

Infrastructure: Buildings, Support Systems, and Industrial Facilities

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Summary

This chapter discusses the potential impacts of climate change on arctic infrastructure. Particular concerns are associated with permafrost warming and degradation, coastal erosion, the stability and maintenance of transportation routes, and industrial development. Adaptation, mitigation, and monitoring techniques will be necessary to minimize the potentially serious detrimental impacts.

Infrastructure is defined as facilities with permanent foundations or the essential elements of a community. It includes schools; hospitals; various types of buildings and structures; and facilities such as roads, railways, airports, harbors, power stations, and power, water, and sewage lines. Infrastructure forms the basis for regional and national economic growth.

Climate change is likely to have significant impacts on existing arctic infrastructure and on all future development in the region. In most cases, engineering solutions are available to address climate change impacts, thus the issue is more economic than technological. It is possible that the uncertainty associated with projections of future climate change will increase the cost of new projects in the Arctic.

Permafrost engineers must address the problem of preserving infrastructure under projected future climate conditions. One solution is to construct new buildings as existing ones are damaged and abandoned. It is possible that this method will be inadequate, since the required rate of new construction rises exponentially using the climate projections presented in this assessment. In areas of warm, discontinuous permafrost, it is very difficult to find economic solutions to address the impacts of climate change on foundations or structures. These areas, together with the coastal zone where the combined problems of increased wave action, sea-level rise, and thermal erosion have no simple engineering solutions, present the greatest challenges in a changing climate.

Projected increases in temperature, precipitation, and storm magnitude and frequency are very likely to increase the frequency of avalanches and landslides. In some areas, the probability of severe impacts on settlements, roads, and railways from these events is very likely to increase. Structures located on sites prone to slope failure are very likely to be more exposed to slide activity as groundwater amounts and pore water pressures increase.

An increasing probability of slides coupled with increasing traffic and population concentrations is very likely to require expensive mitigation measures to maintain a defined risk level. The best way to address these problems is to incorporate the potential for increasing risk in the planning process for new settlements and transportation routes.

16.1. Introduction

There are increased concerns related to the impact of projected climate change on arctic infrastructure, particularly how future climate change may:

- increase the environmental stresses structures are exposed to, particularly in comparison to design specifications, and cause increased risk and damage to infrastructure and threat to human lives;
- affect geohazards and the impacts of extreme events;
- affect natural resource development scenarios in the Arctic; and
- affect socioeconomic development in the Arctic.

Figure 16.1 presents a flow diagram of the questions that need to be answered in order to complete an impact study. Relevant information from indigenous peoples on infrastructure is given in Chapter 3.

16.2. Physical environment and processes related to infrastructure

Chapter 6 has a detailed presentation of the physical environment and processes in the Arctic related to permafrost (section 6.6), snow cover (section 6.4), precipitation (section 6.2), and sea-ice cover and extent (section 6.3), and can be used as a reference for the discussions presented in this chapter.

16.2.1. Observed changes in air temperature

Changes in arctic climate over the past century can be determined by using data from standard climate stations on land and measurements taken on drifting ice floes in the Arctic Ocean. These data show a consistent trend of increasing air temperatures in the Northern Hemisphere during the 20th century, although the

