W.J. Gutowski, M. Holland, R.M. Holmes, H. Huntington, D. Kane, A. Kliskey, C. Lee, J. McClelland, B. Peterson, T.S. Rupp, F. Straneo, M. Steele, R. Woodgate, D. Yang, K. Yoshikawa and T. Zhang, 2007. The Arctic freshwater system: Changes and impacts. Journal of Geophysical Research: Biogeosciences, 112:2006JG000353. doi:10.1029/2006JG000353

Whitfield, P.H., P.D.A. Kraaijenbrink, K.R. Shook and J.W. Pomeroy, 2021. The spatial extent of hydrological and landscape changes across the mountains and prairies of Canada in the Mackenzie and Nelson River basins based on data from a warm-season time window. Hydrology and Earth System Sciences, 25:2513-2541. doi:10.5194/hess-25-2513-2021

Wik, M., R.K. Varner, K.W. Anthony, S. MacIntyre and D. Bastviken, 2016. Climate-sensitive northern lakes and ponds are critical components of methane release. Nature Geoscience, 9:99-105. doi:10.1038/ngeo2578

Wilcox, E.J., B.B. Wolfe and P. Marsh, 2023. Hydrological, meteorological, and watershed controls on the water balance of thermokarst lakes between Inuvik and Tuktoyaktuk, Northwest Territories, Canada. Hydrology and Earth System Sciences, 27:2173-2188. doi:10.5194/hess-27-2173-2023

Williams, G.P., 1965. Correlating freeze-up and break-up with weather conditions. Canadian Geotechnical Journal, 2:313-326. doi:10.1139/t65-047

Wood, M., E. Rignot, I. Fenty, L. An, A. Bjørk, M. Van Den Broeke, C. Cai, E. Kane, D. Menemenlis, R. Millan, M. Morlighem, J. Mouginot, B. Noël, B. Scheuchl, I. Velicogna, J.K. Willis and H. Zhang, 2021. Ocean forcing drives glacier retreat in Greenland. Science Advances, 7. doi:10.1126/sciadv.aba7282

Woolway, R.I., B.M. Kraemer, J.D. Lenters, C.J. Merchant, C.M. O'Reilly and S. Sharma, 2020. Global lake responses to climate change. Nature Reviews Earth and Environment, 1:388-403. doi:10.1038/s43017-020-0067-5

Woolway, R.I., S. Sharma and J.P. Smol, 2022. Lakes in hot water: the impacts of a changing climate on aquatic ecosystems. BioScience, 72:1050-1061. doi:10.1093/biosci/biac052

Wright, S.N., L.M. Thompson, D. Olefeldt, R.F. Connon, O.A. Carpino, C.R. Beel and W.L. Quinton, 2022. Thaw-induced impacts on land and water in discontinuous permafrost: A review of the Taiga Plains and Taiga Shield, northwestern Canada. Earth-Science Reviews, 232:104104. doi:10.1016/j.earscirev.2022.104104

Wrona, F.J., M. Johansson, J.M. Culp, A. Jenkins, J. Mård, I.H. Myers-Smith, T.D. Prowse, W.F. Vincent and P.A. Wookey, 2016. Transitions in Arctic ecosystems: Ecological implications of a changing hydrological regime. Journal of Geophysical Research: Biogeosciences, 121:650-674. doi:10.1002/2015JG003133

Xu, M., Q. Yang, X. Hu, K. Liang and T. Vihma, 2022. Record-breaking rain falls at Greenland summit controlled by warm moist-air intrusion. Environmental Research Letters, 17:044061. doi:10.1088/1748-9326/ac60d8

Yang, R.-M. and T. Zhang, 2022. Dramatic thinning of Alaskan river ice and its climatic controls. Advances in Climate Change Research, 13:623-631. doi:10.1016/j.accre.2022.08.001

Yang, B., M.G. Wells, J. Li and J. Young, 2020. Mixing, stratification, and plankton under lake-ice during winter in a large lake: Implications for spring dissolved oxygen levels. Limnology and Oceanography, 65:2713-2729. doi:10.1002/lno.11543

Yang, X., T.M. Pavelsky and G.H. Allen, 2020. The past and future of global river ice. Nature, 577:69-73. doi:10.1038/s41586-019-1848-1

Yang, D., H. Park, T. Prowse, A. Shiklomanov and E. McLeod, 2021. River ice processes and changes across the northern regions. In: Yang, D. and D.L. Kane (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer, pp. 379-406. doi:10.1007/978-3-030-50930-9_13

Ye, H., D. Yang, A. Behrangi, S.L. Stuefer, X. Pan, E. Mekis, Y. Dibike and J.E. Walsh, 2021. Precipitation characteristics and changes. In: Yang, D. and D.L. Kane (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer, pp. 25-59. doi:10.1007/978-3-030-50930-9_2

Yin, J. and M. Zhao, 2021. Influence of the Atlantic meridional overturning circulation on the U.S. extreme cold weather. Communications Earth and Environment, 2:218. doi:10.1038/s43247-021-00290-9

Yoshikawa, K. and L.D. Hinzman, 2003. Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. Permafrost and Periglacial Processes, 14:151-160. doi:10.1002/ppp.451

Young, K.L., L. Brown and Y. Dibike, 2021. Arctic wetlands and lakes–dynamics and linkages. In: Yang, D. and D.L. Kane (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer, pp. 349-377. doi:10.1007/978-3-030-50930-9_12

Yu, L. and S. Zhong, 2021. Trends in Arctic seasonal and extreme precipitation in recent decades. Theoretical and Applied Climatology, 145:1541-1559. doi:10.1007/s00704-021-03717-7

Zakharova, E., S. Agafonova, C. Duguay, N. Frolova and A. Kouraev, 2021. River ice phenology and thickness from satellite altimetry: potential for ice bridge road operation and climate studies. The Cryosphere, 15:5387-5407. doi:10.5194/tc-15-5387-2021

Zhan, S., C. Song, J. Wang, Y. Sheng and J. Quan, 2019. A global assessment of terrestrial evapotranspiration increase due to surface water area change. Earth's Future, 7:266-282. doi:10.1029/2018EF001066

Zhang, Y., N. Ma, H. Park, J.E. Walsh and K. Zhang, 2021. Evaporation processes and changes over the northern regions. In: Yang, D. and D.L. Kane (Eds.), Arctic Hydrology, Permafrost and Ecosystems. Springer, pp. 101-131. doi:10.1007/978-3-030-50930-9_4

Zhong, X., T. Zhang, S. Kang, K. Wang, L. Zheng, Y. Hu and H. Wang, 2018. Spatiotemporal variability of snow depth across the Eurasian continent from 1966 to 2012. The Cryosphere, 12:227-245. doi:10.5194/tc-12-227-2018

Zorigt, M., G. Battulga, G. Sarantuya, S. Kenner, N. Soninkhishig and M. Hauck, 2019. Runoff dynamics of the upper Selenge basin, a major water source for Lake Baikal, under a warming climate. Regional Environmental Change, 19:2609-2619. doi:10.1007/s10113-019-01564-x

Data references

Data ref. 6.1 Climate Reanalyzer. https://climatereanalyzer.org

Data ref. 6.2 McClelland, J.W., S.E. Tank, R.G.M. Spencer, A.I. Shiklomanov, S. Zolkos and R.M. Holmes. ArcticGRO. The Arctic Great Rivers Observatory. 2024. Discharge Dataset, Version 20240813. https://arcticgreatrivers.org/discharge/

Data ref. 6.3 Shiklomanov, A., 2016. Data of river ice timing and thickness for selected river gauges in Russian pan-Arctic over 1970-2012. Arctic Data Center. doi:10.18739/A2PW9R

Data ref. 6.4 Vuglinsky, V., 2000. Russian River Ice Thickness and Duration, 1917-1992, Version 1 [Data Set]. Boulder, Colorado, USA. National Snow and Ice Data. doi:10.7265/N5J10129

Data ref. 6.5 Fettweis, X. Arctic Land Ice Surface Mass Balance from Regional Climate Model MAR v3.14.0 Run at a resolution of 15km and forced by ERA5. 2023. https://www.climato.uliege.be/cms/c_5855702/fr/climato-arctic

Bellerby, R., N.P. Roden, K. Azetsu-Scott, N. Bednaršek, V. Qutuuq Buschman, P. Calosi, S. Dupont, A. Fransson, R. Tuurraq Glenn, R. Gryba, C. Hauri, D.D.W. Hauser, E.M. Krümmel, S.R. Ólafsdóttir, D. Qi, A.H.C. Rudolf, R. Schaeffer, I. Semiletov, and N. Steiner, 2024. Arctic Ocean acidification. In: AMAP Arctic Climate Change Update 2024: Key Trends and Impacts, pp. 95-115. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://doi.org/10.21352/0az2-v713

7. Arctic Ocean acidification

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Key findings

- *The Arctic Ocean is continuing to acidify and is already witnessing environments that are deleterious to marine life, negatively impacting the activities, wellbeing, and rights of Arctic Indigenous Peoples.*
- *Globally, the greatest declines in pH continue to be projected for the Arctic Ocean and reflect impacts from surface ocean warming, loss of sea ice, and atmospheric CO_2 uptake. Observations indicate that acidification in the Arctic Ocean has occurred at a rate 3–4 times higher than in other ocean basins.*
- *The upper 1000 m of the Arctic Ocean is projected to be undersaturated with respect to aragonite by 2100 for all emission pathways.*
- *Fjord systems are currently undergoing rapid transitions due to the accelerated melting and retreat of glaciers. The freshwater input from glacial meltwaters enhances ocean acidification.*
- *Methane may act as an additional climate change-driven ocean-acidification accelerator, further increasing uncertainties in Arctic ecosystems.*
- *Owing to their high ocean acidification sensitivities, pteropods in the high latitudinal regions are already severely compromised.*
- *Arctic cod* (Boreogadus saida) *eggs and larvae are vulnerable to ocean acidification. Findings highlight the need to determine species responses to ocean acidification across their entire developmental trajectory.*
- *Studies indicate the importance of local adaptation and the need to monitor local variability in carbonate chemistry to evaluate the true biological response to ocean acidification.*
- *All model projection evaluations demonstrate that emission reductions can drastically slow the pace at which multiple drivers emerge or critical thresholds will be crossed.*
- *Community-based monitoring led by Arctic Indigenous Peoples would fill a gap in local and regional observational data, and can be paired with climate model downscaling to assist in policy decision-making.*

7.1 Introduction

The Arctic plays a key role in climate regulation and is a significant sink for carbon dioxide (CO_2) and a conduit for carbon between the atmosphere and the interior ocean (Volk and Hoffert, 1985). Climate change, which is driving ocean warming, cryosphere loss, biodiversity modifications, and increased ocean carbon, is modifying this role of the Arctic within the climate system. Increased ocean carbon is resulting in rapid ocean acidification; namely, a reduction in the pH of the ocean following increased dissolved CO_2 concentrations, which in turn modifies the speciation of the carbonate system. The purpose of this chapter is to provide an update of knowledge concerning new scientific understanding of Arctic Ocean acidification, observed trends in the Arctic seawater carbonate system, and model (CMIP6) projections of trends under increased warming and rising atmospheric CO_2 concentrations.

Hunting, fishing, and harvesting in coastal and marine ecosystems have sustained Arctic Indigenous Peoples, local communities, and livelihoods since time immemorial (Rapinski et al., 2018; Watt-Cloutier, 2018) and this highlights the fundamental importance of these ecosystems to Indigenous health, wellbeing, and overall existence (ICC Alaska, 2015; Proverbs et al., 2020; Carothers et al., 2021; Buschman and Sudlovenick, 2023; Pörtner et al., 2023). Changes in the environment, such as changes in ecosystem structure and function, are thus of major concern for Arctic Indigenous coastal communities. As a result, both Indigenous Knowledge and Indigenous observing, supported by long-held Indigenous practices, have an undeniable place in research, monitoring, mitigation, adaptation, and decision-making in a changing seascape (Ford et al., 2021; Huntington et al., 2022; ICC Alaska, 2022; Yua et al., 2022; Hauser et al., 2023).

The effects of ocean acidification on marine organisms are of particular concern to Arctic Indigenous coastal residents who are at the frontline of climate change (Buschman and Hauri, 2022). As hunters, fishers, and harvesters in this rapidly changing environment, Indigenous Peoples are ideally positioned to contribute to the understanding of climate change impacts, including ocean acidification, on coastal ecosystems (see Box 7.1). Research and monitoring activities that are in line with community-identified and -driven priorities have the highest chance of achieving co-produced outcomes between Indigenous and academic knowledge systems (Fox et al., 2020; Eicken et al., 2021; Hauser et al., 2021, 2023). In terms of ocean acidification, Indigenous Peoples can help identify environmental changes, drivers, cumulative effects, and their consequences on the coastal and marine environment. The effects of ocean acidification are far reaching, with implications for changes in ecosystem

Box 7.1 AAOKH: An observing network

The Alaska Arctic Observatory and Knowledge Hub (AAOKH) works with a network of observers in Arctic Alaska to document long-term environmental observations. Daily to weekly observations are sent in throughout the year. Observations include weather, ocean/sea-ice conditions, wildlife and community activities. Observations from the AAOKH network communicate local perspectives of change rooted in Indigenous worldview and deep connection to place. These observations and insights can inform local to regional decision-making and strengthen Western scientific models to be more relevant to coastal Arctic communities.

Qikiqtaġruk (Kotzebue) is a hub community located in northwest Alaska. The community relies heavily on river and sea ice for travel and subsistence hunting. Bobby Schaeffer is one of the observers in Qikiqtaġruk.

> *"I think everything we are reporting in our observations has Global Warming* [i.e. climate change] *implications. The environment is changing and we are witness to these changes…. Reporting these events* [via the community-based observing project Alaska Arctic Observatory & Knowledge Hub] *from year to year gives me an avenue to compare where global warming is going up here in the Arctic. The changes are happening at a more rapid pace. Not only are these changes happening to the Arctic environment, they are affecting our subsistence resources huge. I feel that the changes will continue to accelerate and recording these changes will present a pattern we can use to plan for the future. How will these changes affect food security? How is ocean acidification affecting our sea mammals, seabirds, and fish that are the most important subsistence resource to the Inuit? What is the expected level of ocean acidification in the near future given known carbon emissions worldwide?"* Bobby Schaeffer (Hauser et al., 2023)

> *"You know we're ocean people; we've always thrived on the whale and the seal for thousands of years. Of course it's changing, but in the long term I worry about the water because if it continues to warm, life in the water will cease to exist"* Bobby Schaeffer (Glenn, 2023)

> *"If carbon dioxide is being absorbed in the waters in white fish* [i.e. a key subsistence species in Qikiqtaġruk] *habitat, what is it doing to the white fish food chain when a bulk of their food is fresh water miniature snails and shrimp-like crustaceans?"* Bobby Schaeffer (Hauser et al., 2023)

function, biodiversity, and the structure of habitats, which in turn may challenge the population dynamics of species that are of critical importance to Indigenous livelihoods, health, and cultural practice.

Inuit are particularly dependent on the health and stability of the Arctic ecosystem since it supports complex food webs of marine-associated species, from the smallest of living creatures such as phytoplankton, through to crustaceans such as shrimp and crab, to the ecosystem's top predators such as polar bears (*Ursus maritimus*), walrus (*Odobenus rosmarus*), beluga (*Delphinapterus leucas*) and bowhead whales (*Balaena mysticetus*) (ICC Alaska, 2015). Shellfish and fish species, such as shrimp, crab, cod, halibut, and salmon, support both subsistence and small-scale commercial fisheries. Arctic marine mammals are of great cultural and subsistence importance within Inuit culture, as integral food and spiritual components of the way of life, but also co-stewarded and observed for impacts of changing conditions in the Arctic (Huntington et al., 2017; Ostertag et al., 2018; Breton-Honeyman et al., 2021). Ocean acidification is expected to affect the physiology and life history of many species important to Indigenous Peoples, which may lead to cascading or compounding effects with wide-reaching impacts on the Arctic food webs. Indigenous Knowledge of these species, ecosystems, and biogeophysical dimensions of the environment is a critical source of information for environmental and biodiversity research, management, and policy, and can lead to novel and unexpected insights as well as to helping promote Indigenous self-determination and sovereignty when equitably included alongside Western science (Wheeler et al., 2020; Reid et al., 2021; ICC, 2022; Yua et al., 2022). Inuit, as well as other Arctic Indigenous Peoples, have intrinsic rights to the hunting, fishing, and harvesting of Arctic species, and are an especially important contributor to efforts to understand, mitigate, and adapt to the climate-driven changes taking place within the Arctic (Buschman and Sudlovenick, 2023).

7.2 Ecosystem hotspots and species response

7.2.1 Biological consequences of ocean acidification

Ocean acidification is a perturbation of the seawater carbonate system leading to multiple stressors for many marine organisms. All the parameters of the carbonate system, such as pH, and the concentrations of CO_2, and bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions, have the potential to affect physiological processes, while a change in saturation state (Ω) for calcium carbonate ($CaCO_3$) can lead to the dissolution of unprotected calcified structures. Some organisms may benefit from these changes (e.g., through enhanced photosynthesis); however, many marine species will experience adverse impacts, including mortality and possibly even extinction (Dupont et al., 2008; Wittmann and Pörtner, 2013; Calosi et al., 2017, 2019; Vargas et al., 2017, 2022). Marine calcifiers, organisms using $CaCO_3$ to build shells or skeletons, were identified early on as particularly at risk under ocean acidification. The reasoning was that the associated changes in the seawater carbonate system would lead, in extreme cases, to water corrosive for $CaCO_3$ structures (i.e., when Ω drops below 1) and to decreased availability of CO_3^{2-} for the calcification process. However, most marine calcifiers use HCO_3^- or metabolic CO_2 for the calcification process, both of which are more available under ocean acidification (Roleda et al., 2012; Fitzer et al., 2019). For pteropods (free-swimming holoplanktonic molluscs), and more specifically *Limacina helicina*, the energy costs of maintaining calcification once rapid dissolution occurs as conditions approach Ω values of 1.4 (Bednaršek et al., 2019) makes them particularly sensitive to ocean acidification (Bednaršek et al., 2014a; Mekkes et al., 2021). See also third quote in Box 7.1.

Crustaceans, bivalves and fish represent key elements of Arctic trophic cascades, and are of major importance for the food security of Arctic Indigenous Peoples, and other Arctic inhabitants. These species are also of great value to Arctic fisheries, which are likely to increase in significance owing to the ongoing poleward migration of several species under global warming and the progressive decline in sea ice, which will make some species more accessible and some types of fisheries possible (e.g., northern shrimp trap fishing). The cultural and socio-economic development of Arctic Indigenous Peoples, and other Arctic inhabitants, greatly depends on the sustainable utilization of these resources in a rapidly changing environment (ICC Alaska, 2015; Proverbs et al., 2020; Carothers et al., 2021; Buschman and Sudlovenick, 2023). Despite this, few studies on the impacts of ocean acidification on target species such as king crab, snow crab, northern shrimp and cod have been published since the previous AMAP assessment (AMAP, 2018). This limits growth in understanding of its impacts on these species in Arctic waters, and therefore its impact on the structure and functioning of the ecosystems in which they live. A lack of studies characterizing the response of target species along discrete pH and pCO_2 (partial pressure of CO_2) gradients prevents the identification of species-specific thresholds (see, for example, Christen et al., 2013; Menu-Courey et al., 2019; Bednaršek et al., 2021a; Noisette et al., 2021), which would be useful for determining ocean acidification hotspots and informing stakeholder decision-making processes. Finally, most studies seeking to understand inter-population variation in sensitivity to ocean acidification along natural gradients do not study actual Arctic populations of the target fishery species (e.g., Guscelli et al., 2023a,b). Despite obvious challenges in working on Arctic marine organisms, this lack of information remains an issue and the fragmented knowledge concerning the impacts of ocean acidification raises major concerns for the ability to produce accurate predictions of risk for target species, ecosystem services, and Indigenous communities.

The following sections summarize recent understanding on the impacts of ocean acidification on key species: northern shrimp, several crab species (including red king crab and snow crab) and Atlantic and Arctic (Polar) cod (hereafter Arctic cod).

7.2.2 Impacts on northern shrimp

Northern shrimp (*Pandalus borealis*) represents a major fishery for Arctic countries, and could become increasingly important in the coming decades as the progressive disappearance of sea ice at higher latitudes increases accessibility for fishing, and *P. borealis* continues to decline in abundance (up to fisheries extinction) at the southern edge of its geographical distribution. This decline is already observed or expected to occur in the near future in the Gulf of Maine, the Estuary and Gulf of St Lawrence, Newfoundland and Labrador waters (DFO, 2021, 2022; Hunter et al., 2021), as well as in southern Sweden and Norway (Cardinale et al., 2023).

Despite the ecological, food security and socio-economic importance of *P. borealis*, only a few studies on the effects of ocean acidification, either in isolation or combined with other global change drivers, have been published since the 2018 AMAP assessment (i.e., Chemel et al., 2020; Guscelli et al., 2023a,b). Those that are available suggest that (adult) female shrimp are tolerant to ocean acidification in isolation, unlike earlier life stages (see Bechmann et al., 2011; Arnberg et al., 2013). Female shrimp survival is not compromised by ocean acidification (Chemel et al., 2020; Guscelli et al., 2023a), unless it is combined with ocean warming and hypoxia, implying that acidification further increases the adverse impacts of these other drivers. Chemel et al. (2020) showed that the nutritional value and organoleptic quality of female shrimp is not affected by ocean acidification. Although at first glance, this appears to contradict the results of Dupont et al. (2014), differences in the natural environmental conditions to which the study populations were exposed can explain this apparently divergent outcome (see discussion by Chemel et al., 2020). In addition, Guscelli et al. (2023a,b) highlighted the existence of population-specific responses to ocean acidification for amino acid synthesis and metabolism, and standard metabolic rates, as well as the presence of non-linear effects of ocean acidification and ocean warming on amino acid synthesis and metabolism. Finally, although concerning ocean warming, a limited potential for further adaptation to ongoing global changes was suggested in *P. borealis* (Leung et al., 2023). These new studies, together with the existing body of information, confirm that ocean acidification impacts on northern shrimp are relatively limited in isolation. While differing across its developmental trajectory, ocean acidification increases shrimp sensitivity to other global change drivers. It is relevant to note that Arctic populations of *P. borealis* have not been studied experimentally within the context of global change biology, and neither have male shrimp (this species being a protandrous hermaphrodite), highlighting important gaps in current knowledge for this species.

7.2.3 Impacts on crab species

Several of the crab species that are found in subarctic and Arctic regions represent key elements of the food webs in their respective habitats and are also of great importance for Indigenous food security, as well as having commercial value (e.g., Punt et al., 2014; Snook et al., 2022). Species of particular commercial interest include: Kamchatka king crab (*Paralithodes camtschaticus*), blue king crab (*P. platypus*), snow crab (*Chionoecetes opilio*), Pacific snow crab (*C. bairdi*) and Dungeness crab (*Metacarcinus magister*). These species are all affected to some extent by ocean acidification. This is supported by an increasing body of evidence for a wide range of species: see AMAP (2018) and recent evidence by Long et al. (2019), Bednaršek et al. (2020), Reinhardt (2020), Stillman et al. (2020), Dickinson et al. (2021), McElhany et al. (2022) and Durant et al. (2023), with the exception of *C. opilio*, which appears to be more tolerant to potential future ocean acidification scenarios (Coffey et al., 2017; Swiney et al., 2017; Long et al., 2019, 2022; Stillman et al., 2020; Algayer et al., 2023). Overall, differences in the sensitivity of the specific life stages along the developmental trajectory of the same crab species were identified. For example, substantial differences in lifestage-specific sensitivity have been observed in *P. camtschaticus*, with adults appearing more sensitive than juveniles based on transcriptomic data (Stillman et al., 2020). These findings reinforce the need to determine species responses to ocean acidification across their entire developmental trajectory (see Walther et al., 2010; Small et al., 2015; Noisette et al., 2021) to improve predictions for particular species by considering the cumulative response to ocean acidification across its developmental trajectory (Tai et al., 2021).

7.2.4 Impacts on Atlantic cod and Arctic cod

Atlantic cod (*Gadus morhua*) and Arctic cod (*Boreogadus saida*) are species of great ecological and economic importance, as well as having an important role in the food security of Arctic Indigenous Peoples (Alton Mackey and Orr, 1987; Marushka et al., 2021). The early life stages of Atlantic cod are known to be more vulnerable to the impact of ocean acidification (see AMAP, 2018; Dahlke et al., 2020; Leo, 2021) than adults, which possess far greater homeostatic abilities. However, this does not mean that adult cod are not vulnerable to ocean acidification (see AMAP, 2018; Coll-Lladó et al., 2021), particularly in combination with other global change drivers such as ocean warming (e.g., Hu et al., 2016). Recent work has also highlighted that Atlantic cod juveniles appear to be more physiologically sensitive to exposure to high levels of ocean acidification than Arctic cod juveniles (Leo, 2021). However, Arctic cod is still considered more vulnerable to ocean acidification, both in isolation and particularly in combination with warming, than Atlantic cod, owing to the former being a stenotherm (i.e., a species only capable of living or surviving in a narrow temperature range) and the latter a more temperature-tolerant eurythermal species (Leo, 2021). A recent synthesis by Geoffroy et al. (2023) on the impact of climate and global changes on Arctic cod highlighted ocean acidification as a principal stressor on this species. They concluded that the added impact of ocean acidification on eggs and larvae is high, but only moderate for juvenile, immature, and adult Arctic cod. However, they rated the confidence for this assessment as medium for eggs and larvae and low for juveniles, immatures, and adults, based on limited information concerning future rates of ocean acidification and effects on older life stages (Kunz et al., 2018; Geoffroy et al., 2023). Both species could also experience indirect effects through impacts on the structure and functioning of Arctic ecosystems (Grandon, 2020).

7.2.5 Local adaptation and its significance

A process that has been overlooked in the first stages of ocean acidification research is that of *local adaptation* to natural variability in the carbonate system. In the coastal areas, strong spatial and temporal variability are observed as this is not only driven by equilibrium with the atmosphere but also by biological processes, currents, or interaction with other environmental parameters. Recent syntheses highlight that sensitivity to low pH is mainly driven by the extremes of the present range of the natural variability (Vargas et al., 2017, 2022). As an example, scallops are a highly valued seafood group of bivalves and about 50 published articles have evaluated the impact of exposure to low pH on this group. However, there is no clear consensus on how they would respond to future ocean acidification. This is partly a consequence of differences in experimental design. Ten articles were published on king scallop (*Pecten maximus*) alone. While two studies showed that exposure to low pH had a negative effect on early life-stage fitness (Andersen et al., 2013, 2017), others showed little effect on juveniles and adults (Sanders et al., 2013; Schalkhausser et al., 2013, 2014; Pratt et al., 2015; Bock et al., 2019; Cameron et al., 2019; Götze et al., 2020) and often concluded that scallops could be resilient to ocean acidification. However, it is difficult to compare the outcome of these studies because they use different life stages (gametes, larvae, juveniles, adults), endpoints (survival, growth, whole-organism physiology, expression of genes, proteins or metabolites, behavior), exposure times (from seven days to three months), or temperature. The scallops used for these experiments were also collected from different regions and a recent study showed that different populations from the same species can have different responses to the same pH levels. While individuals sampled in France had an increased mortality when exposed to a pH_{NBS} of 7.7[1], no additional mortality was observed for scallops from a Norwegian population (Harney et al., 2023). The species- and population-specific response can be explained by local adaptation to the variability in carbonate chemistry (as well as to variability in other environmental drivers) at the different sampling sites (Calosi et al., 2017; Vargas et al., 2017, 2022), with ocean acidification representing a driver for species geographical distribution (e.g., Calosi et al., 2013, 2017). However, the present range of natural variability at the sampling site is rarely considered in experimental studies and the selection of scenarios is often arbitrary or based on open ocean projections by the Intergovernmental Panel on Climate Change (IPCC). For *P. maximus* alone, studies considered between two and four pH values in their design with pH_{NBS} ranging from 8.3 to 7.4.

Using the methodology of Vargas et al. (2022), it is possible to account for the present range of variability. Data on the variability in pCO_2 at the sampling site could be retrieved from public databases for 20 out of the 50 published articles on scallops. Using this information, it is possible to calculate an index (ΔpCO_2) evaluating how the experimental pCO_2 scenarios used in experiments deviated from the extreme upper pCO_2 at the sampling site. A negative ΔpCO_2 would indicate that the tested experimental scenario is within the present range of variability and thus not fully relevant in the context of ocean acidification. A response ratio (lnRR) can be calculated to estimate the impact on different endpoints (survival, growth, respiration) and life-history stages for six different species. Despite such variability in species, populations and experimental design, a clear trend between the ΔpCO_2 and the lnRR could be identified (Figure 7.1). In other words, the more conditions deviate from the extreme of the present range of natural variability, the more negative the impact. This highlights the key importance of local adaptation and the need to monitor the local variability in carbonate chemistry to evaluate the true biological response to ocean acidification.

[1] With regards to pH, the subscript refers to the pH scale in use. pH(NBS) = National Bureau of Standards; pH(Total) = Total hydrogen ion concentration.

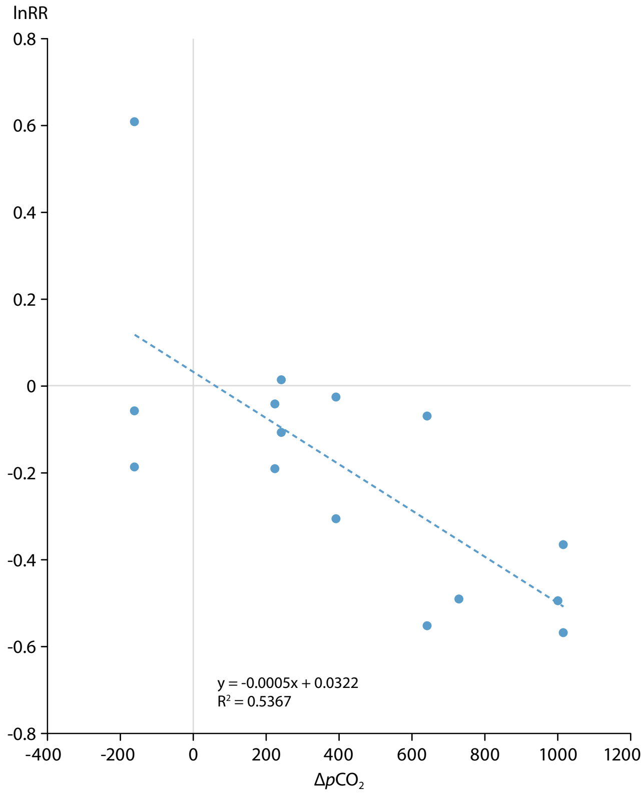


Figure 7.1 Response ratio (lnRR) for different species of scallop to the ΔpCO_2 exposure index. The dashed line shows the linear regression fit.

7.2.6 Pteropods as an indicator of risk

Pteropods are holoplanktonic calcifiers with a biogeographic distribution across the global oceans, and one of the highest biomasses recorded in the subpolar and polar regions over the upper 200 m (Bednaršek et al., 2012a; Knecht et al., 2023). These regions are characterized by low aragonite saturation states (Ω_{ar}) and low buffering capacity (Feely et al., 2018). Pteropods significantly contribute to the biological pump, especially to the carbonate flux (Bednaršek et al., 2012a; Buitenhuis et al., 2013; Anglada-Ortiz et al., 2021, 2023; Knecht et al., 2023). They are also an important component of the food web, channeling energy through the trophic levels and providing essential food resources for economically important fish and decapod species (Bednaršek et al., 2021b). Pteropods are commonly found in the diets of various life stages of Pacific salmon species, such as pink salmon (*Oncorhynchus gorbuscha*), sockeye salmon (*O. nerka*) and chum salmon (*O. keta*) that rely on pteropods to support somatic growth and lipid reserves, especially during the critical summer and autumn growth periods (Auburn and Ignell, 2000; Armstrong et al., 2005; Beauchamp et al., 2007; Zavolokin et al., 2007; Doubleday and Hopcroft, 2015; Daly et al., 2019). They also comprise a small component of the diet for demersal Arctic cod and Arctic char (*Salvelinus alpinus*) (Majewski et al., 2016; Niemi et al., 2021).

Pteropods build shells of aragonite, a metastable form of calcium carbonate that is 50% more soluble than calcite (Mucci, 1983). Experimental and field studies have demonstrated multiple biological pathways through which pteropods may be impacted by reduced Ω_{ar}, compromising their biomineralization (reduced shell calcification and increased shell dissolution), growth, fecundity, and ultimately their survival (Comeau et al., 2009; Lischka et al., 2011; Bednaršek et al., 2014a,b, 2017a,b, 2019; Feely et al., 2016; Manno et al., 2016, 2017). Field studies further demonstrate that pteropods in the subpolar and polar regions already show increased shell dissolution due to current exposure in the field (Bednaršek et al., 2012b, 2021b; Niemi et al., 2021). Owing to this sensitivity, pteropods rank in the top quartile of ecological integrity indicators and are used as a key early-warning indicator for ocean acidification vulnerability assessment and regional monitoring (Bednaršek et al., 2017b). The wealth of understanding on pteropod vulnerability represents a baseline for the expert-based consensus towards selecting at least six Ω_{ar}-related thresholds that delineate the magnitude and duration of ocean acidification exposure resulting in negative responses (Bednaršek et al., 2019) that can be applied to model outputs or observations to identify critical ocean acidification habitats and inform decision-makers.

When assessing species-specific risk, it is important to consider the current magnitude (Ω_{ar}), as well as the rate of change of Ω_{ar} per decade. Climatologies based on observational data for the northern high latitudes over the upper 200 m (Bednaršek et al., 2023) show some of the lowest Ω_{ar} values, which range from 0.5 and 1.5 in the polar regions of the Arctic, including the Kara, Laptev, and Beaufort seas and the Arctic Ocean as a whole (Figure 7.2a). When conditions are below the threshold of Ω_{ar} <1.2, growth and calcification in pteropods are compromised and further exacerbated by the severe dissolution, while conditions below the threshold of Ω_{ar} <0.95 trigger substantial pteropod mortality (Bednaršek et al., 2019). Furthermore, the areas of pteropod dissolution strongly overlap with regions of the lowest Ω_{ar} values, with approximately 40–60% of individuals currently being affected with severe shell dissolution in the Arctic and subarctic seas (Figure 7.2b). Field studies showing regional dissolution observations in the northern high latitudes (Bednaršek et al., 2021b; Niemi et al., 2021) show very similar dissolution values to the projections evaluated here based on the work of Bednaršek et al. (2014a).

Owing to their high ocean acidification sensitivities, pteropods in the high latitude regions are already severely compromised. Population vulnerability is already very high and will increase with continued ocean acidification in combination with multiple other stressors, especially warming. The combination of ocean acidification and warming can cause rapid mortality (Bednaršek et al., 2022) and contribute to population decline. The adaptation potential that could partially offset the anticipated risks is low, given the genetic uniformity of the dominant pteropod species (i.e., the small swimming planktonic mollusc *Limacina helicina*) and could be mainly in the form of the high spatial connectivity (Bednaršek et al., 2021b).

Based on the projected dissolution and population changes, a substantial decline in carbon export and sequestration could occur in the regions northwards of 50°N, calling for targeted monitoring to evaluate pteropod risks and changes in carbonate fluxes in these regions, relevant for carbon sequestration and marine CO_2 removal strategies.

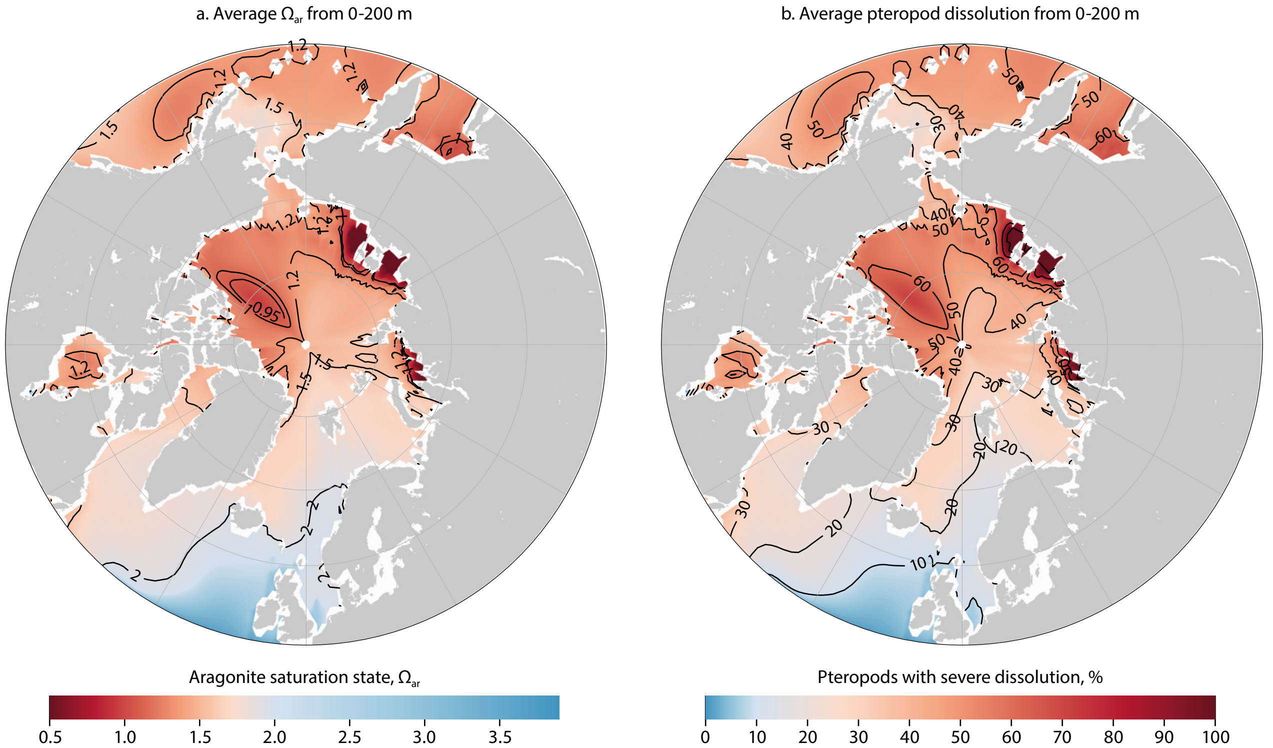


Figure 7.2 Observation-based climatology (mean year 2005) of aragonite saturation state (Ω_{ar}) and the percentage of pteropods with severe dissolution averaged over the upper 200 m of the water column in the Arctic Ocean from 50–90°N. Source: Bednaršek et al. (2023).

7.3 Observations and trends in ocean acidification

7.3.1 Regional scale

Complex signals of climate change and ocean acidification emerge as longer carbonate system time series become available (DeGrandpre et al., 2020; Ouyang et al., 2020; Woosley and Millero, 2020; Qi et al., 2022; Wang et al., 2022; Ericson et al., 2023). Uncertainty in the long-term rate of change remains, likely to be due to the large spatial and temporal variability in Arctic coastal areas, the scarcity of data over time and space, the complexity of the carbonate system related to anthropogenic changes, and a lack of comprehensive total alkalinity data. Long-term changes in the CO_2 sink potential vary from region to region.

Based on observations of the Arctic Ocean from 47 Arctic research cruises over the past three decades (1994–2021), Qi et al. (2022) showed a rapid acidification of the Arctic Ocean at a rate 3–4 times higher than in other ocean basins due to the sea-ice melt. This promotes the rapid uptake of atmospheric CO_2, decreases alkalinity and buffering capacity, and leads to a sharp decrease in pH and Ω_{ar}. There is also an expansion of acidified waters in the upper Arctic Ocean, which is attributed to the transport of Pacific Winter Water due to the intensified eddies of the Beaufort Current (Qi et al., 2017).

In the Canada Basin, summer surface pCO_2 increased at twice the rate of atmospheric pCO_2 between 1992 and 2017 because of the combined effects of anthropogenic CO_2 uptake, warming, and longer sea ice-free periods (Ouyang et al., 2020). Similarly, DeGrandpre et al. (2020) found significantly higher mean surface pCO_2 values in warmer years with low sea-ice concentrations. In the Chukchi Sea, Wang et al. (2022) found that warming has also decreased the summertime CO_2 sink potential over the past two decades, contradicting the findings of Ouyang et al. (2020) that biological production counteracted the impacts of warming and kept surface pCO_2 stable. Using direct measurements of total alkalinity and total dissolved inorganic carbon from cruises spanning two decades, Woosley and Millero (2020) concluded that riverine input has decreased the western Arctic's CO_2 buffering capacity, shifted the carbonate equilibria towards aqueous CO_2, and thereby minimized its potential to take up anthropogenic CO_2. Their results suggested that the freshwater-induced shift in the carbonate system equilibria has led to an observed pH decrease of >0.005/y. This rate of ocean acidification is similar to the findings of Qi et al. (2022), who found a decadal decrease in pH of 0.0069 ± 0.0011, which is three to four times faster than in other ocean basins. Such a fast rate of change could have severe impacts on the ecosystem (Vargas et al., 2017, 2022) despite the large seasonal variability in the carbonate system and the associated wide ecological niche in these shelf seas (Hauri et al., 2024).

In the Canadian Arctic Archipelago, Ahmed and Else (2019) estimated an increase in CO_2 uptake over the previous four decades, attributed to increased sea-ice loss and higher wind speeds. Burgers et al. (2023) demonstrated that distinct water masses and their mixing with local biology contribute to observed carbon dynamics in Nares Strait, the northernmost outflow gateway of the Arctic Ocean in the Canadian Arctic Archipelago. They observed the lowest pH and calcium carbonate saturation states ($pH_T = 7.85$, $\Omega_{ca} = 1.49$, $\Omega_{ar} = 0.94$) in the Subpolar Mode Water transiting northwards from the subpolar North Atlantic. Along with high nutrient and low dissolved oxygen concentrations, the remineralization of organic matter during the transit causes observed enhanced acidification. Hudson Bay is a large, shallow, semi-enclosed sea, characterized by substantial freshwater input from rivers and some permafrost regions in the southern Canadian Arctic Archipelago region. Terrestrial organic carbon remineralization emerges as a significant driver of CO_2 evasion and ocean acidification in the coastal waters of Hudson Bay (Capelle et al., 2020).

The Nordic Seas comprise the Greenland, Iceland, and Norwegian seas. Their surface water pCO_2 values are generally lower than those of the atmosphere, making the Nordic Seas important sinks for atmospheric CO_2. This undersaturation results from several processes, including primary production, cooling of northward flowing Atlantic waters in the east, and the inflow of pCO_2 undersaturated surface waters from the Arctic Ocean water in the west. Changes in ventilation, the process whereby surface water is transported to the ocean interior and interior water is transported back to the surface, have been observed in the Nordic Seas from a well-ventilated state in 1982, to reduced ventilation in the 1990s, to increased ventilation from the 2000s onwards (Jeansson et al., 2023). The evolution of concentrations and the inventory of anthropogenic carbon (C_{ant}) in the Nordic Seas is positively linked to the ventilation state (Jeansson et al., 2023). The majority of C_{ant} within these seas, however, is caused by advective supply of excess C_{ant} from the south and the corresponding changes in buffer capacity (Anderson and Olsen, 2002; Olsen et al., 2006; Jeansson et al., 2011) that contribute to the acidification. During 1981–2019, this caused pH_T in the upper layer of the Nordic Seas to decrease at an average rate of -0.0028 ± 0.0003 pH units/y (Figure 7.3), resulting in a pH decline of 0.11 (Fransner et al., 2022).