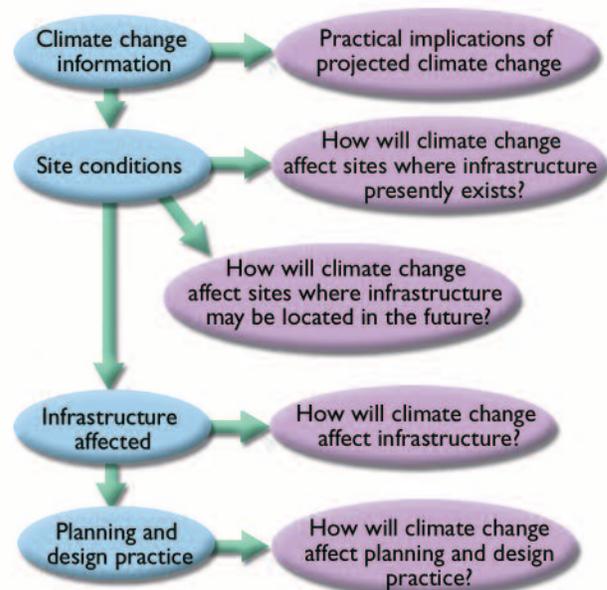
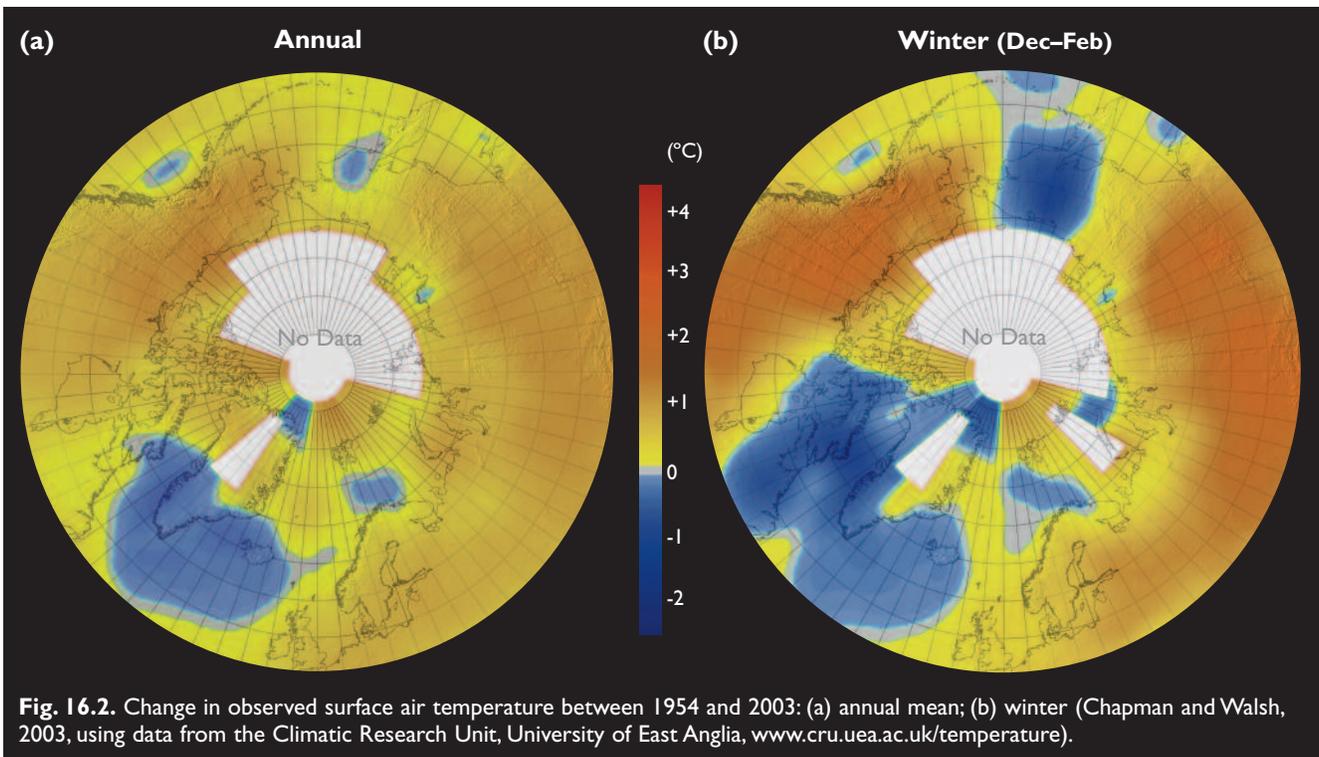


Fig. 16.1. Flow diagram of chapter structure and questions to be answered.



observed changes are not spatially uniform (Anisimov, 2001). While in some regions of the Arctic the warming trend was as great as 5 °C per century, areas of decreasing temperatures were observed in eastern Canada, the North Atlantic, and Greenland (Anisimov and Fitzharris, 2001; Borzenkova, 1999a,b; Jones et al., 1999; Serreze et al., 2000).