The East Greenland Current waters cover the westernmost part of the Iceland Sea. The southern extent of Arctic sea ice in the East Greenland Current has retreated northward making large areas of Polar Water ice-free in summer (Serreze and Meier, 2019). The CO_2 air-sea flux of the relevant water masses in the vicinity of Iceland was reported by Olafsson et al. (2021) showing that in different years the highest ocean CO_2 influx is to the Arctic and Polar waters, -3.8 ± 0.4 and -4.4 ± 0.3 mol C/m^2/y, respectively, and that these waters are CO_2 undersaturated in all seasons. The Iceland Sea time series station, located in the central Iceland Sea, shows that hydrographic conditions there are sensitive to the relative contributions of Atlantic Water and lower salinity,

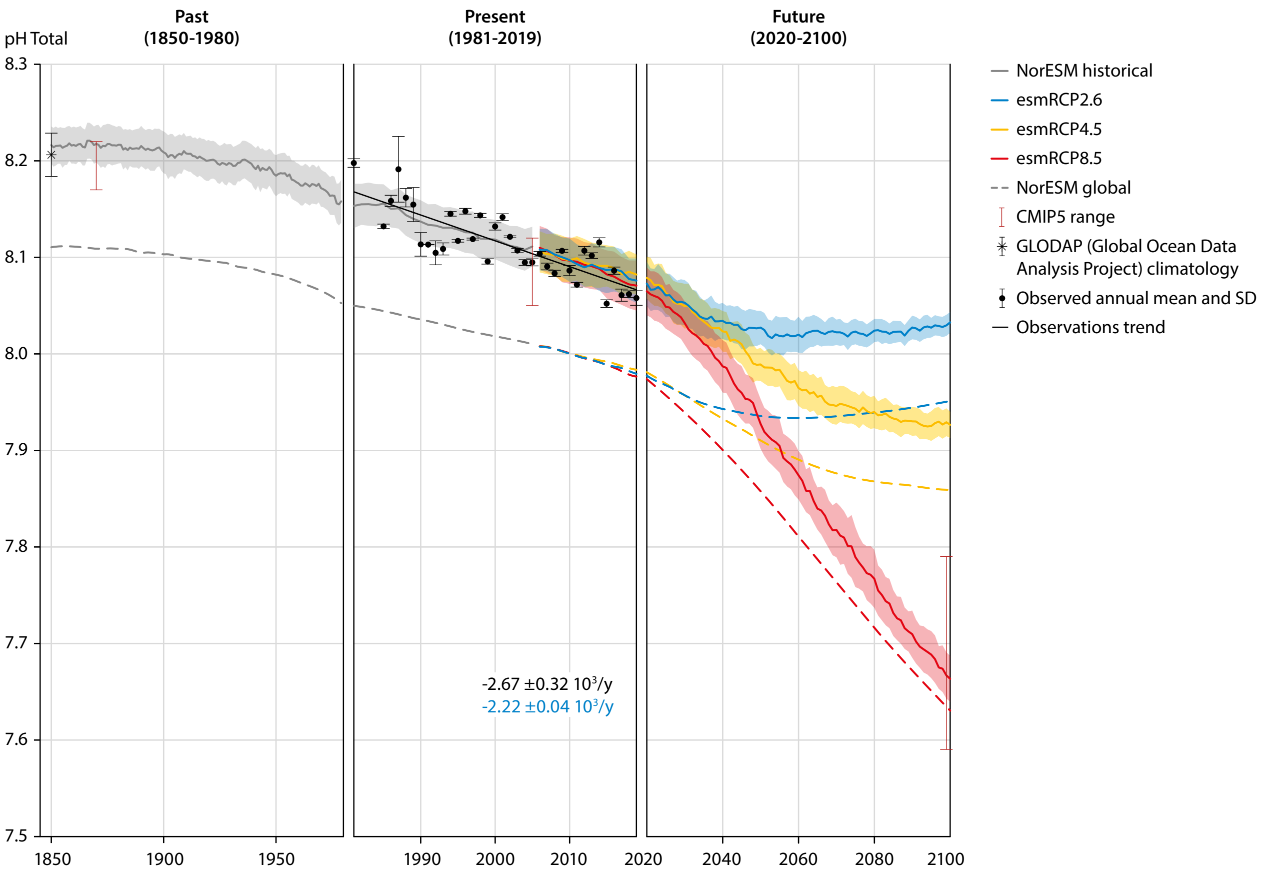


Figure 7.3 pH_T evolution, averaged over the Nordic Seas' surface waters (0–200 m), from 1850 to 2100, shown in sequential panels for past, present, and future. Black dots with error bars show the observed annual mean pH, with standard deviations (due to spatial/seasonal variations) determined from all available observations in the Nordic Seas. The solid black line shows the trend calculated from these observations. The solid colored lines show NorESM1-ME output for emission-driven historical (grey) and future (esmRCP2.6 blue, esmRCP4.5 orange, esmRCP8.5 red) simulations, where the shading depicts the spatial variation (standard deviation). Note that the atmospheric CO_2 increase, as simulated by NorESM1-ME for 1850 to 2005, deviates by 14 ppm from the actual measured increase, which results in a simulated pH decrease that is 0.01 stronger than expected. The red vertical bars display the pH range in the CMIP5 model ensemble for the historical and esmRCP8.5 simulations. The graphic illustrates the actual modelled pH data and not the modelled change applied to observational data. The dashed lines show the evolution of global surface ocean pH from the same simulations. The black asterisk (1850) with error bars shows an estimate of the preindustrial mean pH, with the spatial standard deviation derived from the GLODAPv2 climatology mapped product. The numbers in black and blue show the calculated and significant linear trend, with standard errors from the observations and the model, respectively, for the period 1981–2019. Source: Fransner et al. (2022).

colder Polar or Arctic Waters. For 1991–2020, significant negative trends in pH and Ω_{ar} were observed at this station at all depth levels. The observed pH trends by depth layer for the entire Iceland Sea region (during 1981–2019) are -0.0031 ± 0.0003 pH units/y (0–200 m), -0.00251 ± 0.00027/y (200–500 m), -0.0018 ± 0.00029/y (500–1000 m), and -0.0013 ± 0.00021/y (1000–2000 m) (Fransner et al., 2022). The trends for Ω_{ar} for the same depth layers are -0.0112/y, -0.00637/y, -0.00452/y, and -0.00257/y, respectively (Fransner et al., 2022). The seasonal amplitudes of pH and Ω_{ar} at the surface are approximately 0.2 and 0.5 units. The direct effects of variations in temperature and salinity are of little importance for this observed negative pH and Ω_{ar} trend (Pérez et al., 2021; Fransner et al., 2022).

The Barents Sea and Nansen Basin north of Svalbard are influenced by the warm and saline Atlantic water in the southern part, rich in total alkalinity and CO_2, and the relatively cold and fresh low total alkalinity and low Ω_{ar} Arctic water in the northern part (Fransson et al., 2017; Jones et al., 2021). Larger ocean CO_2 uptake was observed in the marginal ice zone by sea-ice meltwater-induced CO_2 uptake than in the open ocean (Chierici et al., 2019). In the Nansen Basin, less and thinner sea ice caused increased ocean CO_2 uptake during storm events in winter (Fransson et al., 2017). The long-term trends showed a rapid increase in surface water pCO_2 in the northern Barents Sea and adjacent Nansen Basin of 4.2–5.5 ± 0.6–1.1 µatm/y. This is twice as fast as the rate of atmospheric CO_2 increase in the same period 1997–2020 and occurred in the area with the largest decrease in sea-ice cover, implying a link between more open areas and progressing pCO_2 uptake (Ericson et al., 2023).

In the North Pacific along the 165°E section, Ono et al. (2023) showed that the rates of decline in surface pH and Ω_{ar} during 1996–2019 generally followed the increase in atmospheric CO_2 in the tropical and southern subtropical regions (pH -0.002/y, Ω_{ar} -0.011/y) and peaked south of the Kuroshio Extension (pH -0.0026/y, Ω_{ar} -0.015/y), but gradually increased northward across the Subarctic Gyre (pH -0.0012/y, Ω_{ar} -0.006/y). Ono et al. (2019) suggested that acidification along the 137°E section was accelerated in the surface water during 2007–2017 compared to the previous decade, which is modulated by inorganic carbon redistribution associated with the strength of ventilation in the Kuroshio Recirculation. In subsurface waters of the subtropical gyre, Oka et al. (2019) found that natural variability slowed acidification in subtropical mode water during 2010–2016. However, Li et al. (2022) found that the rate of acidification in subtropical mode water during 2005–2020 (pH -0.0028/y, Ω_{ar} -0.0176/y) is about twice that of 1993–2005 (pH -0.0015/y, Ω_{ar} -0.0074/y), and also found that the rapid rate of anthropogenic CO_2 accumulation and acidification is consistently observed across the region between 137°E and 149°E, which is regulated by the transport of subtropical mode water. The faster acidification of subtropical mode water is due to the cooling-induced enhanced anthropogenic CO_2 accumulation in the formation waters in the recent period. This result is generally consistent with the rates observed in the Kuroshio recirculation surface water during 1993–2005 and 2005–2017 (Ono et al., 2019), and the vertical and horizontal consistencies imply the memory function of mode waters in retaining the anthropogenic carbon fingerprint during their formation and transport.

7.3.2 Arctic fjords

Arctic fjords are in rapid transition. Glaciers are retreating at an accelerated rate and freshwater input to the coastal zone is increasing. Glaciers play important roles in physical and biogeochemical processes in polar coastal regions, and thus fjords have high biological productivity and important fisheries. Freshwater enhances coastal ocean acidification. In the Arctic, freshwater sources include sea-ice meltwater, river runoff, glacial meltwater, and precipitation. Fjords in Svalbard have experienced enhanced ocean acidification due to increased glacial discharge, which was further modified by added carbonate ion from glacial drainage, accumulated total dissolved inorganic carbon from brine rejection, and surface primary production (Fransson et al., 2015, 2016, 2020; Ericson et al., 2019). Two studies in Kongsfjorden (west Spitsbergen), in contrasting years, showed lower Ω_{ar} and pH in a cold year with extensive sea-ice cover relative to a warm year with a greater influence from warm and saline Atlantic water inflow (Fransson et al., 2016). However, in a warm year there was more freshwater influence due to melt from glaciers resulting in increased stratification in the surface layer, which influenced CO_2 uptake during primary production, partly compensating for the freshening effect in summer.

A variable corrosive glacial plume was suggested to control the observed seasonal variability of acidification in Prince William Sound, Alaska (Evans et al., 2014). A combination of river water, glacial meltwater and sea-ice meltwater contributed to low Ω values in Cumberland Sound, Canada (Turk et al., 2016). Henson et al. (2023) demonstrated spatial Ω differences in West Greenland and East Greenland fjords and their drivers from an extensive summertime study of 16 fjords. Aragonite undersaturation in West Greenland fjords was observed at depth due to the inflow of shelf waters with low Ω and accumulation of respired organic carbon, while undersaturation in East Greenland fjords was only observed in surface waters due to freshwater (glacial and sea-ice meltwater) dilution of alkalinity. Glacial morphology, marine- or land-terminating glaciers, also influenced local acidification. Subglacial plumes from marine-terminating glaciers entrained the deeper corrosive waters to subsurface layers, while land-terminating glaciers enhanced stratification which contributed to ocean acidification in surface layers.

Another study in a northeast Greenland fjord, Dijmphna Sound, over two summers (2012, 2016) showed that glacial meltwater decreased Ω in the surface layer in both years, and was particularly evident in 2012 (Fransson et al., 2023). Record high loss of surface melt from the Greenland Ice Sheet in 2012 (Nghiem et al., 2012) contributed to a larger decrease in Ω in 2012 than in 2016, by increased freshwater addition that caused dilution of carbonate ions thus reducing total alkalinity (Fransson et al., 2023). However, an increase in Ω due to biological CO_2 drawdown by primary production partly compensated for the decrease in Ω due to freshwater dilution, hence preventing corrosive conditions near the glacier front (Fransson et al., 2023).

To assess the net impact of ongoing ocean acidification in the climate-sensitive Arctic fjords, it is necessary to understand the complex interplay of processes in a changing climate. In the Arctic, fjords and other coastal systems are geomorphologically and oceanographically diverse, and are experiencing rapid changes such as sea-ice loss, an increase in river and glacial meltwater, accelerated organic carbon input due to coastal erosion, and permafrost thawing. However, understanding of the temporal and spatial variability of ocean acidification in these regions is limited. The co-development of an observing system in the Arctic fjords/coastal system with Indigenous Peoples, other local communities, and scientists is urgently required.

7.3.3 Methane and ocean acidification

Methane (CH_4) may act as yet another climate change-driven ocean acidification accelerator, further challenging the Arctic system. How much of the CH_4 carried by bubbles will reach the sea surface and be released to the atmosphere or oxidized to CO_2 largely depends on the CH_4 flux rate, water depth and in-situ release conditions that control transfer processes in different Arctic seas. Sparrow et al. (2018) showed that only a small fraction of the CH_4 released from thawing permafrost and decomposing hydrates on the Beaufort Shelf makes it up to the surface and is emitted to the atmosphere. Most of the CH_4 in the water column is oxidized to CO_2 and may therefore additionally accelerate ocean acidification (Garcia-Tigreros et al., 2021).

In contrast, large-scale CH_4 releases, including release of pre-formed CH_4 long preserved within and beneath subsea permafrost, were documented on the East Siberian Arctic Shelf. Observational data show that at a shallow water depth, approximately 67–72% of CH_4 remains in the bubbles when the bubbles reach the sea surface and enhance its near-surface atmospheric concentrations (Shakhova et al., 2010, 2014, 2015). On the outer East Siberian Arctic Shelf most of the CH_4 dissolves in the water column, building up an aqueous CH_4 inventory. The fate of dissolved CH_4 largely depends on the interaction between several factors: the turnover time of dissolved CH_4 in the water column, the stability of the water column against vertical mixing, and the rates of turbulent diffusion and lateral advection. Dissolved CH_4 on the outer East Siberian Arctic Shelf requires 300–1000 days to be oxidized to CO_2 in the water column because CH_4 oxidation rates are very slow (Shakhova et al., 2015). During this time, some of the aqueous CH_4 inventory is likely to be released to the atmosphere during storms (Shakhova et al., 2014). The remaining dissolved CH_4, captured beneath the sea ice in winter, can spread further from the East Siberian Arctic Shelf via currents, and some can escape to the atmosphere through leads and breaks in the ice. Additional studies are required to evaluate the impact of dissolved CH_4 oxidation on ocean acidification in different Arctic seas.

7.3.4 Permafrost and ocean acidification

The Arctic Ocean is surrounded by permafrost and this is being degraded at an increasing rate under the warming, which is most pronounced in Siberia and Alaska (AMAP, 2017). Thaw and release of organic carbon from Arctic permafrost is postulated to be one of the most powerful mechanisms causing a net redistribution of carbon from land and ocean to the atmosphere (Gruber et al., 2004; Canadell and Raupach, 2009; AMAP, 2017; IPCC, 2023). The extensive East Siberian Arctic Shelf, comprising the Laptev Sea, the East Siberian Sea, and the Russian part of the Chukchi Sea, and which accounts for ~25% of the Arctic continental shelf, is believed to be a particularly vulnerable target area. The massive amount of terrestrial organic carbon delivered by rivers and coastal erosion is partly degraded and subject to further significant degradation during its residence in shelf water (Gustafsson et al., 2011; Vonk et al., 2012). Degradation of terrestrial organic carbon was evident from levels of pCO_2 oversaturation (Semiletov, 1999a,b; Semiletov et al., 2007; Anderson et al., 2009), removal fluxes of both terrestrial dissolved organic carbon and particulate organic carbon (Sánchez-García et al., 2011), and from the molecular-specific shelf-wide $\delta^{13}C$–^{14}C trends in particulate organic carbon and surface bottom organic carbon (Gustafsson et al., 2011; Vonk and Gustafsson, 2013).

The degradation of particulate organic carbon causes the formation of anomalously high pCO_2 and nutrient concentrations in the nearshore zone, where the river signal overlaps with the biogeochemical signal from highly eroded coastal ice complexes enriched by old terrestrial organic matter (Semiletov, 1999a,b; Semiletov et al., 2007, 2011). The particulate organic carbon signal of coastal erosion leads to a pCO_2 increase in bottom waters near the highly eroded ice complexes of up to ~4000 μatm, while pCO_2 values in the surface water, strongly impacted by river runoff, were usually observed up to ~1000 μatm. This is consistent with levels of pCO_2 measured in plumes from the Great Siberian Rivers along the Northern Sea Route (Semiletov et al., 2012). Total dissolved inorganic carbon isotopic data and simulations of water sources using salinity and $\delta^{18}O$ data suggest that the persistent acidification is driven by the degradation of terrestrial organic matter and discharge of Arctic river water with elevated CO_2 concentrations, rather than by uptake of atmospheric CO_2 (Semiletov et al., 2016).

To investigate processes of carbon transport and fate on the East Siberian Arctic Shelf versus ocean acidification effects, the former (~2 million km^2) was evaluated as an integrator of ongoing changes in the surrounding land (~3 million km^2), which create a terrestrial or exogenous signal, and in-situ changes that present a marine or endogenous signal which is generated by increasing coastal and bottom erosion, and the involvement of old carbon in the modern biogeochemical cycle. A notable characteristic of the East Siberian Arctic Shelf is large gradients in hydrological and biogeochemical parameters that correspond to geographically critical contrasts in the Arctic system where the Pacific and local shelf waters interact over the shelf. That is reflected in the sedimentation regime (Semiletov et al., 2005; van Dongen et al., 2008; Gustafsson et al., 2011). The distribution of $\delta^{13}C$-organic carbon in the surface bottom sediments was used to distinguish between two biogeochemical provinces: the Western Biogeochemical Province water (WBP) and the Eastern Biogeochemical Province water (EBP) (Semiletov et al., 2005). The warmer and fresher WBP, located eastwards of the Lena Delta to ~160–170°E, is characterized by strong river and coastal erosion impacts. The saltier and colder EBP, located eastwards of ~160–170°E, is mainly affected by nutrient-rich Pacific water that creates favorable conditions for high summer primary production (Anderson et al., 2011). The lowest Ω_{ar} levels were observed in the heterotrophic WBP, where the influence of both river runoff and terrestrial-organic carbon input is much stronger than in the autotrophic EBP (Semiletov et al., 2005). In the WBP, Ω_{ar} varied from 0.01 to 1.42 (mean 0.45, SD 0.23) in surface water (above the pycnocline) and from 0.01 to 1.27 (mean 0.44, SD 0.23) in bottom water (below the pycnocline). Lower Ω_{ar} in the WBP was associated with higher pCO_2 and lower pH in both surface and bottom water.

In the nearshore WBP water, primary production was shown to be suppressed by lack of sunlight owing to low transparency of shelf water overloaded with suspended particulate matter and riverborne colored dissolved organic matter. Observations showed that mean concentrations (± 1 SD) of suspended particulate matter and colored dissolved organic matter in the WBP surface water were 12.8 ± 26.6 mg/L and 25.6 ± 19.1 µg/L, respectively; that is, up to ten times greater than in the EBP surface water. In some WBP areas, mean suspended particulate matter concentrations increased by a factor of 3–5 times during the 10-year observation period. EBP Ω_{ar} varied from 0.45 to 3.28 (mean 1.74, SD 0.68) in surface water and from 0.35 to 2.21 (mean 0.88, SD 0.42) in bottom water. Lower Ω_{ar} was associated with deeper, saltier, lower-pH water. Low Ω_{ar} observed in the bottom water in both biogeochemical provinces is determined by in-situ organic carbon decomposition. Because rates of coastal erosion and the acidifying effect of terrestrial-organic carbon input due to coastal erosion and river input are higher in the WBP than in the EBP, this results in mean WBP Ω_{ar} that is half that in the EBP (0.44 versus 0.88).

Because two different hydrological and biogeochemical regimes exist in the WBP and EBP of the East Siberian Arctic Shelf, the features of carbon cycling and ocean acidification effects are different and specific to each province. In the WBP the main processes that drive the marine carbon cycle are determined by the combined influence of coastal erosion and riverine runoff from the Lena and other rivers. Transformation of the terrestrial-organic carbon leads to oversaturation of shelf waters in CO_2; CO_2 is highest where the contribution of coastally eroded terrestrial-organic carbon prevails. The decay of terrestrial-organic carbon also lowers the pH leading to the extreme acidification of shelf water on the East Siberian Arctic Shelf, which is especially pronounced in the WBP. In the EBP, which is strongly influenced by Pacific Ocean inflow, the contribution of terrestrial-organic carbon is much lower and marine primary production dominates; there, pCO_2 indicated undersaturation of shelf water in CO_2 and higher Ω_{ar}. Since the compound-specific signal of the bulk organic carbon is related to the extent of permafrost, there may be repercussions for terrestrial-organic carbon remobilization under a warming climate and changing atmospheric circulation patterns.

The results of a multi-year study clearly show a major ocean acidification pattern on the East Siberian Arctic Shelf resulting in severe aragonite undersaturation of shelf waters. This is caused by the degradation of terrestrial-organic carbon exported from thawing coastal permafrost and freshening due to growing Arctic river runoff from extensive permafrost-underlain watersheds and ice melt (Semiletov et al., 2012, 2016). In contrast to other marine ecosystems, where organic carbon originates from planktonic and riverine sources, coastal erosion represents a significant source of terrestrial-organic carbon to the East Siberian Arctic Shelf. The dual carbon isotope ($\delta^{13}C$ and ^{14}C) composition of organic carbon establishes that old permafrost-released erosional carbon dominates the burial of organic carbon on the East Siberian Arctic Shelf, and that 57 ± 2% of this terrestrial-organic carbon is from permafrost-originated ice complexes of Pleistocene age (Vonk et al., 2012). This translocated terrestrial-organic carbon represents a source of ocean acidification different from that of the generally considered atmospheric CO_2 uptake. Multi-year results show that the acidifying effect of terrestrial-organic carbon decomposition at the erosion-dominated site was more than five times stronger than that of estuary freshening (531% versus 100.5%). Persistent and potentially increasing aragonite undersaturation of East Siberian Arctic Shelf water has already far exceeded projected levels for year 2100, which are based only on atmospheric CO_2 uptake (Semiletov et al., 2016). These observation-based results also exceed the modelled saturation declines highlighted in the regional model evaluation for the period 1969–2015 by Mortenson et al. (2020).

Because aragonite undersaturation is characteristic of the entire East Siberian Arctic Shelf bottom water, it is possible that the observed suppression of the benthic calcifying community might be pervasive throughout the entire area, which alone comprises >25% of the Arctic Ocean open water. A recent study showed that the observed export of corrosive shelf waters to the deep ocean can have a potential impact on the ocean water ecosystem in the case of mixing with layers inhabited by calcifying organisms (Pipko et al., 2023). As these waters are exported to the surface of the central Arctic Ocean by the Transpolar Drift as well as into the Beaufort Gyre, the consequences of ocean acidification, triggered by climate change-driven mechanisms, might affect Arctic marine ecosystems over extensive scales. The Pipko et al. (2023) study also calls into question the capacity of the Arctic Ocean to serve as a sink for a growing amount of anthropogenic CO_2.

7.4 Projections of ocean acidification

With increasing warming and rising atmospheric CO_2 concentrations, the aragonite and calcite saturation state of the Arctic Ocean is rapidly declining. Projected changes from the current states for temperature, Ω_{ar}, Ω_{ca} and sea ice in the Arctic are shown in Figure 7.4. The graphic shows an overview of the climatological multi-model mean of ten Earth System Models (ESMs) for 1981–2000 and projected changes by 2081–2100 for SSP2-4.5 and SSP5-8.5. Projection robustness, represented as the magnitude of the mean anomaly exceeding the intermodel standard deviation (Kwiatkowski et al., 2020), suggests robustness across the Arctic for sea-ice concentration and Ω. For temperature, robustness is given across most of the Arctic except for parts of the central Arctic Ocean and the northern North Atlantic. The patterns of change as well as robustness patterns are very similar for the two scenarios, but show less change for SSP2-4.5. Larger temperature changes are evident by the end of the century, once winter sea ice is also disappearing in the Bering, Barents and Kara seas. For regions with the most advanced acidification, Ω_{ar} undersaturation will be reached in both scenarios (SSP5-8.5, SSP2-4.5) before 2080. Some regions (e.g., the East Siberian and Beaufort seas) already

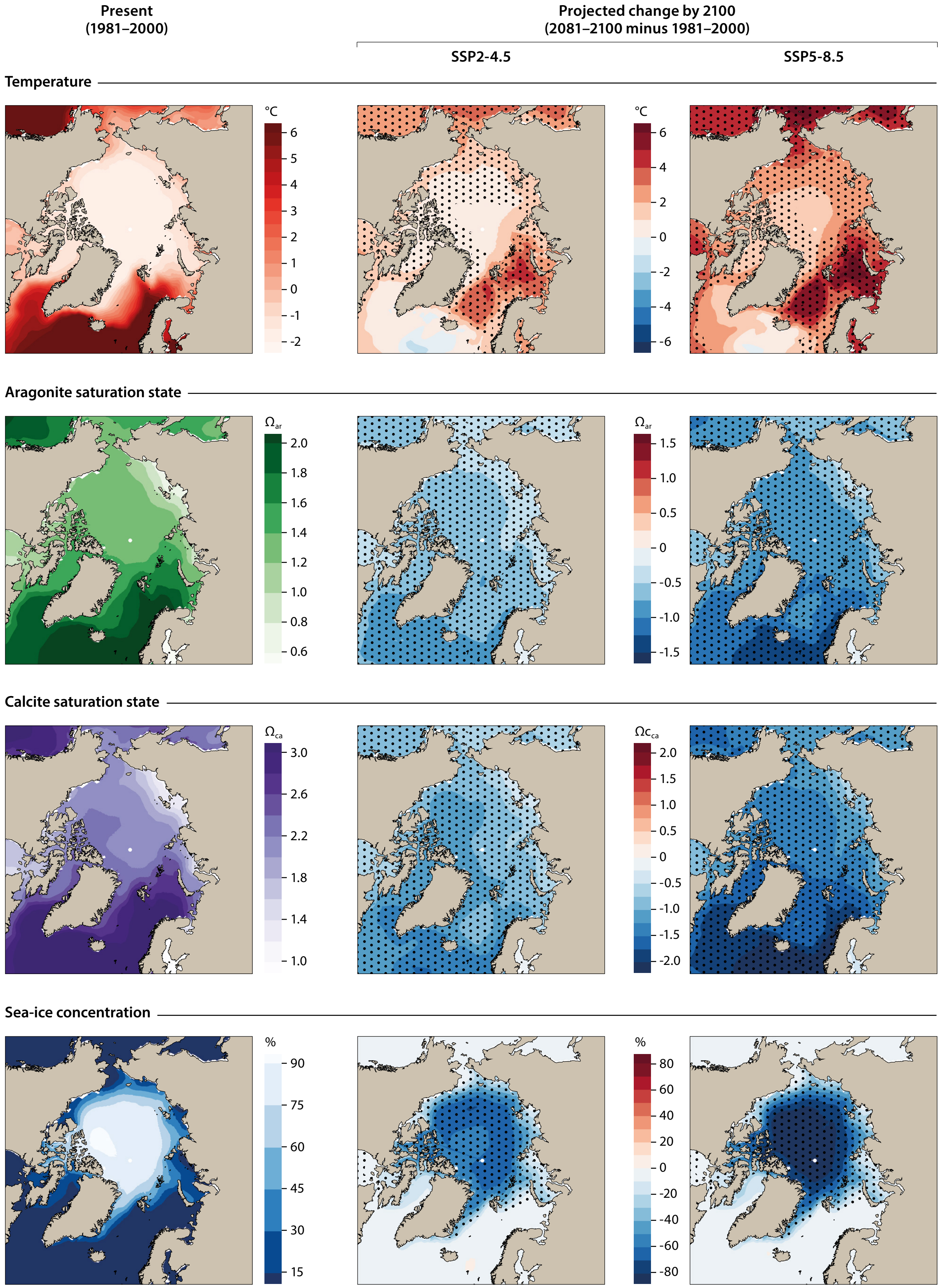


Figure 7.4 Multi-model mean pan-Arctic view of the average for 1981-2000 and the projected change by the end of the century for SSP2-4.5 and SSP5-8.5, for temperature (0–50 m), saturation state for aragonite (0–50 m), saturation state for calcite (0–50 m), and sea-ice concentration. Model estimates are calculated from total dissolved inorganic carbon, total alkalinity, temperature and salinity from Earth System Model simulations and are the mean of ten models (ACCESS-ESM1-5, CanESM5-CanOE, CESM2-WACCM, CNRM-ESM2-1, GFDL-ESM4, MIROC-ES2L, MPI-ESM1-2-HR, MRI-ESM2-0, NorESM2-MM, UKESM1-0-LL). Stippling designates areas of projection robustness represented as the magnitude of the mean anomaly exceeding the inter-model standard deviation (Kwiatkowski et al., 2020). Modified from Steiner and Reader (2024).

reached Ω_{ar} undersaturation in historical times, consistent with observations (Semiletov et al., 2016; Niemi et al., 2021) and regional model results (Mortenson et al., 2020). For other regions the models suggest that lower emissions can still avoid aragonite undersaturation. The regions which are already close to aragonite undersaturation show the smallest change in the future, indicating limitations in uptake capacity, while the largest changes are on the Atlantic side, particularly the Norwegian Sea. Uptake capacity may also be different among models as it depends on solubility and stratification (mixed-layer depth), which vary among regions and models (e.g., Steiner et al., 2014).

In 2021, the IPCC reported an accelerated pace in Arctic Ocean acidification in addition to the 2–3 times accelerated ocean surface temperature increase in the Arctic (Canadell et al., 2021). Kwiatkowski et al. (2020) compared marine ecosystem stressors in the Coupled Model Intercomparison Project (CMIP5 and CMIP6) for the global ocean and found greater surface acidification in CMIP6 models, which they linked to the Shared Socioeconomic Pathways (SSPs) having higher associated atmospheric CO_2 concentrations than their Representative Concentration Pathway (RCP) analogues for the same radiative forcing. They also found lower inter-model uncertainty. The greatest projected pH declines they indicated were in the Arctic Ocean, which reflects impacts from surface ocean warming and loss of sea ice. The latter provides increased surface areas for air-sea gas exchange and simultaneously enhances air-sea CO_2 fluxes by dilution of total dissolved inorganic carbon concentrations with freshwater. Kwiatkowski et al. (2020) highlighted the Arctic Ocean as sensitive to compound warming, acidification, and nutrient stress for both near-surface and bottom waters, threatening pelagic and benthic ecosystems. They found the magnitude of projected changes in bottom waters to be less than in surface and upper-ocean waters, while bottom water uncertainties for any given scenario were larger. They found this contrast to be particularly evident for pH projections with the SSPs. They linked this relative increase in inter-model uncertainty to the surface ocean chemistry being in equilibrium with the same atmospheric CO_2 concentrations for all models. On the other hand, benthic pH changes are strongly influenced by ocean circulation, which is variably impacted by climate change across models (Kwiatkowski et al., 2020, and references therein).

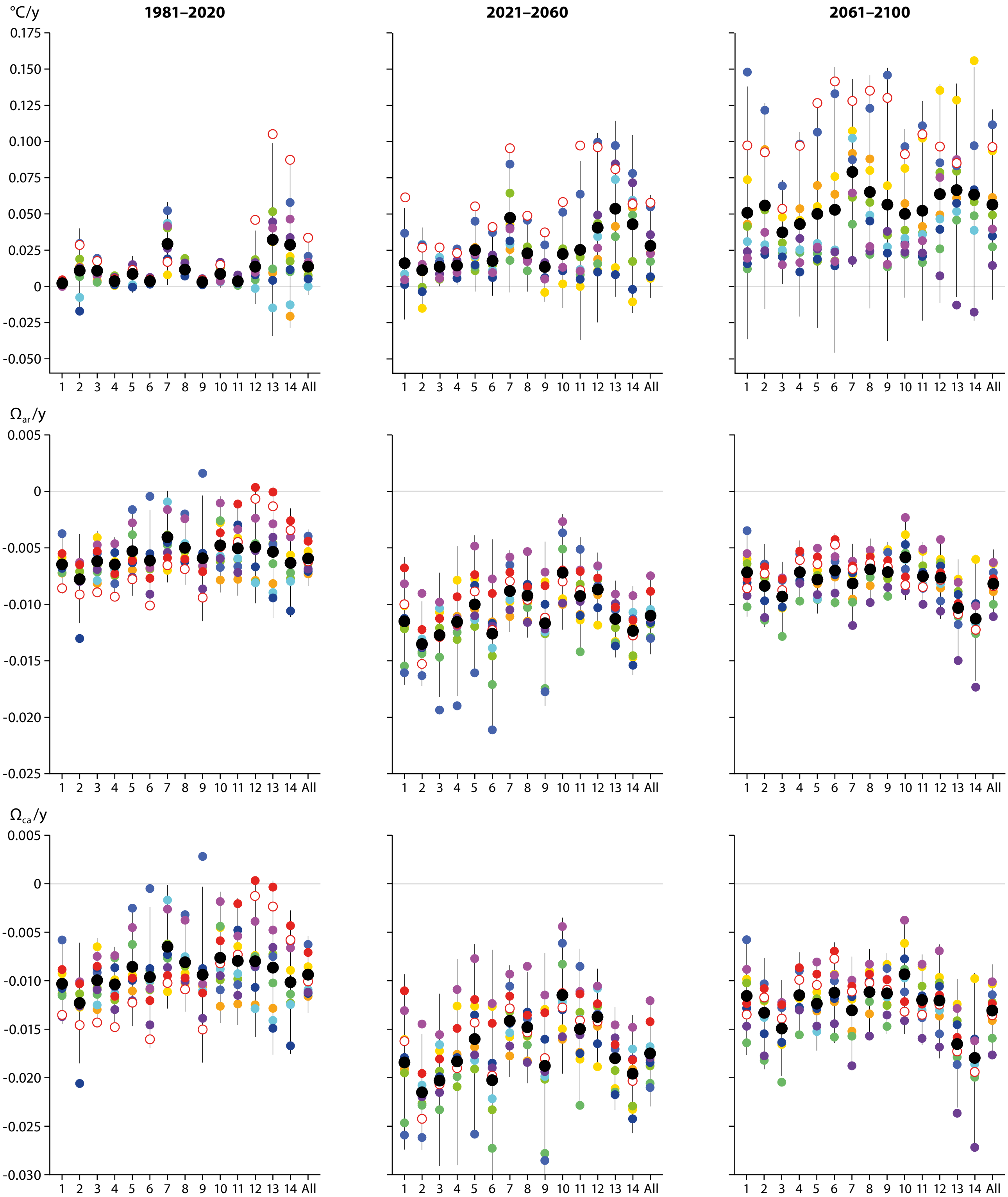
Henson et al. (2017) studied time of emergence (ToE, defined as the year when annual extremes persistently exceed the long-term trend for the remainder of the time series) for marine ecosystem stressors and found that climate change-driven trends of multiple ecosystem drivers emerge from the background of natural variability in 55% of the global ocean within the next 10 to 15 years and in 86% of the ocean by 2050 under a high-emission scenario. However, they pointed out that in the Arctic, ToE has already occurred for sea-surface temperature and pH. Terhaar et al. (2021) investigated Arctic Ocean acidification output from CMIP5 and CMIP6 and found good agreement with respect to projections of the 21st century for the CMIP6 model ensemble as well as reduced model uncertainties (~50%) compared to CMIP5. Terhaar et al. (2021) used ocean density to constrain CMIP6 model projections of ocean acidification, which allowed to further reduce the projected range in Ω. They indicated that, on average, the upper 1000 m of the Arctic Ocean will be undersaturated with respect to aragonite by 2100 for all emission pathways. Steiner and Reader (2024) evaluated ocean acidification and other marine ecosystem stressors in 11 ESMs (CMIP6) and found clear differences among Arctic sub-regions, both in historical times and in future projections. In all regions, model differences in Ω decreased over time. In contrast, temperature and oxygen showed an increase in differences among models over time. This may indicate enhanced model consistency with increased open water for Ω, but may also be driven by the nonlinear dependence of Ω on temperature, salinity, dissolved inorganic carbon, and total alkalinity with reduced sensitivities to input parameters for lower saturation states (Steiner and Reader, 2024). In comparison, for temperature a different pace in sea-ice retreat and other circulation mechanisms drive large differences among models. Higher inter-model uncertainty for sea-surface temperatures was also shown by Kwiatkowski et al. (2020), which they attributed to differences in climate sensitivity (warming response for increased CO_2) among models.

Dividing the time series from 1980 to 2100 into three equal 40-year chunks allows good approximation with linear trend approximations (Figure 7.5). Steiner and Reader (2024) showed that while temperature exhibited the most rapid 40-year rate of change for the end-of-century period (2061–2100), $CaCO_3$ saturation states showed highest 40-year changes for the mid-century period (2021–2060) (Table 7.1). This reflects the opposing impacts on $CaCO_3$ saturation states of increased carbon uptake (decreases saturation states) and increasing temperatures (increases saturation states).

A comparison between the SSP2-4.5 and SSP5-8.5 scenarios shows initially consistent ocean acidification, with faster acidification progression beyond 2040 for SSP5-8.5. For SSP5-8.5 all CMIP6 models project all Arctic regions to reach aragonite undersaturation by 2080, and calcite undersaturation for all but two regions (Barents Sea, Nordic Seas) by 2100 (Steiner and Reader, 2024). The study indicates that despite

Table 7.1 Overall Arctic multi-model mean trends (historical and SSP5-8.5) for pH, saturation state of aragonite (Ω_{ar}), saturation state of calcite (Ω_{ca}), and temperature in the upper 50 m. Source: Steiner and Reader (2024).

Period	Mean annual trend			
	pH	Ω_{ar}	Ω_{ca}	T, °C
1981–2020	-0.0021±0.0007	-0.0058±0.0025	-0.0093±0.004	0.014±0.019
2021–2060	-0.0054±0.0013	-0.0109±0.0034	-0.0175±0.054	0.028±0.035
2061–2100	-0.0066±0.001	-0.0081±0.003	-0.013±0.0047	0.057±0.066



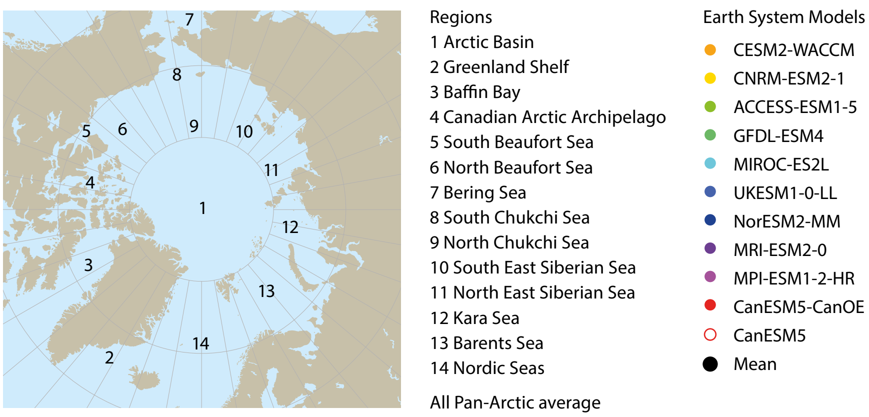


Figure 7.5 Simulated trends for temperature and saturation states for aragonite (Ω_{ar}) and calcite (Ω_{ca}) for 14 regions and the pan-Arctic average for 11 Earth System Models. Regions are indicated on the x-axis and shown in the map. For precise boundaries of subregions used in this analysis, see Steiner and Reader (2024). Trends for each model are indicated in color within each panel (see key). Note: CanESM5 is excluded from the mean trend, indicated in black, to avoid over-emphasizing the same physical model. Trends are provided for three periods: 1981–2020, 2021–2060, 2061–2100. Modified from Steiner and Reader (2024).

initial biases the models converge over time, indicating reduced uncertainty, a feature which may be less obvious if only the change from a common past state is compared among the models. Reduced model uncertainty over time is consistent with CMIP5 evaluations. Frölicher et al. (2016) highlighted that the uncertainty in pH projections is dominated by scenario uncertainty for the mid- and late 21st century, in contrast to temperature, oxygen and primary production, where model uncertainty as well as internal variability play a dominant role throughout the 21st century.

While the model projections show pronounced increases in the seasonal amplitudes of upper ocean temperatures, particularly in the Arctic where retreating summer sea ice is a key driver of seasonality, the seasonal amplitude of carbon system variables is less affected (Kwiatkowski et al., 2020; Steiner and Reader, 2024). Kwiatkowski et al. (2020) found the projected seasonal amplitude of the global surface ocean pH to decrease but indicated that declines in the seasonal amplitude of pH are typically only robust in the low- and mid-latitudes, with inconsistencies in pH seasonal amplitude projections in the Arctic. Steiner and Reader (2024) found that Ω and pH values show little change in their seasonal amplitude, but indications of shifts in the timing of seasonal extremes. Orr et al. (2022) also highlighted seasonal shifts in pCO_2. Their CMIP6 multi-model analysis showed a winter high and summer low for the historical run (consistent with observations) and a projected transition of the summer low into a high across much of the Arctic Ocean under mid-to-high CO_2 emissions scenarios. Seasonal shifts in the carbon system have also been pointed out in earlier studies. Steiner et al. (2013) showed that retreating sea ice in future projections alters the seasonal CO_2-flux cycle by extending the maximum uptake in autumn and reducing the uptake in summer.

Mortenson et al. (2020) pointed out that the seasonal cycle of the carbon system variables in the upper ocean is strongly impacted by the sea-ice carbon pump (the release of carbon out of the ice as it forms and the dilution of near-surface seawater as ice melts), which is not represented in any of the CMIP5 or CMIP6 models. Mortenson et al. (2020) found that excluding the sea-ice carbon pump results in a decrease in seasonal variability of sea-surface total dissolved inorganic carbon and total alkalinity and an overestimation of the annual maximum simulated Ω_{ar}. This leads to an underestimation of the stress aragonite-forming organisms may experience in polar oceans. How the inclusion of this pump may affect the suggested shift in the seasonal cycle of $CaCO_3$ saturation states in ESMs has not yet been evaluated.

Emission reductions can drastically slow the pace at which multiple drivers emerge or critical thresholds will be crossed, and even for bottom waters, intense mitigation strategies can limit ecosystem exposure to potential warming and acidification stress during the 21st century (e.g., Henson et al., 2017; Kwiatkowski et al., 2020; Orr et al., 2022; Steiner and Reader, 2024). In terms of socio-economic impacts and questions of responsibility, Licker et al. (2019) characterized the biological and socio-economic systems in regions facing loss and damage from ocean acidification in the context of climate change and other stressors. They found that more than half of the global surface ocean acidification is attributable to the CO_2 emissions traced to the extraction, refining and combustion of fossil fuels and manufacturing of cement from the 88 largest carbon producers. However, how such responsibility attribution will translate into mitigation or adaptation supporting action is unclear.

Steiner and Reader (2024) assessed ocean acidification in 11 CMIP6 ESMs for 14 subregions (see map in Figure 7.5) in the Arctic. The multi-model mean initial state differs for the various regions and differences among regions are largely retained over time. This is much more pronounced for the top 50 m than at depth. Ω and pH values in the top 50 m are lowest in the East Siberian and Laptev seas, which show advanced ocean acidification. This has also been highlighted by Mortenson et al. (2020), evaluating a regional model for the period 1969–2015. The CMIP6 multi-model mean (0–50 m) shows Ω_{ar} undersaturation in the southern East Siberian Sea before 2020 and Ω_{ca} undersaturation before 2070, and all regions are projected to be undersaturated with respect to Ω_{ar} by 2080.

Steiner and Reader (2024) found limited regional variability in the rate of change in Ω over time for the historical period. Simulated 0–50 m changes (1981–2020) in Ω are lowest in the Bering Sea, highest on the Greenland Shelf, and are generally higher in the western Arctic than the eastern Arctic. Changes in the 50–200 m layer are slightly lower (~15% less) and those in the 200–500 m layer about 40–50% less. Rates of change in Ω_{ca} are generally higher (almost double) than those for Ω_{ar} (Figure 7.5). For CMIP6, Ω shows the largest rate of change in all regions for mid-century and consistent values for all depth layers. The model results show a decrease in the rate of change for the late-century period in the upper ocean, along with a decrease in model range. By contrast, model results show a further increase in the magnitude of the negative trend in pH for the late-century period (not shown). By late century, consistent rates of change are simulated for all three depth layers, indicating a deepening of the acidification signal, which agrees with previous CMIP5 analyses (Steiner et al., 2014).

Fransner et al. (2022) used in-situ observations, gridded climatological data, and model projections for three different future scenarios with the Norwegian Earth System Model (NorESM1-ME) to investigate changes in pH and Ω_{ar} in the Nordic Seas. They found that from the pre-industrial era (1850–1860) to the present day (1996–2005) the pH of surface water in the region dropped by 0.1 pH units with a slight shallowing of the Ω_{ar} horizon. During 1981–2019, when regular sampling of carbonate system variables was made, the pH of the Nordic Seas upper layer decreased by 0.11 pH units. Beyond 2019, an additional reduction of 0.1–0.4 pH units is projected by the end of the 21st century, depending on the emissions scenario being simulated (Figure 7.3). In the high emissions scenario, esmRCP8.5, the Ω_{ar} horizon shoals enough that all cold-water coral reefs in the Nordic Seas region will be exposed to corrosive waters (Ω_{ar} <1) by the end of the 21st century. The acidification in all periods was mainly driven by increasing levels of total dissolved inorganic carbon in response to the rising C_{ant} concentrations (Pérez et al., 2021). This agrees with previous studies of the region (Skogen et al., 2014; Skjelvan et al., 2022), but with increased certainty due to greater availability of observational data and with some regional differences being highlighted.

7.5 Conclusions

It is evident that research efforts to characterize further the response of Arctic species to ocean acidification must be revitalized and targeted to specific research needs in order to preserve Arctic biodiversity and ecosystem function, as well as stocks of culturally and commercially important species. Examples of studies involving Arctic and subarctic populations do exist (e.g., Long et al., 2013; Calosi et al., 2017; Thor et al., 2018), but efforts should also prioritize the co-production of knowledge and partnering of Western science with Indigenous Knowledge. Achieving this would enable all to benefit from a multifaceted critical understanding of the fast-changing Arctic marine ecosystems and would provide additional information to Indigenous Peoples, and other Arctic inhabitants, to make adaptation decisions (e.g., proactive choices to counter changes imposed by the environmental forcing) (Ford et al., 2021; Huntington et al., 2022; ICC, 2022; Yua et al., 2022). A good example is the Central Arctic Ocean Fisheries Agreement (Schatz et al., 2019), which supports the science to better understand the impact of commercial fisheries on climate change and Arctic ecosystems affected by ocean acidification.

Long-term time-series monitoring of the seawater carbonate system is crucial for establishing and understanding the trends and drivers of ocean acidification. Indigenous-led community-based monitoring is a viable option for furthering such research, in line with Indigenous community-identified priorities and Indigenous-driven programs (Fox et al., 2020; Eicken et al., 2021; Hauser et al., 2021, 2023). When research questions are co-developed and relevant to Indigenous Peoples, Indigenous priorities can be adequately reflected in the process. Research and monitoring activities should also focus on growing the capacity of Indigenous Peoples, and other Arctic inhabitants, (e.g., through training and funding for community-based monitoring programs). Ways to include 'Western' science approaches and Indigenous Knowledge should be developed and improved, as should communications to better reflect the contributions Indigenous Knowledge and observing can make to ongoing research. This also includes the need to communicate to various audiences the constraints and assumptions associated with the applications of science and Indigenous Knowledge in providing answers, estimates, and projections of anticipated changes (e.g., Yua et al., 2022; Gryba et al., 2025). Specific to the monitoring of ocean acidification, improved methods and sensor development are required to limit the use of toxic substances in the relevant sampling methods (Buschman and Hauri, 2022).

Global projections representing Arctic ocean acidification have improved and are more constrained than the respective temperature projections. Nonetheless, large model differences in the rate of sea-ice retreat, a key factor that affects many biogeochemical cycles, impacts consensus. As such, ocean acidification projections would benefit from improvements in the ability of models to project sea-ice decline.

The Arctic Ocean, particularly its coastal seas, is characterized by complex coastlines, archipelagos, terrestrial runoff, and shallow shelves. These characteristics are not adequately represented in ESMs. Coastal regions are often linked to highly productive ecosystems, often related to sea ice, and support coastal fisheries and Indigenous subsistence harvesting activities (e.g., Fox et al., 2020; Gryba et al., 2021; Hauser et al., 2021, 2023; Steiner et al., 2021; Huntington et al., 2022). Adequately representing the progress of ocean acidification in these regions, together with the simultaneous occurrence of coastal acidification events, requires better climate model downscaling from regional scales (country/national) to local scales (harvesting around individual communities). Downscaling efforts are hampered by the limited availability of observation data in coastal regions and can be improved through collaborative research and knowledge co-production between Indigenous Peoples and scientists, and through Indigenous-led community-based monitoring.