Figure 16.2 shows the change in observed surface air temperature between 1954 and 2003 (see also section 2.6.2). Patterns of annual air temperature change indicate that the recent warming has been greatest in Alaska, northwestern Canada, and Siberia (Fig. 16.2a). Temperature increases in winter were much greater than increases in the annual mean temperature: up to 3 to 4 °C over Alaska, northwestern Canada, and Siberia (Fig. 16.2b). In southern Greenland and Iceland, annual mean temperatures decreased by approximately 1 °C, while winter temperatures decreased by 1 to 2 °C. A winter temperature decrease of 1 to 2 °C was also observed in Chukotka.

On the North Slope of Alaska and in northern Siberia, air temperatures increased by 2 to 4 °C, while the global mean air temperature increase over the 20th century was only about 0.6 °C. This pattern is consistent with the hypothesis that the contemporary warming is largely caused by anthropogenic greenhouse gas emissions. Section 2.6.2 discusses observed arctic temperature changes in detail, while section 4.4.2 provides projections of future arctic temperature change.

16.2.2. Permafrost

Permafrost underlies most of the surfaces in the terrestrial Arctic. Permafrost depths vary from a few to

many hundreds of meters (Brown et al., 1997).

At selected locations in Yakutia with a cold continental climate, permafrost occurs to depths of 1500 m. Most biogeochemical and hydrological processes in permafrost are confined to the active (seasonally thawed) layer, which varies from several tens of centimeters to several meters in depth. Seasonal thaw depth and the temperature of the frozen ground are two important parameters that must be accounted for in the design of infrastructure built on permafrost. These parameters control key cryogenic processes, such as creep, thaw settlement, adfreeze bond (bond between frozen soil and the material embedded in it), frost heave, and frost jacking (annually repeated foundation uplift caused by frost heave; see Andersland and Ladanyi (1994) for further discussion of these processes). Seasonal thaw depth and frozen-ground temperature both depend on ground-surface temperature, heat flow from the interior of the earth, snow cover, vegetation, and soil properties.

Owing to their low thermal conductivity, snow cover and vegetation (with the underlying organic layer) attenuate annual variations in air temperature and are important regulators of permafrost temperature and depth of seasonal thaw at the local scale. The temperature of permafrost under a thick layer of snow may be several degrees higher than in nearby permafrost that lacks snow cover. In summer, the thermal conductivity of the vegetation and underlying organic layer is typically much smaller than in winter. This reduces summer heat fluxes and keeps permafrost temperatures lower than they would be in the absence of vegetation. A controlled experiment near Fairbanks, Alaska, produced permafrost degradation to a depth of 6.7 m over a 26-year period, simply by removing the insulating

layer of vegetation (Linell, 1973). Finally, thermal conductivity is typically 20 to 35% lower in thawed mineral soils than in frozen mineral soils. Consequently, the mean annual temperature below the level of seasonal thawing may be 0.5 to 1.5 °C lower than on the ground surface.

The extreme arctic environment requires unique cold-regions engineering and infrastructure solutions that account for severe climate conditions, the presence of permafrost, and various cryogenic processes that may have destructive effects on structures. Since infrastructure is designed to withstand variations in environmental parameters within a prescribed range, information about past changes in arctic climate and environmental conditions is crucial for developing optimum engineering solutions for future infrastructure and safe management of existing structures.

16.2.2.1. Observed changes in permafrost

Changes in permafrost temperature due to increasing air temperatures were observed in Russia as early as 1970. Pavlov (1997) presented data indicating that the mean annual permafrost temperature increased by 2.0 to 2.5 °C at a depth of 3 m and by 1.0 °C at a depth of 10 m between 1979 and 1995. Observations of soil temperature changes at the Marre-Sale geocryological station in the southwestern region of the Yamal Peninsula (Table 16.1) are especially illustrative. Similar changes have been observed in Alaska (Osterkamp and Romanovsky,

1999) and elsewhere (section 6.6.1.2). Changes in active-layer thickness have also been observed.