The seasonal cycle of the carbonate system in the upper ocean is strongly affected by the sea-ice carbon pump, which is not represented in CMIP6 models. Excluding this pump results in a decrease in the seasonal variability of total dissolved inorganic carbon and total alkalinity in surface waters and an overestimation of the annual maximum simulated $CaCO_3$ saturation state. This leads the CMIP6 models to underestimate the stress aragonite-forming organisms may experience in polar oceans.

River discharge, ice melt, and anthropogenic pollution all contribute to ocean acidification (Steinacher et al., 2009; Yamamoto-Kawai et al., 2009). However, most models do not include key natural Arctic system processes, such as the degradation of terrestrial organic carbon translocated from thawed permafrost to the shelf, possibly amplified by regional warming. These processes may serve as coupled mechanisms to further exacerbate ocean acidification in the Arctic.

Ocean acidification and its cumulative impacts are likely to lead to loss and damage of natural resources within the biogeochemical system, further exacerbating the necessary adaptation and mitigation Indigenous communities will need to undertake in order to continue to thrive in the rapidly changing Arctic. Research priorities on ocean acidification should support understanding, adaptation, and mitigation efforts, including support at the science-policy interface and the mechanisms by which loss and damage are assessed and compensated. In line with Indigenous rights to self-determination and self-governance, Indigenous Peoples should have access to both research and policy spaces and they, in turn, need to recognize the importance of seeking Indigenous authority and guidance on matters occurring in, or related to, Indigenous homelands.

References

Ahmed, M. and B.G.T. Else, 2019. The ocean CO_2 sink in the Canadian Arctic Archipelago: a present-day budget and past trends due to climate change. Geophysical Research Letters, 46:9777-9785. doi:10.1029/2019GL083547

Algayer, T., A. Mahmoud, S. Saksena, W.C. Long, K.M. Swiney, R.J. Foy, B.V. Steffel, K.E. Smith, R.B. Aronson and G.H. Dickinson, 2023. Adult snow crab, *Chionoecetes opilio*, display body-wide exoskeletal resistance to the effects of long-term ocean acidification. Marine Biology, 170:63. doi:10.1007/s00227-023-04209-0

Alton Mackey, M.G. and R.D. Orr, 1987. An evaluation of household country food use in Makkovik, Labrador, July 1980-June 1981. Arctic, 40:60-65. www.jstor.org/stable/40510565

AMAP, 2017. Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2017. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway.

AMAP, 2018. AMAP Assessment 2018: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

Andersen, S., E.S. Grefsrud and T. Harboe, 2013. Effect of increased pCO_2 level on early shell development in great scallop (*Pecten maximus* Lamarck) larvae. Biogeosciences, 10:6161-6184. doi:10.5194/bg-10-6161-2013

Andersen, S., E.S. Grefsrud and T. Harboe, 2017. Sensitivity towards elevated pCO_2 in great scallop (*Pecten maximus* Lamarck) embryos and fed larvae. Biogeosciences, 14:529-539. doi:10.5194/bg-14-529-2017

Anderson, L.G. and A. Olsen, 2002. Air–sea flux of anthropogenic carbon dioxide in the North Atlantic. Geophysical Research Letters, 29:16-1-16-4. doi:10.1029/2002GL014820

Anderson, L.G., S. Jutterström, S. Hjalmarsson, I. Wåhlström and I.P. Semiletov, 2009. Out-gassing of CO_2 from Siberian Shelf seas by terrestrial organic matter decomposition. Geophysical Research Letters, 36:L20601. doi:10.1029/2009GL040046

Anderson, L.G., G. Björk, S. Jutterström, I.I. Pipko, N. Shakhova, I.P. Semiletov and I. Wåhlström, 2011. East Siberian Sea, an Arctic region of very high biogeochemical activity. Biogeosciences, 8:1745-1754. doi:10.5194/bg-8-1745-2011

Anglada-Ortiz, G., K. Zamelczyk, J. Meilland, P. Ziveri, M. Chierici, A. Fransson and T.L. Rasmussen, 2021. Planktic foraminiferal and pteropod contributions to carbon dynamics in the Arctic Ocean (North Svalbard Margin). Frontiers in Marine Science, 8:661158. doi:10.3389/fmars.2021.661158

Anglada-Ortiz, G., J. Meilland, P. Ziveri, M. Chierici, A. Fransson, E. Jones and T.L. Rasmussen, 2023. Seasonality of marine calcifiers in the northern Barents Sea: Spatiotemporal distribution of planktonic foraminifers and shelled pteropods and their contribution to carbon dynamics. Progress in Oceanography, 218:103121. doi:10.1016/j.pocean.2023.103121

Armstrong, J.L., J.L. Boldt, A.D. Cross, J.H. Moss, N.D. Davis, K.W. Myers, R.V. Walker, D.A. Beauchamp and L.J. Haldorson, 2005. Distribution, size, and interannual, seasonal and diel food habits of northern Gulf of Alaska juvenile pink salmon, *Oncorhynchus gorbuscha*. Deep Sea Research II, 52:247-265. doi:10.1016/j.dsr2.2004.09.019

Arnberg, M., P. Calosi, J.I. Spicer, A.H.S. Tandberg, M. Nilsen, S. Westerlund and R.K. Bechmann, 2013. Elevated temperature elicits greater effects than decreased pH on the development, feeding and metabolism of northern shrimp (*Pandalus borealis*) larvae. Marine Biology, 160:2037-2048. doi:10.1007/S00227-012-2072-9

Auburn, M.E. and S.E. Ignell, 2000. Food habits of juvenile salmon in the Gulf of Alaska July-August 1996. North Pacific Anadromous Fish Commission, 2:89-97.

Beauchamp, D.A., A.D. Cross, J.L. Armstrong, K.W. Myers, J.H. Moss, J.L. Boldt and L.J. Haldorson, 2007. Bioenergetic responses by Pacific salmon to climate change and ecosystem variation. North Pacific Anadromous Fish Commission, 4:257-269.

Bechmann, R.K., I.C. Taban, S. Westerlund, B.F. Godal, M. Arnberg, S. Vingen, A. Ingvarsdottir and T. Baussant, 2011. Effects of ocean acidification on early life stages of shrimp (*Pandalus borealis*) and mussel (*Mytilus edulis*). Journal of Toxicology and Environmental Health A, 74:424-438. doi:10.1080/15287394.2011.550460

Bednaršek, N., J. Možina, M. Vogt, C. O'Brien and G.A. Tarling, 2012a. The global distribution of pteropods and their contribution to carbonate and carbon biomass in the modern ocean. Earth System Science Data, 4:167-186. doi:10.5194/essd-4-167-2012

Bednaršek, N., G.A. Tarling, D.C.E. Bakker, S. Fielding, E.M. Jones, H.J. Venables, P. Ward, A. Kuzirian, B. Lézé, R.A. Feely and E.J. Murphy, 2012b. Extensive dissolution of live pteropods in the Southern Ocean. Nature Geoscience, 5:881-885. doi:10.1038/ngeo1635

Bednaršek, N., R.A. Feely, J.C.P. Reum, B. Peterson, J. Menkel, S.R. Alin and B. Hales, 2014a. *Limacina helicina* shell dissolution as an indicator of declining habitat suitability owing to ocean acidification in the California Current Ecosystem. Proceedings of the Royal Society B, 281:20140123. doi:10.1098/rspb.2014.0123

Bednaršek, N., G.A. Tarling, D.C.E. Bakker, S. Fielding and R.A. Feely, 2014b. Dissolution dominating calcification process in polar pteropods close to the point of aragonite undersaturation. PLoS ONE, 9:e109183. doi:10.1371/journal.pone.0109183

Bednaršek, N., R.A. Feely, N. Tolimieri, A.J. Hermann, S.A. Siedlecki, G.G. Waldbusser, P. McElhany, S.R. Alin, T. Klinger, B. Moore-Maley and H.O. Pörtner, 2017a. Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. Scientific Reports, 7:4526. doi:10.1038/s41598-017-03934-z

Bednaršek, N., T. Klinger, C.J. Harvey, S. Weisberg, R.M. McCabe, R.A. Feely, J. Newton and N. Tolimieri, 2017b. New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. Ecological Indicators, 76:240-244. doi:10.1016/j.ecolind.2017.01.025

Bednaršek, N., R.A. Feely, E.L. Howes, B.P.V. Hunt, F. Kessouri, P. León, S. Lischka, A.E. Maas, K. McLaughlin, N.P. Nezlin, M. Sutula and S.B. Weisberg, 2019. Systematic review and meta-analysis toward synthesis of thresholds of ocean acidification impacts on calcifying pteropods and interactions with warming. Frontiers in Marine Science, 6:227. doi:10.3389/fmars.2019.00227

Bednaršek, N., R.A. Feely, M.W. Beck, S.R. Alin, S.A. Siedlecki, P. Calosi, E.L. Norton, C. Saenger, J. Štrus, D. Greeley, N.P. Nezlin, M. Roethler and J.I. Spicer, 2020. Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. Science of the Total Environment, 716:136610. doi:10.1016/J.SCITOTENV.2020.136610

Bednaršek, N., R. Ambrose, P. Calosi, R.K. Childers, R.A. Feely, S.Y. Litvin, W.C. Long, J.I. Spicer, J. Štrus, J. Taylor, F. Kessouri, M. Roethler, M. Sutula and S.B. Weisberg, 2021a. Synthesis of thresholds of ocean acidification impacts on decapods. Frontiers in Marine Science, 8:1542. doi:10.3389/fmars.2021.651102

Bednaršek, N., K.-A. Naish, R.A. Feely, C. Hauri, K. Kimoto, A.J. Hermann, C. Michel, A. Niemi and D. Pilcher, 2021b. Integrated assessment of ocean acidification risks to pteropods in the northern high latitudes: regional comparison of exposure, sensitivity and adaptive capacity. Frontiers in Marine Science, 8:1282. doi:10.3389/fmars.2021.671497

Bednaršek, N., B.R. Carter, R.M. McCabe, R.A. Feely, E. Howard, F.P. Chavez, M. Elliott, J.L. Fisher, J. Jahncke and Z. Siegrist, 2022. Pelagic calcifiers face increased mortality and habitat loss with warming and ocean acidification. Ecological Applications, 32:e2674. doi:10.1002/eap.2674

Bednaršek, N., R. Feely, G. Pelletier and F. Desmet, 2023. Global synthesis of the status and trends of ocean acidification impacts on shelled pteropods. Oceanography, 36:130-137. doi:10.5670/oceanog.2023.210

Bock, C., F.C. Wermter, B. Schalkhausser, M.E. Blicher, H.-O. Pörtner, G. Lannig and M.K. Sejr, 2019. *In vivo* ^{31}P-MRS of muscle bioenergetics in marine invertebrates: Future ocean limits scallops' performance. Magnetic Resonance Imaging, 61:239-246. doi:10.1016/j.mri.2019.06.003

Breton-Honeyman, K., H.P. Huntington, M. Basterfield, K. Campbell, J. Dicker, T. Gray, A.E.R. Jakobsen, F. Jean-Gagnon, D. Lee, R. Laing, L. Loseto, P. McCarney, J. Noksana Jr, T. Palliser, L. Ruben, C. Tartak, J. Townley and E. Zdor, 2021. Beluga whale stewardship and collaborative research practices among Indigenous peoples in the Arctic. Polar Research, 40:S1. doi:10.33265/polar.v40.5522

Buitenhuis, E.T., M. Vogt, R. Moriarty, N. Bednaršek, S.C. Doney, K. Leblanc, C. Le Quéré, Y.-W. Luo, C. O'Brien, T. O'Brien, J. Peloquin, R. Schiebel and C. Swan, 2013. MAREDAT: towards a world atlas of MARine Ecosystem DATa. Earth System Science Data, 5:227-239. doi:10.5194/essd-5-227-2013

Burgers, T.M., L.A. Miller, S. Rysgaard, J. Mortensen, B. Else, J.-É. Tremblay and T. Papakyriakou, 2023. Distinguishing physical and biological controls on the carbon dynamics in a High-Arctic outlet strait. Journal of Geophysical Research: Oceans, 128:e2022JC019393. doi:10.1029/2022JC019393

Buschman, V.Q. and C. Hauri, 2022. Seasonal peak in Arctic Ocean acidity could shift to the summer. Nature, 610:36-37. doi:10.1038/d41586-022-03076-x

Buschman, V.Q. and E. Sudlovenick, 2023. Indigenous-led conservation in the Arctic supports global conservation practices. Arctic Science, 9:714-719. doi:10.1139/as-2022-0025

Calosi, P., S.P.S. Rastrick, M. Graziano, S.C. Thomas, C. Baggini, H.A. Carter, J.M. Hall-Spencer, M. Milazzo and J.I. Spicer, 2013. Distribution of sea urchins living near shallow water CO_2 vents is dependent upon species acid–base and ion-regulatory abilities. Marine Pollution Bulletin, 73:470-484. doi:10.1016/j.marpolbul.2012.11.040

Calosi, P., S. Melatunan, L.M. Turner, Y. Artioli, R.L. Davidson, J.J. Byrne, M.R. Viant, S. Widdicombe and S.D. Rundle, 2017. Regional adaptation defines sensitivity to future ocean acidification. Nature Communications, 8:13994. doi:10.1038/ncomms13994

Calosi, P., H.M. Putnam, R.J. Twitchett and F. Vermandele, 2019. Marine metazoan modern mass extinction: improving predictions by integrating fossil, modern, and physiological data. Annual Review of Marine Science, 11:369-390. doi:10.1146/annurev-marine-010318-095106

Cameron, L.P., C.E. Reymond, F. Müller-Lundin, I. Westfield, J.H. Grabowski, H. Westphal and J.B. Ries, 2019. Effects of temperature and ocean acidification on the extrapallial fluid pH, calcification rate, and condition factor of the king scallop *Pecten maximus*. Journal of Shellfish Research, 38:763-777. doi:10.2983/035.038.0327

Canadell, J.G. and M.R. Raupach, 2009. Land Carbon Cycle Feedbacks. In: Sommerkorn, M. and S.J. Hassol (Eds.), Arctic Climate Feedbacks: Global Implications. pp. 70-80. Oslo, Norway.

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi: 10.1017/9781009157896.007.

Capelle, D.W., Z.Z.A. Kuzyk, T. Papakyriakou, C. Guéguen, L.A. Miller and R.W. Macdonald, 2020. Effect of terrestrial organic matter on ocean acidification and CO_2 flux in an Arctic shelf sea. Progress in Oceanography, 185:102319. doi:10.1016/j.pocean.2020.102319

Cardinale, M., F. Zimmermann, G. Søvik, C.A. Griffiths, M. Bergenius Nord and H. Winker, 2023. Spatially explicit stock assessment uncovers sequential depletion of northern shrimp stock components in the North Sea. ICES Journal of Marine Science, 80:1868-1880. doi:10.1093/icesjms/fsad111

Carothers, C., J. Black, S.J. Langdon, R. Donkersloot, D. Ringer, J. Coleman, E.R. Gavenus, W. Justin, M. Williams, F. Christiansen, J. Samuelson, C. Stevens, B. Woods, S.J. Clark, P.M. Clay, L. Mack, J. Raymond-Yakoubian, A.A. Sanders, B.L. Stevens and A. Whiting, 2021. Indigenous peoples and salmon stewardship: a critical relationship. Ecology and Society, 26:16. doi:10.5751/ES-11972-260116

Chemel, M., F. Noisette, D. Chabot, E. Guscelli, L. Leclerc and P. Calosi, 2020. Good news – bad news: combined ocean change drivers decrease survival but have no negative impact on nutritional value and organoleptic quality of the northern shrimp. Frontiers in Marine Science, 7:611. doi:10.3389/fmars.2020.00611

Chierici, M., M. Vernet, A. Fransson and K.Y. Børsheim, 2019. Net community production and carbon exchange from winter to summer in the Atlantic Water inflow to the Arctic Ocean. Frontiers in Marine Science, 6:528. doi:10.3389/fmars.2019.00528

Christen, N., P. Calosi, C.L. McNeill and S. Widdicombe, 2013. Structural and functional vulnerability to elevated pCO_2 in marine benthic communities. Marine Biology, 160:2113-2128. doi:10.1007/s00227-012-2097-0

Coffey, W.D., J.A. Nardone, A. Yarram, W.C. Long, K.M. Swiney, R.J. Foy and G.H. Dickinson, 2017. Ocean acidification leads to altered micromechanical properties of the mineralized cuticle in juvenile red and blue king crabs. Journal of Experimental Marine Biology and Ecology, 495:1-12. doi:10.1016/j.jembe.2017.05.011

Coll-Lladó, C., F. Mittermayer, P.B. Webb, N. Allison, C. Clemmesen, M. Stiasny, C.R. Bridges, G. Göttler and D. Garcia de la serrana, 2021. Pilot study to investigate the effect of long-term exposure to high pCO_2 on adult cod (*Gadus morhua*) otolith morphology and calcium carbonate deposition. Fish Physiology and Biochemistry, 47:1879-1891. doi:10.1007/s10695-021-01016-6

Comeau, S., G. Gorsky, R. Jeffree, J.-L. Teyssié and J.-P. Gattuso, 2009. Impact of ocean acidification on a key Arctic pelagic mollusc (*Limacina helicina*). Biogeosciences, 6:1877-1882. doi:10.5194/bg-6-1877-2009

Dahlke, F., M. Lucassen, U. Bickmeyer, S. Wohlrab, V. Puvanendran, A. Mortensen, M. Chierici, H.-O. Pörtner and D. Storch, 2020. Fish embryo vulnerability to combined acidification and warming coincides with low capacity for homeostatic regulation. Journal of Experimental Biology, 223:jeb212589. doi:10.1242/jeb.212589

Daly, E.A., J.H. Moss, E. Fergusson and C. Debenham, 2019. Feeding ecology of salmon in eastern and central Gulf of Alaska. Deep Sea Research II, 165:329-339. doi:10.1016/j.dsr2.2019.06.006

DeGrandpre, M., W. Evans, M. Timmermans, R. Krishfield, B. Williams and M. Steele, 2020. Changes in the Arctic Ocean carbon cycle with diminishing ice cover. Geophysical Research Letters, 47:e2020GL088051. doi:10.1029/2020GL088051

DFO, 2021. Assessment of northern shrimp (*Pandalus borealis*) and striped shrimp (*Pandalus montagui*) in the eastern and western assessment zones, February 2021. Department of Fisheries and Oceans (DFO). publications.gc.ca/pub?id=9.899014&sl=0 [accessed 11.2.23].

DFO, 2022. Assessment of northern shrimp stocks in the Estuary and Gulf of St. Lawrence in 2021. Department of Fisheries and Oceans (DFO). publications.gc.ca/pub?id=9.911012&sl=0 [accessed 11.2.23].

Dickinson, G.H., S. Bejerano, T. Salvador, C. Makdisi, S. Patel, W.C. Long, K.M. Swiney, R.J. Foy, B.V. Steffel, K.E. Smith and R.B. Aronson, 2021. Ocean acidification alters properties of the exoskeleton in adult Tanner crabs, *Chionoecetes bairdi*. Journal of Experimental Biology, 224:jeb232819. doi:10.1242/jeb.232819

Doubleday, A.J. and R.R. Hopcroft, 2015. Interannual patterns during spring and late summer of larvaceans and pteropods in the coastal Gulf of Alaska, and their relationship to pink salmon survival. Journal of Plankton Research, 37:134-150. doi:10.1093/plankt/fbu092

Dupont, S., J. Havenhand, W. Thorndyke, L. Peck and M. Thorndyke, 2008. Near-future level of CO_2-driven ocean acidification radically affects larval survival and development in the brittlestar *Ophiothrix fragilis*. Marine Ecology Progress Series, 373:285-294. doi:10.3354/meps07800

Dupont, S., E. Hall, P. Calosi and B. Lundve, 2014. First evidence of altered sensory quality in a shellfish exposed to decreased pH relevant to ocean acidification. Journal of Shellfish Research, 33:857-861. doi:10.2983/035.033.0320

Durant, A., E. Khodikian and C.S. Porteus, 2023. Ocean acidification alters foraging behaviour in Dungeness crab through impairment of the olfactory pathway. Global Change Biology, 29:4126-4139. doi:10.1111/GCB.16738

Eicken, H., F. Danielsen, J.-M. Sam, M. Fidel, N. Johnson, M.K. Poulsen, O.A. Lee, K.V. Spellman, L. Iversen, P. Pulsifer and M. Enghoff, 2021. Connecting top-down and bottom-up approaches in environmental observing. Bioscience, 71:467-483. doi:10.1093/biosci/biab018

Ericson, Y., E. Falck, M. Chierici, A. Fransson and S. Kristiansen, 2019. Marine CO_2 system variability in a high arctic tidewater-glacier fjord system, Tempelfjorden, Svalbard. Continental Shelf Research, 181:1-13. doi:10.1016/j.csr.2019.04.013

Ericson, Y., A. Fransson, M. Chierici, E.M. Jones, I. Skjelvan, A. Omar, A. Olsen and M. Becker, 2023. Rapid fCO_2 rise in the northern Barents Sea and Nansen Basin. Progress in Oceanography, 217:103079. doi:10.1016/j.pocean.2023.103079

Evans, W., J.T. Mathis and J.N. Cross, 2014. Calcium carbonate corrosivity in an Alaskan inland sea. Biogeosciences, 11:365-379. doi:10.5194/bg-11-365-2014

Feely, R.A., S.R. Alin, B. Carter, N. Bednaršek, B. Hales, F. Chan, T.M. Hill, B. Gaylord, E. Sanford, R.H. Byrne, C.L. Sabine, D. Greeley and L. Juranek, 2016. Chemical and biological impacts of ocean acidification along the west coast of North America. Estuarine, Coastal and Shelf Science, 183:260-270. doi:10.1016/j.ecss.2016.08.043

Feely, R.A., R.R. Okazaki, W.-J. Cai, N. Bednaršek, S.R. Alin, R.H. Byrne and A. Fassbender, 2018. The combined effects of acidification and hypoxia on pH and aragonite saturation in the coastal waters of the California current ecosystem and the northern Gulf of Mexico. Continental Shelf Research, 152:50-60. doi:10.1016/j.csr.2017.11.002

Fitzer, S.C., V.B.S. Chan, Y. Meng, K.C. Rajan, M. Suzuki, C. Not, T. Toyofuku, L. Falkenberg, M. Byrne, B.P. Harvey, P. de Wit, M. Cusack, K.S. Gao, P. Taylor, S. Dupont, J.M. Hall-Spencer and V. Thiyagarajan, 2019. Established and emerging techniques for characterising the formation, structure and performance of calcified structures under ocean acidification. In: Oceanography and Marine Biology. CRC Press, pp. 89-125. doi:10.1201/9780429026379-2

Ford, J.D., T. Pearce, I.V. Canosa and S. Harper, 2021. The rapidly changing Arctic and its societal implications. WIREs Climate Change, 12:e735. doi:10.1002/wcc.735