The Global Terrestrial Network for Permafrost (GTN-P) and the Circumpolar Active Layer Monitoring (CALM) program were established to monitor such changes. The GTN-P was initiated by the International Permafrost Association (IPA) to organize and manage a global network of permafrost observatories for detecting, monitoring, and projecting climate change (Burgess et al., 2000b). The network, authorized under the Global Climate Observing System and its associated organizations, consists of two observational components: the active layer and the thermal state of the underlying permafrost. CALM, established in 1990, provides the active-layer monitoring component (Brown et al., 2000), while GTN-P provides monitoring of the thermal state of the permafrost. The European Community project, Permafrost and Climate in Europe, contributes to the GTN-P and monitors nine boreholes in mountain permafrost (see also IPCC, 2001).

16.2.2.2. Observed changes in freezing and thawing indices

The strength and deformation characteristics of frozen soils are dependent on soil type, temperature, density, ice content, unfrozen water content, salinity, stress state, and strain rate (section 16.2.2.5). Thawing of frozen soil, or even an increase in the temperature of frozen soil, may lead to deteriorating strength and deformation characteristics, accelerated settlement, and possible foundation failure.

The design of foundations in permafrost regions must, therefore, always include an evaluation of the maximum active-layer thickness and permafrost temperature that may occur in the foundation soils during the lifetime of the structure. The initial and long-term bearing capacity of the foundation can then be determined.

Table 16.1. Soil temperatures measured between 1979 and 1995 at the Marre-Sale station, southwestern Yamal Peninsula, Russia (Pavlov, 1997).

Description of ground surface and subsurface soil type	Depth (m)	Soil temperature (°C)	
		Mean	Increase
Slope with willow–green moss cover; sand to 0.7 m, loam	3	-5.4	2.2
	6	-5.3	1.2
	10	-5.2	0.8
Horizontal hilly peatland with grass–shrub–moss–lichen cover; peat to 0.75 m, ice, sand	3	-5.6	1.1
	6	-5.6	1.0
	10	-5.6	0.7
Polygonal tundra with moss–lichen–grass–shrub cover; sand	3	-6.5	1.3
	6	-6.5	1.1
	10	-6.4	0.6
Runoff zone on gentle southern slope, cloudberry–sedge–sphagnum–hypnum bog; sand, loam	3	-3.6	0.5
	6	-3.8	0.2
	10	-3.9	0.1
Bottom of dried lakes, meadow bottom with sedge–hypnum bog; peat-enriched sand	3	-3.4	1.1
	6	-3.8	0.7
	10	-3.9	0.5
Hilly and tussocky polygonal tundra covered with shrub, grass, and lichen; sand	3	-4.2	1.2
	6	-4.4	1.0
	10	-4.4	0.7

Table 16.2. Number of meteorological stations in each ACIA region (Instanes and Mjureke, 2002a).

	ACIA region	Number of stations
Iceland	1	1
Svalbard	1	1
Norway and Finland	1	2
Northwest Russia	1	1
Siberia	2	6
Alaska	3	5
Canada	4	3
Greenland	4	2
Region 1: Arctic Europe, East Greenland, European Russian North, North Atlantic		
Region 2: Central Siberia		
Region 3: Chukotka, Bering Sea, Alaska, western arctic Canada		
Region 4: Northeast Canada, Labrador Sea, Davis Strait, West Greenland		

Instanes A. (2003) presented a review of the use of air freezing and thawing indices for permafrost engineering design. The air thawing index (ATI) is a useful parameter to determine the “magnitude” of the thawing season and can be used to calculate active-layer thickness and maximum permafrost temperatures. The air thawing index is defined as the integral of the sinusoidal variation in mean daily or monthly air temperature (T) during one year for $T > 0$ °C (the air freezing index, AFI, is defined as the integral of the sinusoidal air temperature variation during one year for $T < 0$ °C).

Ground-surface temperatures differ from air temperatures. If observations of ground-surface temperatures are not available, they can be estimated from air temperatures using an empirically determined n -factor. Andersland and Ladanyi (1994) listed approximate n -factors for different types of surfaces. Variations in snow cover will also affect ground temperatures.

Instanes A. and Mjureke (2002a) carried out an extensive analysis of historic freezing and thawing indices for arctic meteorological stations. Many of these stations have more than 100 years of continuous temperature records. The data used in this analysis were mean monthly air temperatures from Russian datasets pro-

vided by O. Anisimov (State Hydrological Institute, St. Petersburg, Russia, 2001).

Twenty-one stations were chosen for this study, using the following criteria:

- the four ACIA regions (section 18.3) should be represented;
- station time series should be of considerable length (>30 years);
- station time series should be continuous;
- priority should be given to meteorological stations located near population concentrations and major infrastructure; and
- stations should be evenly distributed throughout the Arctic.

All the stations are north of 60° N and within the area covered by the Arctic Monitoring and Assessment Programme (AMAP) and the ACIA. Table 16.2 shows the number of stations in each ACIA region.

From an engineering point of view, current and past design levels of thawing and freezing indices are of interest mainly in comparison with values projected for the future. The impact of climate change on arctic

Table 16.3. Percentage of unusually warm summers and unusually warm winters between 1981 and 2000 (Instanes and Mjureke, 2002a).

Station	Location	Summer			Winter		
		Observed 1981–2000 ^a (%)	Expected ^b (%)	Trend ^c	Observed 1981–2000 ^d (%)	Expected ^b (%)	Trend ^c
Akureyri	Iceland	22	17	(+)	19	17	0
Ammassalik	Greenland	0	19	-	7	19	-
Anadyr	Russia	15	20	(-)	18	19	0
Barrow	Alaska	39	24	+	46	24	+
Bethel	Alaska	37	25	+	31	25	(+)
Kuglutuk (Coppermine)	Canada	60	32	+	49	32	(+)
Coral Harbour	Canada	29	35	(-)	37	35	0
Fairbanks	Alaska	52	21	+	28	20	(+)
Fort Smith	Canada	46	24	+	55	24	+
Naryan-Mar	Russia	33	26	(+)	18	26	(-)
Nome	Alaska	50	20	+	33	20	+
Nuuk	Greenland	0	14	-	5	14	-
Salekhard	Russia	35	17	+	29	16	+
Sodankylä	Finland	7	21	-	15	21	(-)
Svalbard Airport	Svalbard	47	25	+	26	25	0
Turukhansk	Russia	20	17	0	33	17	+
Valdez	Alaska	64	24	+	80	24	+
Vardø	Norway	9	13	0	21	13	(+)
Verkhoyansk	Russia	40	17	+	51	17	+
Vilyuysk	Russia	34	19	+	41	19	+
Yakutsk	Russia	22	16	(+)	50	16	+

^apercentage of years with an air thawing index higher than the mean for the entire period of record plus one standard deviation; ^bthe value from an ideal random data series, without trends; ^c + indicates warming, (+) indicates weak or possible warming, 0 indicates no trend, (-) indicates possible or weak cooling, and - indicates cooling; ^dpercentage of years with an air freezing index lower than the mean for the entire period of record minus one standard deviation.

infrastructure will be very dependent on how future temperature levels relate to past design levels and historic variability at a specific site. However, an analysis of historic records in terms of freezing and thawing indices can provide indications of temperature increases between 1981 and 2000 (Instanes A. and Mjureke, 2002a).

Table 16.3 presents the percentage of unusually warm summers and unusually warm winters between 1981 and 2000. An unusually warm summer is defined as having an ATI higher than the mean value for the entire station record plus one standard deviation; an unusually warm winter is defined as having an AFI lower than the mean value for the entire station record minus one standard deviation.