Fox, S., E. Qillaq, I. Angutikjuak, D.J. Tigullaraq, R. Kautuk, H. Huntington, G.E. Liston and K. Elder, 2020. Connecting understandings of weather and climate: steps towards co-production of knowledge and collaborative environmental management in Inuit Nunangat. Arctic Science, 6:267-278. doi:10.1139/as-2019-0010

Fransner, F., F. Fröb, J. Tjiputra, N. Goris, S.K. Lauvset, I. Skjelvan, E. Jeansson, A. Omar, M. Chierici, E. Jones, A. Fransson, S.R. Ólafsdóttir, T. Johannessen and A. Olsen, 2022. Acidification of the Nordic Seas. Biogeosciences, 19:979-1012. doi:10.5194/bg-19-979-2022

Fransson, A., M. Chierici, D. Nomura, M.A. Granskog, S. Kristiansen, T. Martma and G. Nehrke, 2015. Effect of glacial drainage water on the CO_2 system and ocean acidification state in an Arctic tidewater-glacier fjord during two contrasting years. Journal of Geophysical Research: Oceans, 120:2413-2429. doi:10.1002/2014JC010320

Fransson, A., M. Chierici, H. Hop, H.S. Findlay, S. Kristiansen and A. Wold, 2016. Late winter-to-summer change in ocean acidification state in Kongsfjorden, with implications for calcifying organisms. Polar Biology, 39:1841-1857. doi:10.1007/s00300-016-1955-5

Fransson, A., M. Chierici, I. Skjelvan, A. Olsen, P. Assmy, A.K. Peterson, G. Spreen and B. Ward, 2017. Effects of sea-ice and biogeochemical processes and storms on under-ice water fCO_2 during the winter-spring transition in the high Arctic Ocean: Implications for sea-air CO_2 fluxes. Journal of Geophysical Research: Oceans, 122:5566-5587. doi:10.1002/2016JC012478

Fransson, A., M. Chierici, D. Nomura, M.A. Granskog, S. Kristiansen, T. Martma and G. Nehrke, 2020. Influence of glacial water and carbonate minerals on wintertime sea-ice biogeochemistry and the CO_2 system in an Arctic fjord in Svalbard. Annals of Glaciology, 61:320-340. doi:10.1017/AOG.2020.52

Fransson, A., M. Chierici, M.A. Granskog, P. Dodd and C.A. Stedmon, 2023. Impacts of glacial and sea-ice meltwater, primary production and ocean CO_2 uptake on ocean acidification state of waters by the 79 North Glacier and northeast Greenland shelf. Frontiers in Marine Science, 10:1155126. doi:10.3389/FMARS.2023.1155126

Frölicher, T.L., K.B. Rodgers, C.A. Stock and W.W.L. Cheung, 2016. Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. Global Biogeochemical Cycles, 30:1224-1243. doi:10.1002/2015GB005338

Garcia-Tigreros, F., M. Leonte, C.D. Ruppel, A. Ruiz-Angulo, D.J. Joung, B. Young and J.D. Kessler, 2021. Estimating the impact of seep methane oxidation on ocean pH and dissolved inorganic radiocarbon along the U.S. Mid-Atlantic Bight. Journal of Geophysical Research: Biogeosciences, 126:e2019JG005621. doi:10.1029/2019JG005621

Geoffroy, M., C. Bouchard, H. Flores, D. Robert, H. Gjøsaeter, C. Hoover, H. Hop, N.E. Hussey and 33 others, 2023. The circumpolar impacts of climate change and anthropogenic stressors on Arctic cod (*Boreogadus saida*) and its ecosystem. Elementa: Science of the Anthropocene, 11: 00097. doi:10.1525/elementa.2022.00097

Glenn, R., 2023. Insights from Coastal Arctic Indigenous Observers: Perspectives from community-based observers on the impacts of rapid and unprecedented Arctic environmental change. Alaska Arctic Observatory and Knowledge Hub, StoryMap. https://storymaps.arcgis.com/stories/30d30ab062ea4aadb39b3734dd7770ae

Götze, S., C. Bock, C. Eymann, G. Lannig, J.B.M. Steffen and H.-O. Pörtner, 2020. Single and combined effects of the "Deadly trio" hypoxia, hypercapnia and warming on the cellular metabolism of the great scallop *Pecten maximus*. Comparative Biochemistry and Physiology B, 243-244:110438. doi:10.1016/j.cbpb.2020.110438

Grandon, N., 2020. Effects of Ocean Acidification on Species Composition and Biodiversity in the Region of Kongsfjord (Svalbard). Thesis. Halmstad University, Sweden.

Gruber, N., P. Friedlingstein, C.B. Field, R. Valentini, M. Heimann, J.E. Richey, P.R. Lankao, E.-D. Schulze and C.-T.A Chen, 2004. The vulnerability of the carbon cycle in the 21st century: An assessment of carbon-climate-human interactions. In: Field, C.B. and M.R. Raupach (Eds.), The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World. Island Press, pp. 45-76.

Gryba, R., H.P. Huntington, A.L. Von Duyke, B. Adams, B. Frantz, J. Gatten, Q. Harcharek, H. Olemaun, R. Sarren, J. Skin, G. Henry and M. Auger-Méthé, 2021. Indigenous Knowledge of bearded seal (*Erignathus barbatus*), ringed seal (*Pusa hispida*), and spotted seal (*Phoca largha*) behaviour and habitat use near Utqiaġvik, Alaska, USA. Arctic Science, 7:832-858. doi:10.1139/as-2020-0052

Gryba, R., A. Von Duyke, H.P. Huntington, B. Adams, B. Frantz, J. Gatten, Q. Harcharek, R. Sarren, G. Henry and M. Auger-Méthé, 2025. Indigenous Knowledge as a sole data source in habitat selection functions. Proceedings of the National Academy of Sciences, U.S.A., 122:e2411946122. doi:10.1073/pnas.2411946122

Guscelli, E., D. Chabot, F. Vermandele, D. Madeira and P. Calosi, 2023a. All roads lead to Rome: inter-origin variation in metabolomics reprogramming of the northern shrimp exposed to global changes leads to a comparable physiological status. Frontiers in Marine Science, 10:1170451. doi:10.3389/FMARS.2023.1170451

Guscelli, E., F. Noisette, D. Chabot, P.U. Blier, T. Hansen, M. Cassista-Da Ros, P. Pepin, K.R. Skanes and P. Calosi, 2023b. Northern shrimp from multiple origins show similar sensitivity to global change drivers, but different cellular energetic capacity. Journal of Experimental Biology, 226:jeb245400. doi:10.1242/jeb.245400

Gustafsson, Ö., B.E. van Dongen, J.E. Vonk, O.V. Dudarev and I.P. Semiletov, 2011. Widespread release of old carbon across the Siberian Arctic echoed by its large rivers. Biogeosciences, 8:1737-1743. doi:10.5194/bg-8-1737-2011

Harney, E., S.P.S. Rastrick, S. Artigaud, J. Pisapia, B. Bernay, P. Miner, V. Pichereau, O. Strand, P. Boudry and G. Charrier, 2023. Impacts of ocean acidification and warming on post-larval growth and metabolism in two populations of the great scallop (*Pecten maximus*). Journal of Experimental Biology, 226:jeb245383. doi:10.1242/jeb.245383

Hauri, C., B. Irving, S. Dupont, P. Pagés, D.D.W. Hauser and S.L. Danielson, 2024. Insights into carbonate environmental conditions in the Chukchi Sea. Biogeosciences, 21:1135-1159. doi:10.5194/bg-21-1135-2024

Hauser, D.D.W., A.V. Whiting, A.R. Mahoney, J. Goodwin, C. Harris, R.J. Schaeffer, R. Schaeffer, N.J.M. Laxague, A. Subramaniam, C.R. Witte, S. Betcher, J.M. Lindsay and C.J. Zappa, 2021. Co-production of knowledge reveals loss of Indigenous hunting opportunities in the face of accelerating Arctic climate change. Environmental Research Letters, 16:095003. doi:10.1088/1748-9326/ac1a36

Hauser, D.D.W., R.T. Glenn, E.D. Lindley, K.K. Pikok, K. Heeringa, J. Jones, B. Adams, J.M. Leavitt, G.N. Omnik, R. Schaeffer, C. SimsKayotuk, E.B. Sparrow, A.M. Ravelo, O. Lee and H. Eicken, 2023. Nunaaqqit Savaqatigivlugich – working with communities: evolving collaborations around an Alaska Arctic observatory and knowledge hub. Arctic Science, 9:635-656. doi:10.1139/as-2022-0044

Henson, S.A., C. Beaulieu, T. Ilyina, J.G. John, M. Long, R. Séférian, J. Tjiputra and J.L. Sarmiento, 2017. Rapid emergence of climate change in environmental drivers of marine ecosystems. Nature Communications, 8:14682. doi:10.1038/ncomms14682

Henson, H.C., J.M. Holding, L. Meire, S. Rysgaard, C.A. Stedmon, A. Stuart-Lee, J. Bendtsen and M.K. Sejr, 2023. Coastal freshening drives acidification state in Greenland fjords. Science of the Total Environment, 855:158962. doi:10.1016/j.scitotenv.2022.158962

Hu, M.Y., K. Michael, C.M. Kreiss, M. Stumpp, S. Dupont, Y.-C. Tseng and M. Lucassen, 2016. Temperature modulates the effects of ocean acidification on intestinal ion transport in Atlantic cod, *Gadus morhua*. Frontiers in Physiology, 7:198115. doi:10.3389/fphys.2016.00198

Hunter, M., R. Atwood, A. Miller, S. Wilcox, K. Drew and D. Colson Leaning, 2021. Northern shrimp stock assessment update. Atlantic States Marine Fisheries Commission. Arlington. www.asmfc.org/uploads/file/63ee4ae1NShrimpAssessmentUpdateReport_2021.pdf

Huntington, H.P., L.T. Quakenbush and M. Nelson, 2017. Evaluating the effects of climate change on indigenous marine mammal hunting in northern and western Alaska using Traditional Knowledge. Frontiers in Marine Science, 4:307725. doi:10.3389/fmars.2017.00319

Huntington, H.P., A. Zagorsky, B.P. Kaltenborn, H.C. Shin, J. Dawson, M. Lukin, P.E. Dahl, P. Guo, and D.N. Thomas, 2022. Societal implications of a changing Arctic Ocean. Ambio, 51:298-306. doi:10.1007/s13280-021-01601-2

ICC, 2022. Circumpolar Inuit Protocols for Equitable and Ethical Engagement. Inuit Circumpolar Council. www.inuitcircumpolar.com/wp-content/uploads/EEE-Protocols-LR-WEB.pdf

ICC Alaska, 2015. Alaskan Inuit Food Security Conceptual Framework: How to Assess the Arctic from an Inuit Perspective. Inuit Circumpolar Council-Alaska. https://iccalaska.org/wp-icc/wp-content/uploads/2016/05/Food-Security-Full-Technical-Report.pdf

ICC Alaska, 2022. Food Sovereignty and Self-Governance Workshop. Summary Reports: Inuit Coming Together from Across Alaska and the Inuvialuit Settlement Region. Inuit Circumpolar Council - Alaska. https://iccalaska.org/wp-icc/wp-content/uploads/2022/08/ICC-Compiled-Book-Lo-Res.pdf

IPCC, 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland. doi:10.59327/IPCC/AR6-9789291691647

Jeansson, E., A. Olsen, T. Eldevik, I. Skjelvan, A.M. Omar, S.K. Lauvset, J.E.Ø. Nilsen, R.G.J. Bellerby, T. Johannessen and E. Falck, 2011. The Nordic Seas carbon budget: Sources, sinks, and uncertainties. Global Biogeochemical Cycles, 25:GB4010. doi:10.1029/2010GB003961

Jeansson, E., T. Tanhua, A. Olsen, W.M. Smethie, B. Rajasakaren, S.R. Ólafsdóttir and J. Ólafsson, 2023. Decadal changes in ventilation and anthropogenic carbon in the Nordic Seas. Journal of Geophysical Research: Oceans, 128:e2022JC019318. doi:10.1029/2022JC019318

Jones, E.M., M. Chierici, S. Menze, A. Fransson, R.B. Ingvaldsen and H.H. Lødemel, 2021. Ocean acidification state variability of the Atlantic Arctic Ocean around northern Svalbard. Progress in Oceanography, 199:102708. doi:10.1016/j.pocean.2021.102708

Knecht, N.S., F. Benedetti, U. Hofmann Elizondo, N. Bednaršek, S. Chaabane, C. de Weerd, K.T.C.A. Peijnenburg, R. Schiebel and M. Vogt, 2023. The impact of zooplankton calcifiers on the marine carbon cycle. Global Biogeochemical Cycles, 37:e2022GB007685. doi:10.1029/2022GB007685

Kunz, K.L., G. Claireaux, H.-O. Pörtner, R. Knust and F.C. Mark, 2018. Aerobic capacities and swimming performance of Polar cod (*Boreogadus saida*) under ocean acidification and warming conditions. Journal of Experimental Biology, 221:jeb184473. doi:10.1242/jeb.184473

Kwiatkowski, L., O. Torres, L. Bopp, O. Aumont, M. Chamberlain, J.R. Christian, J.P. Dunne and 21 others, 2020. Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. Biogeosciences, 17:3439-3470. doi:10.5194/bg-17-3439-2020

Leo, E., 2021. Cellular Metabolism of Different Life Stages of Marine Teleosts during Ocean Acidification and Warming. Thesis. University of Bremen. doi:10.26092/elib/1060

Leung, C., E. Guscelli, D. Chabot, A. Bourret, P. Calosi and G.J. Parent, 2023. The lack of genetic variation underlying thermal transcriptomic plasticity suggests limited adaptability of the Northern shrimp, *Pandalus borealis*. Frontiers in Ecology and Evolution, 11:1125134. doi:10.3389/fevo.2023.1125134

Li, C.-L., Y. Wu, X.-C. Wang, R.A. Feely, W.-J. Cai, L. Han, X. Lin and D. Qi, 2022. Accelerated accumulation of anthropogenic CO_2 drives rapid acidification in the North Pacific subtropical mode water during 1993-2020. Geophysical Research Letters, 49:e2022GL101639. doi:10.1029/2022GL101639

Licker, R., B. Ekwurzel, S.C. Doney, S.R. Cooley, I.D. Lima, R. Heede and P.C. Frumhoff, 2019. Attributing ocean acidification to major carbon producers. Environmental Research Letters, 14:124060. doi:10.1088/1748-9326/ab5abc

Lischka, S., J. Büdenbender, T. Boxhammer and U. Riebesell, 2011. Impact of ocean acidification and elevated temperatures on early juveniles of the polar shelled pteropod *Limacina helicina*: mortality, shell degradation, and shell growth. Biogeosciences, 8:919-932. doi:10.5194/bg-8-919-2011

Long, W.C., K.M. Swiney, C. Harris, H.N. Page and R.J. Foy, 2013. Effects of ocean acidification on juvenile red king crab (*Paralithodes camtschaticus*) and tanner crab (*Chionoecetes bairdi*) growth, condition, calcification, and survival. PLoS One, 8:e60959. doi:10.1371/journal.pone.0060959

Long, W.C., P. Pruisner, K.M. Swiney and R.J. Foy, 2019. Effects of ocean acidification on the respiration and feeding of juvenile red and blue king crabs (*Paralithodes camtschaticus* and *P. platypus*). ICES Journal of Marine Science, 76:1335-1343. doi:10.1093/icesjms/fsz090

Long, W.C., K.M. Swiney and R.J. Foy, 2022. Effects of high pCO_2 on snow crab embryos: Ocean acidification does not affect embryo development or larval hatching. bioRxiv 2022.10.06.511099. doi:10.1101/2022.10.06.511099

Majewski, A.R., W. Walkusz, B.R. Lynn, S. Atchison, J. Eert and J.D. Reist, 2016. Distribution and diet of demersal Arctic cod, *Boreogadus saida*, in relation to habitat characteristics in the Canadian Beaufort Sea. Polar Biology, 39:1087-1098. doi:10.1007/s00300-015-1857-y

Manno, C., V.L. Peck and G.A. Tarling, 2016. Pteropod eggs released at high pCO_2 lack resilience to ocean acidification. Scientific Reports, 6:25752. doi:10.1038/srep25752

Manno, C., N. Bednaršek, G.A. Tarling, V.L. Peck, S. Comeau, D. Adhikari, D.C.E. Bakker, E. Bauerfeind, A.J. Bergan, M.I. Berning, E. Buitenhuis, A.K. Burridge, M. Chierici, S. Flöter, A. Fransson, J. Gardner, E.L. Howes, N. Keul, K. Kimoto, P. Kohnert, G.L. Lawson, S. Lischka, A. Maas, L. Mekkes, R.L. Oakes, C. Pebody, K.T.C.A. Peijnenburg, M. Seifert, J. Skinner, P.S. Thibodeau, D. Wall-Palmer and P. Ziveri, 2017. Shelled pteropods in peril: Assessing vulnerability in a high CO_2 ocean. Earth-Science Reviews, 169:132-145. doi:10.1016/j.earscirev.2017.04.005

Marushka, L., M. Batal, C. Tikhonov, T. Sadik, H. Schwartz, A. Ing, K. Fediuk and H.M. Chan, 2021. Importance of fish for food and nutrition security among First Nations in Canada. Canadian Journal of Public Health, 112:64-80. doi:10.17269/s41997-021-00481-z

McElhany, P., D.S. Busch, A. Lawrence, M. Maher, D. Perez, E.M. Reinhardt, K. Rovinski and E.M. Tully, 2022. Higher survival but smaller size of juvenile Dungeness crab (*Metacarcinus magister*) in high CO_2. Journal of Experimental Marine Biology and Ecology, 555:151781. doi:10.1016/j.jembe.2022.151781

Mekkes, L., W. Renema, N. Bednaršek, S.R. Alin, R.A. Feely, J. Huisman, P. Roessingh and K.T.C.A. Peijnenburg, 2021. Pteropods make thinner shells in the upwelling region of the California Current Ecosystem. Scientific Reports, 11:1731. doi:10.1038/s41598-021-81131-9

Menu-Courey, K., F. Noisette, S. Piedalue, D. Daoud, T. Blair, P.U. Blier, K. Azetsu-Scott and P. Calosi, 2019. Energy metabolism and survival of the juvenile recruits of the American lobster (*Homarus americanus*) exposed to a gradient of elevated seawater pCO_2. Marine Environmental Research, 143:111-123. doi:10.1016/j.marenvres.2018.10.002

Mortenson, E., N. Steiner, A.H. Monahan, H. Hayashida, T. Sou and A. Shao, 2020. Modeled impacts of sea ice exchange processes on Arctic Ocean carbon uptake and acidification (1980–2015). Journal of Geophysical Research: Oceans, 125:e2019JC015782. doi:10.1029/2019JC015782

Mucci, A., 1983. The solubility of calcite and aragonite in seawater at various salinities, temperatures, and one atmosphere total pressure. American Journal of Science, 283:780-799. doi:10.2475/ajs.283.7.780

Nghiem, S.V., D.K. Hall, T.L. Mote, M. Tedesco, M.R. Albert, K. Keegan, C.A. Shuman, N.E. DiGirolamo and G. Neumann, 2012. The extreme melt across the Greenland ice sheet in 2012. Geophysical Research Letters, 39. doi:10.1029/2012GL053611

Niemi, A., N. Bednaršek, C. Michel, R.A. Feely, W. Williams, K. Azetsu-Scott, W. Walkusz and J.D. Reist, 2021. Biological impact of ocean acidification in the Canadian Arctic: Widespread severe pteropod shell dissolution in Amundsen Gulf. Frontiers in Marine Science, 8:222. doi:10.3389/fmars.2021.600184

Noisette, F., P. Calosi, D. Madeira, M. Chemel, K. Menu-Courey, S. Piedalue, H. Gurney-Smith, D. Daoud and K. Azetsu-Scott, 2021. Tolerant larvae and sensitive juveniles: integrating metabolomics and whole-organism responses to define life-stage specific sensitivity to ocean acidification in the American lobster. Metabolites, 11:584. doi:10.3390/metabo11090584

Oka, E., K. Yamada, D. Sasano, K. Enyo, T. Nakano and M. Ishii, 2019. Remotely forced decadal physical and biogeochemical variability of North Pacific subtropical mode water over the last 40 years. Geophysical Research Letters, 46:1555-1561. doi:10.1029/2018GL081330

Olafsson, J., S.R. Olafsdottir, T. Takahashi, M. Danielsen and T.S. Arnarson, 2021. Enhancement of the North Atlantic CO_2 sink by Arctic Waters. Biogeosciences, 18:1689-1701. doi:10.5194/bg-18-1689-2021

Olsen, A., A.M. Omar, R.G.J. Bellerby, T. Johannessen, U. Ninnemann, K.R. Brown, K.A. Olsson, J. Olafsson, G. Nondal, C. Kivimäe, S. Kringstad, C. Neill and S. Olafsdottir, 2006. Magnitude and origin of the anthropogenic CO_2 increase and ^{13}C Suess effect in the Nordic seas since 1981. Global Biogeochemical Cycles, 20,GB3027. doi:10.1029/2005GB002669

Ono, H., N. Kosugi, K. Toyama, H. Tsujino, A. Kojima, K. Enyo, Y. Iida, T. Nakano and M. Ishii, 2019. Acceleration of ocean acidification in the Western North Pacific. Geophysical Research Letters, 46:13161-13169. doi:10.1029/2019GL085121

Ono, H., K. Toyama, K. Enyo, Y. Iida, D. Sasano, S. Nakaoka and M. Ishii, 2023. Meridional variability in multi-decadal trends of dissolved inorganic carbon in surface seawater of the western North Pacific along the 165°E line. Journal of Geophysical Research: Oceans, 128:e2022JC018842. doi:10.1029/2022JC018842

Orr, J.C., L. Kwiatkowski and H.-O. Pörtner, 2022. Arctic Ocean annual high in CO_2 could shift from winter to summer. Nature, 610:94-100. doi:10.1038/s41586-022-05205-y

Ostertag, S.K., L.L. Loseto, K. Snow, J. Lam, K. Hynes and D.V. Gillman, 2018. "That's how we know they're healthy": The inclusion of traditional ecological knowledge in beluga health monitoring in the Inuvialuit Settlement Region. Arctic Science, 4:292-320. doi:10.1139/as-2017-0050

Ouyang, Z., D. Qi, L. Chen, T. Takahashi, W. Zhong, M.D. DeGrandpre, B. Chen, Z. Gao, S. Nishino, A. Murata, H. Sun, L.L. Robbins, M. Jin and W.-L. Cai, 2020. Sea-ice loss amplifies summertime decadal CO_2 increase in the western Arctic Ocean. Nature Climate Change, 10:678-684. doi:10.1038/s41558-020-0784-2

Pérez, F.F., J. Olafsson, S.R. Ólafsdóttir, M. Fontela and T. Takahashi, 2021. Contrasting drivers and trends of ocean acidification in the subarctic Atlantic. Scientific Reports, 11:13991. doi:10.1038/s41598-021-93324-3

Pilcher, D.J., D.M. Naiman, J.N. Cross, A.J. Hermann, S.A. Siedlecki, G.A. Gibson and J.T. Mathis, 2019. Modeled effect of coastal biogeochemical processes, climate variability, and ocean acidification on aragonite saturation state in the Bering Sea. Frontiers in Marine Science, 5:508. doi:10.3389/fmars.2018.00508