Five stations exhibit both significant winter air temperature increases after 1970 and an unusually high frequency of warm winter events between 1981 and 2000. These stations are Fort Smith (Canada), Valdez (Alaska), and Verkhoyansk, Vilyuysk, and Yakutsk (central Russia). Four additional stations had a significantly high frequency of warm winter seasons between 1981 and 2000: Barrow and Nome (Alaska), and Salekhard and Turukhansk (central Russia). Two Greenland stations, Ammassalik and Nuuk, show clear evidence of a recent decrease in winter air temperatures.

Eight stations show evidence of significant recent summer air temperature increases in combination with a significantly high number of very warm summer seasons between 1981 and 2000 compared to the entire period of record. These are Barrow, Fairbanks, Nome, and Valdez (Alaska); Kuglutuk (Coppermine) and Fort Smith (Canada); Svalbard Airport; and Verkhoyansk (Central Russia). Bethel (Alaska) and Salekhard and Vilyuysk (central Russia) had a significantly high frequency of warm summer seasons between 1981 and 2000.

The two Greenland stations and Sodankylä (Finland) show evidence of recent air temperature decreases in both the mean ATI and the extreme summer values.

Table 16.4. Comparison of maximum thaw depths simulated for 1990–1999 and 2090–2099 (Instanes A. and Mjureke, 2002b).

	Maximum thaw depth ^a (m)		Increase (%)
	1990–1999	2090–2099	
Barrow	0.7	1	43
Bethel	1.8	13	622
Naryan-Mar	1.4	1.8	29
Nuuk	1.1	1.7	55
Svalbard Airport	0.8	1.1 ^b	38
Turukhansk	1.3	1.6	23
Verkhoyansk	1.4	1.5	7

^aThaw depths calculated for a theoretical sandy soil layer. Soil profile may not be representative for every location; ^bprojection for 2040–2049.

The results suggest a spatial pattern of recent climate change and are in agreement with results from other studies (e.g., AMAP, 1997). According to Table 16.3, temperatures have increased in central Russia, Alaska, and western Canada, while temperatures have decreased in southern Greenland. The trends are less clear in the Nordic countries and northwestern Russia.

16.2.2.3. Projected changes in permafrost

A constant rate of increase in air temperature is projected to have two related effects on ground temperature:

- an increase in the mean annual temperature at the ground surface, which will slowly propagate to greater depths and, depending on latitude, produce either a thinning or a complete disappearance of the permafrost layer; and
- changes in the annual amplitude of seasonal ground-temperature variation, damped with depth, and affected by related changes in precipitation (snow cover), groundwater hydrology, and vegetation. However, Riseborough (1990) pointed out that at temperatures close to 0 °C, latent heat effects may dominate and result in a smaller amplitude depending on the ice content of the soils.

Climate change is very likely to reduce the area occupied by frozen ground and to cause shifts between the zones of continuous, discontinuous, and sporadic permafrost. These changes can be projected using mathematical models of permafrost driven by scenarios of climate change. Projections of permafrost change in 2030, 2050, and 2080 using output from the five ACIA-designated climate models are presented in section 6.6.1.3.

The potential effects of increasing mean annual ground-surface temperature on permafrost will be very different for continuous and discontinuous permafrost zones. In the continuous zones, increasing air temperatures are very likely to increase permafrost temperatures and possibly increase the depth of the active layer (Burgess

Table 16.5. Mean ground-surface temperature for 1990–1999 (observed) and 2090–2099 (simulated) and the resulting loss in soil bearing strength at 10 m depth between the two periods (Instanes A. and Mjureke, 2002b; strength loss calculated after Ladanyi, 1996).

	Mean ground-surface temperature (°C)		Soil strength loss (%)
	1990–1999	2090–2099	
Barrow	-12	-7	23
Bethel	-2	0	40
Naryan-Mar	-4	-3	12
Nuuk	-2.5	-0.5	34
Svalbard Airport	-6	-4 ^a	17
Turukhansk	-7	-5	15
Verkhoyansk	-16	-12	14

^aProjection for 2040–2049.

et al., 2000a; Esch and Osterkamp, 1990; Osterkamp and Lachenbruch, 1990). In the discontinuous zone, the effects of a few degrees increase in the mean annual permafrost temperature are very likely to be substantial (Harris, 1986). Since the temperature of most of this permafrost is presently within a few degrees of the melting point, the permafrost is likely to disappear. Except for the southernmost zone of sporadic permafrost, many centuries will be required for the frozen ground to disappear entirely. However, increases in active-layer depth and thawing of the warmest permafrost from the top have already been observed (Burgess et al., 2000a; Esch and Osterkamp, 1990; Harris, 1986; Osterkamp and Lachenbruch, 1990).