Pipko, I.I., S. Pugach, I.P. Semiletov and O. Konstantinov, 2023. Dynamics of the seawater carbonate system in the East Siberian Sea: The diversity of driving forces. Water, 15:2670. doi:10.3390/w15142670

Pörtner, H.-O., R.J. Scholes, A. Arneth, D.K.A. Barnes, M.T. Burrows, S.E. Diamond, C.M. Duarte, W. Kiessling, P. Leadley, S. Managi, P. McElwee, G. Midgley, H.T. Ngo, D. Obura, U. Pascual, M. Sankaran, Y.J. Shin and A.L. Val, 2023. Overcoming the coupled climate and biodiversity crises and their societal impacts. Science, 380. doi:10.1126/science.abl4881

Pratt, N., B.J. Ciotti, E.A. Morgan, P. Taylor, H. Stahl and C. Hauton, 2015. No evidence for impacts to the molecular ecophysiology of ion or CO_2 regulation in tissues of selected surface-dwelling bivalves in the vicinity of a sub-seabed CO_2 release. International Journal of Greenhouse Gas Control, 38:193-201. doi:10.1016/j.ijggc.2014.10.001

Proverbs, T.A., T.C. Lantz, S.I. Lord, A. Amos and N.C. Ban, 2020. Social-ecological determinants of access to fish and well-being in four Gwich'in communities in Canada's Northwest Territories. Human Ecology, 48:155-171. doi:10.1007/s10745-020-00131-x

Punt, A.E., D. Poljak, M.G. Dalton and R.J. Foy, 2014. Evaluating the impact of ocean acidification on fishery yields and profits: The example of red king crab in Bristol Bay. Ecological Modelling, 285:39-53. doi:10.1016/J.ECOLMODEL.2014.04.017

Qi, D., L. Chen, B. Chen, Z. Gao, W. Zhong, R.A. Feely, L.G. Anderson, H. Sun, J. Chen, M. Chen, L. Zhan, Y. Zhang and W.-J. Cai, 2017. Increase in acidifying water in the western Arctic Ocean. Nature Climate Change, 7:195-201. www.nature.com/articles/nclimate3228

Qi, D., Z. Ouyang, L. Chen, Y. Wu, R. Lei, B. Chen, R.A. Feely, L.G. Anderson, W. Zhong, H. Lin, A. Polukhin, Y. Zhang, Y. Zhang, H. Bi, X. Lin, Y. Luo, Y. Zhuang, J. He, J. Chen and W.-J. Cai, 2022. Climate change drives rapid decadal acidification in the Arctic Ocean from 1994 to 2020. Science, 377:1544-1550. doi:10.1126/science.abo0383

Rapinski, M., A. Cuerrier, C. Harris and M. Lemire, 2018. Inuit perception of marine organisms: From folk classification to food harvest. Journal of Ethnobiology, 38:333-355. doi:10.2993/0278-0771-38.3.333

Reid, A.J., L.E. Eckert, J. Lane, N. Young, S.G. Hinch, C.T. Darimont, S.J. Cooke, N.C. Ban and A. Marshall, 2021. "Two-Eyed Seeing": An Indigenous framework to transform fisheries research and management. Fish and Fisheries, 22:243-261. doi:10.1111/faf.12516

Reinhardt, E., 2020. The effects of ocean acidification on molt rate and carapace area in juvenile Dungeness crabs (*Cancer magister*). Thesis. Georgia Institute of Technology. https://repository.gatech.edu/entities/publication/8978152f-46ce-4c33-bbb3-4e38cbef21bd

Roleda, M.Y., P.W. Boyd and C.L. Hurd, 2012. Before ocean acidification: Calcifier chemistry lessons. Journal of Phycology, 48:840-843. doi:10.1111/j.1529-8817.2012.01195.x

Sánchez-García, L., V. Alling, S. Pugach, J. Vonk, B. van Dongen, C. Humborg, O. Dudarev, I.P. Semiletov and Ö. Gustafsson, 2011. Inventories and behavior of particulate organic carbon in the Laptev and East Siberian seas. Global Biogeochemical Cycles, 25:GB2007. doi:10.1029/2010GB003862

Sanders, M.B., T.P. Bean, T.H. Hutchinson and W.J.F. Le Quesne, 2013. Juvenile king scallop, *Pecten maximus*, is potentially tolerant to low levels of ocean acidification when food is unrestricted. PLoS One, 8:e74118. doi:10.1371/journal.pone.0074118

Schalkhausser, B., C. Bock, K. Stemmer, T. Brey, H.-O. Pörtner and G. Lannig, 2013. Impact of ocean acidification on escape performance of the king scallop, *Pecten maximus*, from Norway. Marine Biology, 160:1995-2006. doi:10.1007/s00227-012-2057-8

Schalkhausser, B., C. Bock, H.-O. Pörtner and G. Lannig, 2014. Escape performance of temperate king scallop, *Pecten maximus* under ocean warming and acidification. Marine Biology, 161:2819-2829. doi:10.1007/s00227-014-2548-x

Schatz, V.J., A. Proelss and N. Liu, 2019. The 2018 Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean: A Critical Analysis. The International Journal of Marine and Coastal Law, 34:195-244. doi:10.1163/15718085-23342015

Semiletov, I.P., 1999a. Aquatic sources and sinks of CO_2 and CH_4 in the polar regions. Journal of the Atmospheric Sciences, 56:286-306. doi:10.1175/1520-0469(1999)056<0286:ASASOC>2.0.CO;2

Semiletov, I.P., 1999b. Destruction of the coastal permafrost as an important factor in biogeochemistry of the Arctic shelf waters. Transactions [Doklady] of Russian Academy of Sciences, 368:679-682.

Semiletov, I., O. Dudarev, V. Luchin, A. Charkin, K. Shin and N. Tanaka, 2005. The East Siberian Sea as a transition zone between Pacific-derived waters and Arctic shelf waters. Geophysical Research Letters, 32:L10614. doi:10.1029/2005GL022490

Semiletov, I.P., I.I. Pipko, I. Repina and N.E. Shakhova, 2007. Carbonate chemistry dynamics and carbon dioxide fluxes across the atmosphere–ice–water interfaces in the Arctic Ocean: Pacific sector of the Arctic. Journal of Marine Systems, 66:204-226. doi:10.1016/j.jmarsys.2006.05.012

Semiletov, I.P., I.I. Pipko, N.E. Shakhova, O.V. Dudarev, S.P. Pugach, A.N. Charkin, C.P. Mcroy, D. Kosmach and Ö. Gustafsson, 2011. Carbon transport by the Lena River from its headwaters to the Arctic Ocean, with emphasis on fluvial input of terrestrial particulate organic carbon vs. carbon transport by coastal erosion. Biogeosciences, 8:2407-2426. doi:10.5194/BG-8-2407-2011

Semiletov, I.P., N.E. Shakhova, V.I. Sergienko, I.I. Pipko and O.V. Dudarev, 2012. On carbon transport and fate in the East Siberian Arctic land–shelf–atmosphere system. Environmental Research Letters, 7:015201. doi:10.1088/1748-9326/7/1/015201

Semiletov, I.P., I.I. Pipko, Ö. Gustafsson, L.G. Anderson, V. Sergienko, S. Pugach, O. Dudarev, A. Charkin, A. Gukov, L. Bröder, A. Andersson, E. Spivak and N. Shakhova, 2016. Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon. Nature Geoscience, 9:361-365. doi:10.1038/ngeo2695

Serreze, M.C. and W.N. Meier, 2019. The Arctic's sea ice cover: trends, variability, predictability, and comparisons to the Antarctic. Annals of the New York Academy of Sciences, 1436:36-53. doi:10.1111/nyas.13856

Shakhova, N., I. Semiletov, A. Salyuk, V. Yusupov, D. Kosmach and Ö. Gustafsson, 2010. Extensive methane venting to the atmosphere from sediments of the East Siberian Arctic Shelf. Science, 327:1246-1250. doi:10.1126/science.1182221

Shakhova, N., I. Semiletov, I. Leifer, V. Sergienko, A. Salyuk, D. Kosmach, D. Chernykh, C. Stubbs, D. Nicolsky, V. Tumskoy and Ö. Gustafsson, 2014. Ebullition and storm-induced methane release from the East Siberian Arctic Shelf. Nature Geoscience, 7:64-70. doi:10.1038/ngeo2007

Shakhova, N., I. Semiletov, V. Sergienko, L. Lobkovsky, V. Yusupov, A. Salyuk, A. Salomatin, D. Chernykh, D. Kosmach, G. Panteleev, D. Nicolsky, V. Samarkin, S. Joye, A. Charkin, O. Dudarev, A. Meluzov and Ö. Gustafsson, 2015. The East Siberian Arctic Shelf: towards further assessment of permafrost-related methane fluxes and role of sea ice. Philosophical Transactions of the Royal Society A, 373:20140451. doi:10.1098/rsta.2014.0451

Skjelvan, I., S.K. Lauvset, T. Johannessen, K. Gundersen and Ø. Skagseth, 2022. Decadal trends in ocean acidification from the ocean weather Station M in the Norwegian Sea. Journal of Marine Systems, 234:103775. doi:10.1016/j.jmarsys.2022.103775

Skogen, M.D., A. Olsen, K.Y. Børsheim, A.B. Sandø and I. Skjelvan, 2014. Modelling ocean acidification in the Nordic and Barents Seas in present and future climate. Journal of Marine Systems, 131:10-20. doi:10.1016/j.jmarsys.2013.10.005

Small, D.P., P. Calosi, D. Boothroyd, S. Widdicombe and J.L. Spicer, 2015. Stage-specific changes in physiological and life-history responses to elevated temperature and pCO_2 during the larval development of the European lobster *Homarus gammarus* (L.). Physiological and Biochemical Zoology, 88:494-507. doi:10.1086/682238

Snook, J., A. Cunsolo, J. Ford, C. Furgal, A. Jones-Bitton and S. Harper, 2022. "Just because you have a land claim, that doesn't mean everything's going to fall in place": An Inuit social struggle for fishery access and well-being. Marine Policy, 140:105071. doi:10.1016/j.marpol.2022.105071

Sparrow, K.J., J.D. Kessler, J.R. Southon, F. Garcia-Tigreros, K.M. Schreiner, C.D. Ruppel, J.B. Miller, S.J. Lehman and X. Xu, 2018. Limited contribution of ancient methane to surface waters of the U.S. Beaufort Sea shelf. Science Advances, 4:eaao4842. doi:10.1126/sciadv.aao4842

Steinacher, M., F. Joos, T.L. Frölicher, G.K. Plattner and S.C. Doney, 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences, 6:515-533. doi:10.5194/bg-6-515-2009

Steiner, N.S. and C.M. Reader, 2024. Trends and projections in climate-related stressors impacting Arctic marine ecosystems—A CMIP6 model analysis. Journal of Geophysical Research: Oceans, 129:e2024JC020970. doi:10.1029/2024JC020970

Steiner, N.S., W.G. Lee and J.R. Christian, 2013. Enhanced gas fluxes in small sea ice leads and cracks: Effects on CO_2 exchange and ocean acidification. Journal of Geophysical Research: Oceans, 118:1195-1205. doi:10.1002/jgrc.20100

Steiner, N.S., J.R. Christian, K.D. Six, A. Yamamoto and M. Yamamoto-Kawai, 2014. Future ocean acidification in the Canada Basin and surrounding Arctic Ocean from CMIP5 earth system models. Journal of Geophysical Research: Oceans, 119:332-347. doi:10.1002/2013JC009069

Steiner, N.S., J. Bowman, K. Campbell, M. Chierici, E. Eronen-Rasimus, M. Falardeau, H. Flores, A. Fransson, H. Herr, S.J. Insley, H.M. Kauko, D. Lannuzel, L. Loseto, A. Lynnes, A. Majewski, K.M. Meiners, L.A. Miller, L.N. Michel, S. Moreau, M. Nacke, D. Nomura, L. Tedesco, J.A. van Franeker, M.A. van Leeuwe and P. Wongpan, 2021. Climate change impacts on sea-ice ecosystems and associated ecosystem services. Elementa: Science of the Anthropocene, 9:00007. doi:10.1525/ELEMENTA.2021.00007

Stillman, J.H., S.A. Fay, S.M. Ahmad, K.M. Swiney and R.J. Foy, 2020. Transcriptomic response to decreased pH in adult, larval and juvenile red king crab, *Paralithodes camtschaticus*, and interactive effects of pH and temperature on juveniles. Journal of the Marine Biological Association of the United Kingdom, 100:251-265. doi:10.1017/S002531541900119X

Swiney, K.M., W.C. Long and R.J. Foy, 2017. Decreased pH and increased temperatures affect young-of-the-year red king crab (*Paralithodes camtschaticus*). ICES Journal of Marine Science, 74:1191-1200. doi:10.1093/icesjms/fsw251

Tai, T.C., P. Calosi, H.J. Gurney-Smith and W.W.L. Cheung, 2021. Modelling ocean acidification effects with life stage-specific responses alters spatiotemporal patterns of catch and revenues of American lobster, *Homarus americanus*. Scientific Reports, 11:23330. doi:10.1038/s41598-021-02253-8

Terhaar, J., O. Torres, T. Bourgeois and L. Kwiatkowski, 2021. Arctic Ocean acidification over the 21st century co-driven by anthropogenic carbon increases and freshening in the CMIP6 model ensemble. Biogeosciences, 18:2221-2240. doi:10.5194/bg-18-2221-2021

Thor, P., A. Bailey, S. Dupont, P. Calosi, J.E. Søreide, P. De Wit, E. Guscelli, L. Loubet-Sartrou, I.M. Deichmann, M.M. Candee, C. Svensen, A.L. King and R.G.J. Bellerby, 2018. Contrasting physiological responses to future ocean acidification among Arctic copepod populations. Global Change Biology, 24:e365-e377. doi:10.1111/GCB.13870

Turk, D., J.M. Bedard, W.J. Burt, S. Vagle, H. Thomas, K. Azetsu-Scott, W.R. McGillis, S.J. Iverson and D.W.R. Wallace, 2016. Inorganic carbon in a high latitude estuary-fjord system in Canada's eastern Arctic. Estuarine, Coastal and Shelf Science, 178:137-147. doi:10.1016/j.ecss.2016.06.006

van Dongen, B.E., I.P. Semiletov, J.W.H. Weijers and Ö. Gustafsson, 2008. Contrasting lipid biomarker composition of terrestrial organic matter exported from across the Eurasian Arctic by the five great Russian Arctic rivers. Global Biogeochemical Cycles, 22:GB1011. doi:10.1029/2007GB002974

Vargas, C.A., N.A. Lagos, M.A. Lardies, C. Duarte, P.H. Manríquez, V.M. Aguilera, B. Broitman, S. Widdicombe and S. Dupont, 2017. Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. Nature Ecology & Evolution, 1:0084. doi:10.1038/s41559-017-0084

Vargas, C.A., L.A. Cuevas, B.R. Broitman, V.A. San Martin, N.A. Lagos, J.D. Gaitán-Espitia, and S. Dupont, 2022. Upper environmental pCO_2 drives sensitivity to ocean acidification in marine invertebrates. Nature Climate Change, 12:200-207. doi:10.1038/s41558-021-01269-2

Volk, T. and M.I. Hoffert, 1985. Ocean carbon pumps: analysis of relative strengths and efficiencies in ocean-driven atmospheric CO_2 changes. In: Sundquist, E.T. and W.S. Broecker (Eds.), The Carbon Cycle and Atmospheric CO_2: Natural Variations, Archean to Present. American Geophysical Union (AGU), Washington, D.C., pp. 99-110. doi:10.1029/GM032p0099

Vonk, J.E. and Ö. Gustafsson, 2013. Permafrost-carbon complexities. Nature Geoscience, 6:675-676. doi:10.1038/ngeo1937

Vonk, J.E., L. Sánchez-García, B.E. van Dongen, V. Alling, D. Kosmach, A. Charkin, I.P. Semiletov, O.V. Dudarev, N. Shakhova, P. Roos, T.I. Eglinton, A. Andersson and Ö. Gustafsson, 2012. Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia. Nature, 489:137-140. doi:10.1038/nature11392

Walther, K., K. Anger and H. Pörtner, 2010. Effects of ocean acidification and warming on the larval development of the spider crab *Hyas araneus* from different latitudes (54° vs. 79°N). Marine Ecology Progress Series, 417:159-170. doi:10.3354/meps08807

Wang, H., P. Lin, R.S. Pickart and J.N. Cross, 2022. Summer surface CO_2 dynamics on the Bering Sea and Eastern Chukchi Sea shelves from 1989 to 2019. Journal of Geophysical Research: Oceans, 127:e2021JC017424. doi:10.1029/2021JC017424

Watt-Cloutier, S., 2018. The Right to Be Cold: One Woman's Fight to Protect the Arctic and Save the Planet from Climate Change. University of Minnesota Press.

Wheeler, H.C., F. Danielsen, M. Fidel, V. Hausner, T. Horstkotte, N. Johnson, O. Lee, N. Mukherjee, A. Amos, H. Ashthorn, Ø. Ballari, C. Behe, K. Breton-Honeyman, G. Retter, V. Buschman, P. Jakobsen, F. Johnson, B. Lyberth, J.A. Parrott, M. Pogodaev, R. Sulyandziga and N. Vronski, 2020. The need for transformative changes in the use of Indigenous knowledge along with science for environmental decision-making in the Arctic. People and Nature, 2:544-556. doi:10.1002/pan3.10131

Wittmann, A.C. and H.-O. Pörtner, 2013. Sensitivities of extant animal taxa to ocean acidification. Nature Climate Change, 3:995-1001. doi:10.1038/nclimate1982

Woosley, R.J. and F.J. Millero, 2020. Freshening of the western Arctic negates anthropogenic carbon uptake potential. Limnology and Oceanography, 65:1834-1846. doi:10.1002/lno.11421

Yamamoto-Kawai, M., F.A. McLaughlin, E.C. Carmack, S. Nishino and K. Shimada, 2009. Aragonite undersaturation in the Arctic Ocean: effects of ocean acidification and sea ice melt. Science, 326:1098-1100. doi:10.1126/science.1174190

Yua, E., J. Raymond-Yakoubian, R.A. Daniel and C. Behe, 2022. A framework for co-production of knowledge in the context of Arctic research. Ecology and Society, 27:34. doi:10.5751/ES-12960-270134

Zavolokin, A.V., A.Ya. Efimkin, A.M. Slabinskiy and N.S. Kosenok, 2007. Food supply and trophic relationships of Pacific salmon (*Oncorhynchus* spp.) and Atka mackerel (*Pleurogrammus monopterygius*) in the western Bering Sea in fall 2002-2004. North Pacific Anadromous Fish Commission, 4:127-131.

Overland, J., R. Corell, S.-J. Kim, P. Langen, J. Ukita and T. Vihma, 2024. Arctic/midlatitude weather connectivity. In: AMAP Arctic Climate Change Update 2024: Key Trends and Impacts, pp. 117-120. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. https://doi.org/10.21352/m8j7-wt56

8. Arctic/midlatitude weather connectivity

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Key findings

- *Arctic climate change can influence midlatitude weather and climate, impacting millions of people.*
- *Understanding the meteorological processes for this connection remains controversial: the physics includes both local Arctic forcing such as sea-ice loss and temperature increases (Arctic amplification), and internal atmospheric variability such as tropospheric jet stream and stratospheric polar vortex dynamics.*
- *The movement of the stratospheric polar vortex over continents can help explain some of the location, timing and duration of Arctic/midlatitude weather connections, such as cold-air outbreaks over the eastern parts of Asia and North America.*

8.1 Introduction

This chapter updates the previous AMAP report, *AMAP Arctic Climate Update 2021: Key Trends and Impacts,* specifically Chapter 5: Arctic/midlatitude weather connectivity (Overland et al., 2021a).

Accompanied by a rapid loss of Arctic sea ice in recent decades, the winter Arctic has warmed three times faster (Sweeney et al., 2023; Zhou et al., 2024) than the global mean based on observed data since 1980 (Dai et al., 2019; Rantanen et al., 2022), as noted in previous chapters. Despite this Arctic amplification (i.e., amplification of Arctic warming relative to the rest of the globe), and although continental minimum air-temperature averages have increased (Blackport and Screen, 2021), a number of recent cold-air events have occurred in the United States, Scandinavia and eastern Asia (Ding et al., 2021, 2022; Yao et al., 2023). The meteorology of this Arctic/midlatitude weather connection does not imply a single physical linkage; such linkage depends on different polar vortex / jet-stream locations and surface conditions. Characterizing Arctic/midlatitude linkages is a controversial task; existing knowledge shows a range of results and the topic is an active area of research (Screen et al., 2018; Overland et al., 2021b). Much of the previous evidence in favor of an Arctic/midlatitude connection is from simultaneous geographic trends and case studies in observational time series. Contrasting evidence emphasizes weak statistical and modeling connections. Focusing on internal atmospheric variability and poleward and equatorward heat transports, rather than just on the loss of sea ice, is the current state of the science.

8.2 Connectivity reflects a combination of drivers

Climate models project a range of midlatitude responses to Arctic change (Smith et al., 2019; Cheung et al., 2022, among others), which is unsurprising given that they are known to struggle with the representation of persistent large-amplitude circulation anomalies, such as north-south extensions of a wavy jet stream (Cohen et al., 2020). Arctic connections are not the whole midlatitude weather story as equatorial influences are also noted (Clancy et al., 2021; Ma et al., 2022). The differences in observational and model results for Arctic/midlatitude weather connections is confounding for those who would like a single, simple answer to understand the science and to anticipate seasonal outlooks. Allowing for multiple scientific viewpoints is representative of the current state of knowledge (Shepherd, 2021). Instead of asking whether the recent cold winter events in the midlatitudes are due to Arctic warming or interannual atmospheric variability, it is more appropriate to accept that evidence suggests a combination of the two (Outten et al., 2022).