Anisimov et al. (1997) used a permafrost model and climate scenarios for 2050 produced by general circulation models (GCMs) to project changes in active-layer thickness in the Arctic. The results of this study indicated that changes in active-layer thickness will vary by region, increasing by 10 to 15% to more than 50% between the mid-1990s and 2050. Instanes A. and Mjureke (2002b) used the ACIA-designated models (section 4.2.7) to project changes in active-layer thickness and maximum permafrost temperature for seven of the sites in Table 16.3: Barrow, Bethel, Naryan-Mar, Nuuk, Svalbard Airport, Turukhansk, and Verkhoyansk. The analysis used an identical soil profile with the same thermal properties for all the locations; therefore, it can only be used as an indication of relative climate differences between sites. The increase in maximum thaw depths between 1990–1999 and 2090–2099 and the changes in mean ground-surface temperature and soil bearing strength between 1990–1999 and 2090–2099 are presented in Tables 16.4 and 16.5, respectively.

The response of permafrost to climate change involves an important temperature threshold associated with

phase change beyond which future temperature increases will cause thawing of the frozen ground. The time required to reach this temperature threshold depends on the initial permafrost temperature and the rate of temperature increase. Table 16.6 presents projected changes in various types of permafrost soils for different rates of warming.

The projections discussed in this section suggest that a progressive increase in active-layer depth and temperature of the frozen ground is likely to be a relatively short-term reaction to climate change in permafrost regions. Changes in seasonal thaw depth are very likely to change the water-storage capacity of near-surface permafrost at local and regional scales, with substantial effects on vegetation, soil hydrology, and runoff, which will ultimately lead to changes in larger-scale processes such as landslides, erosion, and sedimentation.

With respect to cold-regions engineering and infrastructure in locations affected by permafrost, the temperature of the frozen ground and the depth of seasonal thawing is of critical importance for effective construction planning and the evaluation of potentially hazardous situations at existing facilities. Although the effects of an increase in mean annual air temperature on permafrost can be projected in a general sense, it is more difficult to project these effects for specific locations and regions. Factors such as microclimate, as well as soil type, ice content, and salinity will play a role, and may not necessarily be well known or readily projected (Riseborough, 1990; Smith M. and Riseborough, 1983, 1985).

16.2.2.4. Projected changes in freezing and thawing indices

Freezing and thawing indices were calculated using mean monthly air temperatures projected for 2000 to

Table 16.6. Projected changes in permafrost soils between 2000 and 2100 for different rates of increase in mean annual air temperature and different soil types (Parmuzin and Chepurinov, 2001).

Warming trend (°C/yr)	T _{ini} (°C)	T ₂₁₀₀ (°C)			Year thawing begins			Thaw depth in 2100 (m)		
		0.06	0.03	0.01	0.06	0.03	0.01	0.06	0.03	0.01
Sands, loamy sands, loams	-7 to -9	-2 to -4	-5 to -7	-6 to -8	no permafrost thawing			<1.5	<1.2	<0.8
Sands								<6	<1.3	<0.8
Loamy sands, loams	-5 to -7	-1 to -2	-2 to -4	-4 to -6	2080–2090	no permafrost thawing		<3.5		
Peat								<1.5		
Sands								6–13	<6	<1.2
Loamy sands, loams	-3 to -5	-0.5 to -1	-1 to -2	-2 to -4	2050–2070	2080–2100	little thawing	3.5–8	<4	
Peat								1.5–3		
Sands								13–20	10–15	<1.2
Loamy sands, loams	-1 to -3	0 to -0.5	0 to -1	-0.5 to -2	2010–2040	2030–2080	little thawing	8–15	6–8	
Peat								3–5	<4	
Sands								15–25	13–20	10–15
Loamy sands, loams	0 to -1		~0		2000–2010	2010–2030	2060–2090	10–16	7–12	1.5–4
Peat								4–6	<5	<1.5

T_{ini}: initial mean annual temperature of permafrost soils; T₂₁₀₀: mean annual temperature of permafrost soils projected for 2100.