8.3 Scientific interest operating across multiple fronts

A literature search for the period 2020 to 2022 using the search terms *Arctic AND Midlatitude AND (Jet Stream OR Polar Vortex)* generated 82 references from Web of Science, with a few additional references added from other sources. This large number of publications illustrates the high level of interest in the topic. There are multiple approaches to the issue of Arctic/midlatitude connections. Blackport and Screen (2021) and Dai and Song (2020) reported little evidence for midlatitude climate impacts from the Arctic and showed a decrease in the frequency and intensity of midlatitude cold temperature extremes. Cohen et al. (2020) reported that observations provide more support for the Arctic/midlatitude weather connections than climate models. Further papers showed a range of statistical and causal connections in the winter tropospheric weather (McGraw and Barnes, 2020; Sun et al., 2022). They noted that correlations may not represent, or may overestimate, a response to Arctic variability. Cheung et al. (2022) reported multiple results from Coupled Model Intercomparison Project Phase 5 (CMIP5) models. One modeling group underscored the need to investigate multi-model and single-model ensembles (Peings et al., 2021). The two largest groupings were observational studies on Arctic/midlatitude connections and a focus on dynamics. Four connection studies specifically mentioned loss

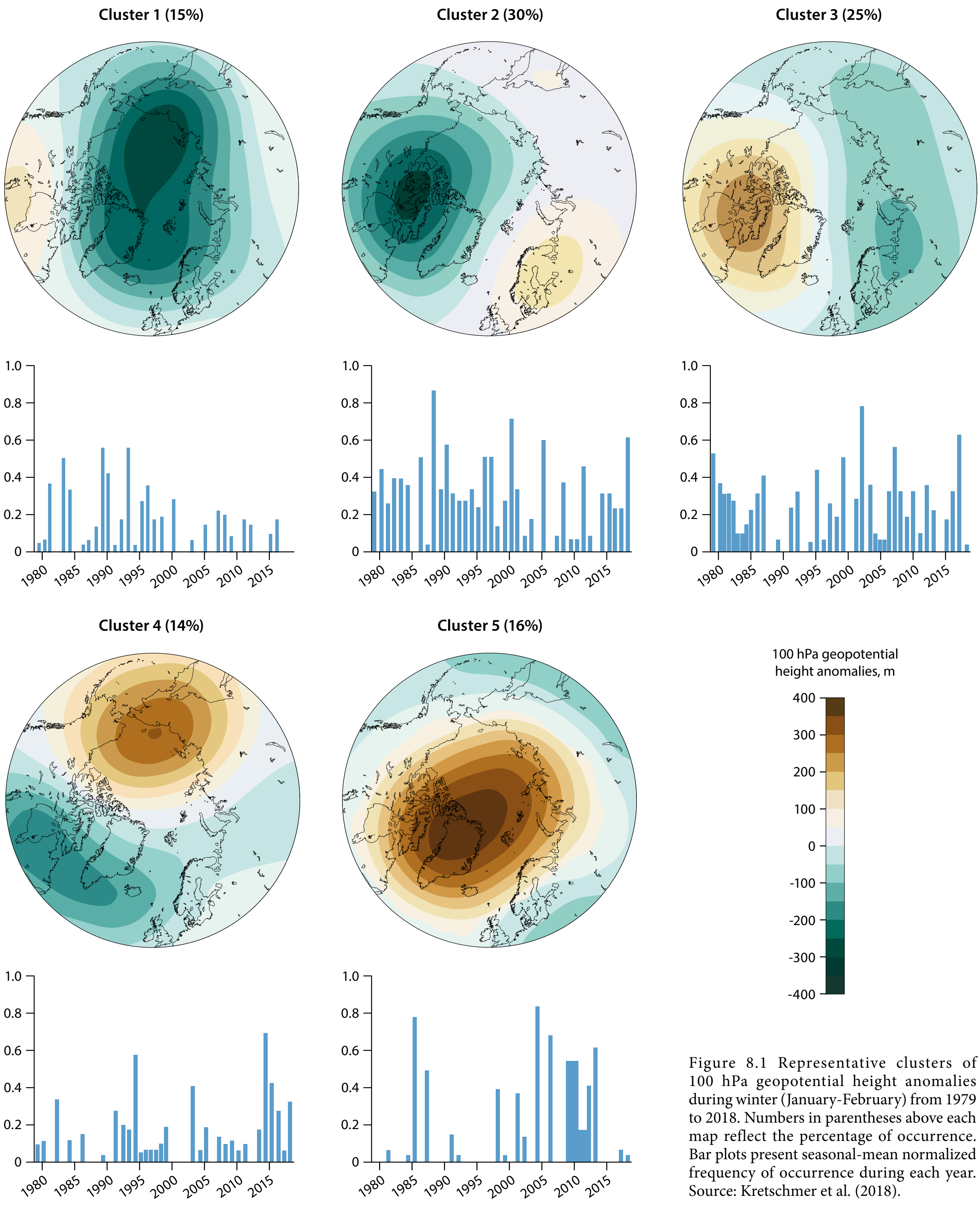

Figure 8.1 Representative clusters of 100 hPa geopotential height anomalies during winter (January-February) from 1979 to 2018. Numbers in parentheses above each map reflect the percentage of occurrence. Bar plots present seasonal-mean normalized frequency of occurrence during each year. Source: Kretschmer et al. (2018).

of sea ice (Kim and Kim, 2020; Chripko et al., 2021; He et al., 2021; Cheung et al., 2022). The other five connection studies focused on Arctic variability (Huguenin et al., 2020; Jung et al., 2020; Cohen et al., 2021; Harwood et al., 2021; Huang et al., 2021). There was some emphasis on case studies; for example, a study on recent trends in waviness (Martin, 2021) and an earlier study on Ural blocking (Tyrlis et al., 2019). There was also an emphasis on multiple processes: internal atmospheric variability and temperature advection working together with local heat flux forcing (Overland et al., 2021b,c). For the papers with a dynamics focus, one mentioned the stratosphere (Ding et al., 2022). The focus of the remaining papers ranged from meanders, Rossby wave breaking, blocking, and non-linearity (De et al., 2020; Chen X. et al., 2021; Jolly et al., 2021; Kim and Choi, 2021; Song and Wu, 2021; Xu et al., 2021; Chen G. et al., 2022). Most papers focused on the link between warm Arctic and cold midlatitude events, although connections have also been reported between cold Arctic anomalies and warm winter events in the midlatitudes, especially in Europe (Vihma et al., 2020).

8.4 Variability in the polar vortex is of particular interest

One area of research focus is the movement of the polar vortex over continents and its connection to eastern continental outbreaks of cold temperatures. There is often vertical coherence between the stratospheric level (100 hPa) and lower jet stream level (500 hPa) geopotential height features and surface weather (Cohen et al., 2021). A cluster analysis showed the preference for five lower stratospheric height patterns of the polar vortex: centered on the pole; over North America; over Eurasia; a stretching/North American dipole; and a weak pattern associated with sudden stratospheric warmings (SSW). These patterns are illustrated for winter (taken as January-February; anomalies fields, Figure 8.1) after Kretschmer et al. (2018) and Cohen et al. (2021); the patterns are statistically significant. The central Arctic location (Cluster 1) shows a long-term downward frequency trend. Cluster 2, with the polar vortex partially moving over North America, is associated with cold temperatures over the eastern United States. Cluster 3, with the polar vortex centered toward the opposite side of the pole, draws cold air across Eurasia (Kretschmer et al., 2018). Cluster 4 is referred to as a dipole/stretching pattern event. The polar stratosphere is zonally asymmetric, with the warming focused on the northwest Pacific / eastern Siberia side of the Arctic and cold temperatures over central North America (Messori et al., 2022). The stretched polar vortex excites upward wave energy propagation on the Asia side that is reflected off the upper stratosphere and enhances the pattern over North America (Cohen et al., 2021). Cluster 5 is a weak vortex associated with SSW (Hall et al., 2015). Rather than the atmospheric layers being vertically coherent as in the other four patterns, this SSW pattern is noted for upward and downward propagation of energy, with multiple surface impacts depending on circulation details. Variability in the polar vortex is certainly not responsible for the whole Arctic/midlatitude weather connection story, but does highlight that Arctic/midlatitude weather connections are more than simple forcing from Arctic amplification.

8.5 Conclusions and recommendations

The statement from Shepherd (2021), "allowing for multiple viewpoints about Arctic/midlatitude weather connections," represents the continuing state of the science. The key findings from the 2021 AMAP report (AMAP, 2021) remain valid: namely, that possible Arctic/midlatitude weather connections are societally relevant as a result of previous and future Arctic conditions. Extreme weather events are an aspect of both ongoing internal atmospheric weather and anthropogenic global change (Overland, 2022).

In relation to the present update:

> A source of intermittency in Arctic/midlatitude weather connections arises from the chaotic nature of the atmosphere. Internal shifts in atmospheric dynamics – variability in the location, strength, and character of the jet stream, blocking, and the stratospheric polar vortex – are important direct causes of this intermittency. Interdependence of atmospheric internal variability with loss of sea ice and Arctic temperature amplification are important research topics.

Two main recommendations for further work are suggested from this update:

1. Further evaluate the use of models, especially multiple ensemble versions. This should include better representation of high amplitude atmospheric dynamics such as blocking, and direct Arctic/midlatitude forecast case studies.
2. Improve understanding of atmospheric blocking and polar vortex/midlatitude cold-air and warm-air events, especially pattern persistence (Smith and Sheridan, 2019; Luo et al., 2023).

References

AMAP, 2021. AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. viii+148pp.

Blackport, R. and J.A. Screen, 2021. Observed statistical connections overestimate the causal effects of Arctic sea ice changes on midlatitude winter climate. Journal of Climate, 34:3021-3038. doi:10.1175/jcli-d-20-0293.1

Chen, X., D. Luo, Y. Wu, E. Dunn-Sigouin and J. Lu, 2021. Nonlinear response of atmospheric blocking to early winter Barents-Kara Seas warming: An idealized model study. Journal of Climate, 34:2367-2383. doi:10.1175/jcli-d-19-0720.1

Chen, G., Y. Nie and Y. Zhang, 2022. Jet stream meandering in the Northern Hemisphere winter: An advection-diffusion perspective. Journal of Climate, 35:2055-2073. doi:10.1175/jcli-d-21-0411.1

Cheung, H.N., N. Keenlyside, T. Koenigk, S. Yang, T. Tian, Z. Xu, et al., 2022. Assessing the influence of sea surface temperature and arctic sea ice cover on the uncertainty in the boreal winter future climate projections. Climate Dynamics, 59:433-454. doi:10.1007/s00382-022-06136-0

Chripko, S., R. Msadek, E. Sanchez-Gomez, L. Terray, L. Bessieres and M.-P. Moine, 2021. Impact of reduced Arctic sea ice on Northern Hemisphere climate and weather in autumn and winter. Journal of Climate, 34:5847-5867. doi:10.1175/Jcli-D-20-0515.1

Clancy, R., C. Bitz and E. Blanchard-Wrigglesworth, 2021. The influence of ENSO on Arctic sea ice in large ensembles and observations. Journal of Climate, 34:9585-9604. doi:10.1175/JCLI-D-20-0958.1

Cohen, J., X. Zhang, J. Francis, T. Jung, R. Kwok, J. Overland, et al., 2020. Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. Nature Climate Change, 10:20-29. doi:10.1038/s41558-019-0662-y

Cohen, J., L. Agel, M. Barlow, C.I. Garfinkel and I. White, 2021. Linking Arctic variability and change with extreme winter weather in the United States. Science, 373:1116-1121. doi:10.1126/science.abi9167

Dai, A. and M. Song, 2020. Little influence of Arctic amplification on mid-latitude climate. Nature Climate Change, 10:231-237. doi:10.1038/s41558-020-0694-3

Dai, A., D. Luo, M. Song and J. Liu, 2019. Arctic amplification is caused by sea-ice loss under increasing CO_2. Nature Communications, 10: 121. https://doi.org/10.1038/s41467-018-07954-9

De, B., Y. Wu and L.M. Polvani, 2020. Non-additivity of the midlatitude circulation response to regional Arctic temperature anomalies: The role of the stratosphere. Geophysical Research Letters, 47:e2020GL088057. doi:10.1029/2020gl088057

Ding, T., H. Gao and X. Li, 2021. Increasing occurrence of extreme cold surges in North China during the recent global warming slowdown and the possible linkage to the extreme pressure rises over Siberia. Atmospheric Research, 248:105198. doi:10.1016/j.atmosres.2020.105198

Ding, X., G. Chen, L. Sun and P. Zhang, 2022. Distinct North American cooling signatures following the zonally symmetric and asymmetric modes of winter stratospheric variability. Geophysical Research Letters, 49:e2021GL096076. doi:10.1029/2021gl096076

Hall, R., R. Edélyi, E. Hanna, J.M. Jones and A.A. Scaife, 2015. Drivers of North Atlantic polar front jet stream variability. International Journal of Climatology, 35:1697-1720. doi:10.1002/joc.4121

Harwood, N., R. Hall, G. Di Capua, A. Russell and A. Tucker, 2021. Using Bayesian networks to investigate the influence of subseasonal Arctic variability on midlatitude North Atlantic circulation. Journal of Climate, 34:2319-2335. doi:10.1175/jcli-d-20-0369.1

He, X., R. Zhang, S. Ding and Z. Zuo, 2021. Interdecadal linkage between the winter Northern Hemisphere climate and Arctic sea ice of diverse location and seasonality. Frontiers in Earth Science, 9:758619. doi:10.3389/feart.2021.758619

Huang, J., P. Hitchcock, A.C. Maycock, C.M. McKenna and W. Tian, 2021. Northern Hemisphere cold air outbreaks are more likely to be severe during weak polar vortex conditions. Communications Earth & Environment, 2:147. doi:10.1038/s43247-021-00215-6

Huguenin, M.F., E.M. Fischer, S. Kotlarski, S.C. Scherrer, C. Schwierz and R. Knutti, 2020. Lack of change in the projected frequency and persistence of atmospheric circulation types over Central Europe. Geophysical Research Letters, 47:e2019GL086132. doi:10.1029/2019gl086132

Jolly, E., F. D'Andrea, G. Riviere and S. Fromang, 2021. Linking warm Arctic winters, Rossby waves, and cold spells: An idealized numerical study. Journal of the Atmospheric Sciences, 78:2783-2799. doi:10.1175/jas-d-20-0088.1

Jung, E., J.H. Jeong, S.H. Woo, B.M. Kim, J.H. Yoon and G.H. Lim, 2020. Impacts of the Arctic-midlatitude teleconnection on wintertime seasonal climate forecasts. Environmental Research Letters, 15:094045. doi:10.1088/1748-9326/aba3a3

Kim, S.J. and H.S. Choi, 2021. Role of polar vortex weakening in cold events in central Asia during late winter. Polar Science, 30:100640. doi:10.1016/j.polar.2021.100640

Kim, J. and K.Y. Kim, 2020. Characteristics of stratospheric polar vortex fluctuations associated with sea ice variability in the Arctic winter. Climate Dynamics, 54:3599-3611. doi:10.1007/s00382-020-05191-9

Kretschmer, M., J. Cohen, V. Matthias, J. Runge and D. Coumou, 2018. The different stratospheric influence on cold-extremes in Eurasia and North America. npj Climate and Atmospheric Science, 1:44. doi:10.1038/s41612-018-0054-4

Luo, D., B. Luo and W. Zhang, 2023. A perspective on the evolution of atmospheric blocking theories: From eddy-mean flow interaction to nonlinear multiscale interaction. Advances in Atmospheric Sciences, 40:553–569. doi:10.1007/s00376-022-2194-z

Ma, X., L. Wang, D. Smith, L. Hermanson, R. Eade, N. Dunstone, S. Hardiman and J. Zhang, 2022. ENSO and QBO modulation of the relationship between Arctic sea ice loss and Eurasian winter climate. Environmental Research Letters, 17:124016. doi:10.1088/1748-9326/aca4e9

Martin, J.E., 2021. Recent trends in the waviness of the Northern Hemisphere wintertime polar and subtropical jets. Journal of Geophysical Research-Atmospheres, 126:e2020JD033668. doi:10.1029/2020jd033668

McGraw, M.C. and E.A. Barnes, 2020. New insights on subseasonal Arctic-midlatitude causal connections from a regularized regression model. Journal of Climate, 33:213-228. doi:10.1175/Jcli-D-19-0142.1

Messori, G., M. Kretschmer, S.H. Lee and V. Wendt, 2022. Stratospheric downward wave reflection events modulate North American weather regimes and cold spells. Weather and Climate Dynamics, 3:1215-1236. doi:10.5194/wcd-3-1215-2022

Outten, S., C. Li, M.P. King, L. Suo, P.Y.F. Siew, R. Davy, E. Dunn-Sigouin, S. He, H. Cheung, E. Madonna, T. Furevik, S. Sobolowski, T. Spengler and T. Woollings, 2022. Reconciling conflicting evidence for the cause of the observed early 21st century Eurasian cooling. Weather and Climate Dynamics Discussions. https://wcd.copernicus.org/preprints/wcd-2022-32/wcd-2022-32.pdf

Overland, J.E., 2022. Arctic climate extremes. Atmosphere, 13:1670, doi:10.3390/atmos13101670

Overland, J.E., M. Sigmond, S.-J. Kim, P. Langen, J. Ukita, T. Vihma and M. Wang, 2021a. Arctic/mid-latitude weather connectivity. In: AMAP Arctic Climate Change Update 2021: Key Trends and Impacts. pp. 75-84. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway.

Overland, J.E., T.J. Ballinger, J. Cohen, J.A. Francis, E. Hanna, R. Jaiser, et al., 2021b. How do intermittency and simultaneous processes obfuscate the Arctic influence on midlatitude winter extreme weather events? Environmental Research Letters, 16:043002. doi:10.1088/1748-9326/abdb5d

Overland, J.E., B.M. Kim and Y. Tachibana, 2021c. Communicating Arctic-midlatitude weather and ecosystem connections: direct observations and sources of intermittency. Environmental Research Letters, 16:105006. doi:10.1088/1748-9326/ac25bc

Peings, Y., Z.M. Labe and G. Magnusdottir, 2021. Are 100 ensemble members enough to capture the remote atmospheric response to +2°C Arctic sea ice loss? Journal of Climate, 34:3751-3769. doi:10.1175/jcli-d-20-0613.1

Rantanen, M., A.Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma and A. Laaksonen, 2022. The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment, 3:168. doi:10.1038/s43247-022-00498-3

Screen, J.A., C. Deser, D.M. Smith, X. Zhang, R. Blackport, P.J. Kushner, et al., 2018. Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models. Nature Geoscience, 11:155-163. doi:10.1038/s41561-018-0059-y

Shepherd, T., 2021. Bringing physical reasoning into statistical practice in climate-change science. Climatic Change, 169:2. doi:10.1007/s10584-021-03226-6

Smith, E.T. and S.C. Sheridan, 2019. The influence of atmospheric circulation patterns on cold air outbreaks in the eastern United States. International Journal of Climatology, 39:2080-2095. doi:10.1002/joc.5935

Smith, D., J.A. Screen, C. Deser, J. Cohen, J.C. Fyfe, J. Garcia-Serrano, T. Jung, et al., 2019. The Polar Amplification Model Intercomparison Project (PAMIP) contribution to CMIP6: investigating the causes and consequences of polar amplification. Geoscientific Model Development, 12:1139-1164. doi:10.5194/gmd-12-1139-2019

Song, L. and R. Wu, 2021. Two types of Rossby wave breaking events and their influences on East Asian winter temperature. Journal of Geophysical Research-Atmospheres, 126:e2020JD033917. doi:10.1029/2020jd033917

Sun, L., C. Deser, I. Simpson and M. Sigmond, 2022. Uncertainty in the winter tropospheric response to Arctic sea ice loss: The role of stratospheric polar vortex internal variability. Journal of Climate, 35:3109-3130. doi:10.1175/jcli-d-21-0543.1

Sweeney, A., Q. Fu, S. Po-Chedley, H. Wang and M. Wang, 2023. Internal variability increased Arctic amplification during 1980–2022. Geophysical Research Letters, 50:e2023GL106060. doi:10.1029/2023GL106060

Tyrlis, E., E. Manzini, J. Bader, J. Ukita, H. Nakamura and D. Matei, 2019. Ural blocking driving extreme Arctic sea ice loss, cold Eurasia, and stratospheric vortex weakening in autumn and early winter. Journal of Geophysical Research-Atmospheres, 124:11313-11329. doi:10.1029/2019jd031085

Vihma, T., R. Graversen, L. Chen, D. Handorf, N. Skific, J.A. Francis, N. Tyrrell, R. Hall, E. Hanna, P. Uotila, K. Dethloff, A. Karpechko, H. Björnsson and J.E. Overland, 2020. Effects of the tropospheric large-scale circulation on European winter temperatures during the period of amplified Arctic warming. International Journal of Climatology, 40:509-529, doi:10.1002/joc.6225

Xu, X., S. He, Y. Gao, B. Zhou and H.J. Wang, 2021. Contributors to linkage between Arctic warming and East Asian winter climate. Climate Dynamics, 57:2543-2555. doi:10.1007/s00382-021-05820-x

Yao, Y., W. Zhou, Z. Gong, B. Luo, D. Luo, F. Zheng, L. Zhong, F. Huang, S. Ma, C. Zhu and T. Zhou, 2023. Extreme cold events in North America and Eurasia in November-December 2022: A potential vorticity gradient perspective. Advances in Atmospheric Sciences, 40:953-962. doi:10.1007/s00376-023-2384-3

Zhou, W., L.R. Leung and J. Lu, 2024. Steady threefold Arctic amplification of externally forced warming masked by natural variability. Nature Geoscience, 17:508-515. doi:10.1038/s41561-024-01441-1

Acronyms and Abbreviations

Ω_{ar}	Saturation state for aragonite
Ω_{ca}	Saturation state for calcite
ACIA	Arctic Climate Impact Assessment
ALT	Active-layer thickness
AMAP	Arctic Monitoring and Assessment Programme
AR6	Sixth Assessment Report of the Intergovernmental Panel on Climate Change
CAFF	Conservation of Arctic Flora and Fauna
$CaCO_3$	Calcium carbonate
CALM	Circumpolar Active Layer Monitoring network
C_{ant}	Anthropogenic carbon
CH_4	Methane
CMIP5	The Coupled Model Intercomparison Project phase 5
CMIP6	The Coupled Model Intercomparison Project phase 6
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate ion
DOC	Dissolved organic carbon
EBP	Eastern Biogeochemical Province water
ERA5	European Global Reanalysis version five
ESM	Earth system model
GCM	Global climate model
GPCP	Global Precipitation Climatology Project
HCO_3^-	Bicarbonate ion
IPCC	Intergovernmental Panel on Climate Change
LEO	Local Environmental Observer network/database
MRIT	Maximum river-ice thickness
NDVI	Normalized differential vegetation index
NorESM1-ME	Norwegian Earth System Model
NSIDC	National Snow and Ice Data Center (US)
P-ET	Precipitation minus evapotranspiration
PADB	Pan-Arctic drainage basin
pCO_2	Partial pressure of CO_2
$PM_{2.5}$	Particulate matter with a mean diameter of less than 2.5 µm
RCP	Representative Concentration Pathway
SAT	Surface-air temperature
SCE	Snow-cover extent
SIA	Sea-ice area
SIE	Sea-ice extent
SSP	Shared Socioeconomic Pathway
SST	Sea-surface temperature
SWE	Snow-water equivalent
SWIPA	Snow, Water, Ice and Permafrost in the Arctic (assessment)
WBP	Western Biogeochemical Province water

Arctic Monitoring and Assessment Programme

The Arctic Monitoring and Assessment Programme (AMAP) was established in June 1991 by the eight Arctic countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden and the United States) to implement parts of the Arctic Environmental Protection Strategy (AEPS). AMAP is now one of six working groups of the Arctic Council, members of which include the eight Arctic countries, the six Arctic Council Permanent Participants (Indigenous Peoples' organizations), together with observing countries and organizations.

AMAP's objective is to provide 'reliable and sufficient information on the status of, and threats to, the Arctic environment, and to provide scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions to reduce adverse effects of contaminants and climate change'.

AMAP produces, at regular intervals, assessment reports that address a range of Arctic pollution and climate change issues, including effects on health of Arctic human populations. These are presented to Arctic Council Ministers in 'State of the Arctic Environment' reports that form a basis for necessary steps to be taken to protect the Arctic and its inhabitants.

This report has been subject to a formal and comprehensive peer review process. The results and any views expressed in this series are the responsibility of those scientists and experts engaged in the preparation of the reports.

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