2100 by the ACIA-designated climate models for the 21 stations shown in Table 16.3 (Instanes A. and Mjureke, 2002b). Output from four of the five ACIA-designated models (CGCM2 – Canadian Centre for Climate Modelling and Analysis, CSM_1.4 – National Center for Atmospheric Research, GFDL-R30_c – Geophysical Fluid Dynamics Laboratory, and HadCM3 – Hadley Centre for Climate Prediction and Research) was used for the analysis, along with a composite four-model mean (MEAN4).

In addition, results from empirical downscaling (Hanssen-Bauer et al., 2000) using the 2 m air temperature field from the ECHAM4/OPYC3 GSDIO integration (see section 4.6.2) were applied to Svalbard Airport.

Figures 16.3 and 16.4 show observed and projected freezing and thawing indices for Kugluktuk (Coppermine), Canada, from 1933 to 2100. The indices for 1933 to 2000 were calculated from meteorological observations, while the indices from 2000 to 2100 are based on output from the ACIA-designated models.

The figures show that the projections based on output from the different models “fit” the observed record to

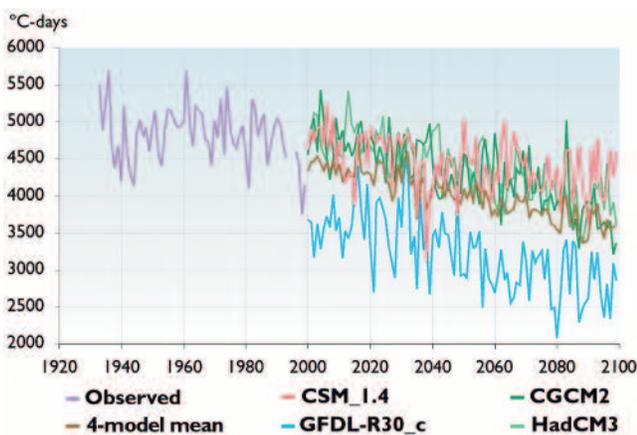


Fig. 16.3. Observed and projected freezing indices for Kugluktuk (Coppermine), Canada (Instanes A. and Mjureke, 2002b).

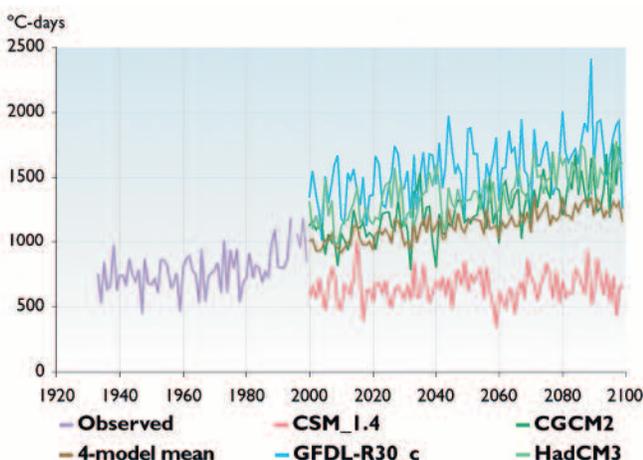


Fig. 16.4. Observed and projected thawing indices for Kugluktuk (Coppermine), Canada (Instanes A. and Mjureke, 2002b).

varying degrees. This is one of the major problems with using GCMs for impact studies. However, indices computed using output from the different models show generally similar trends. This suggests that the raw model output can probably be adjusted so that computed indices start where the observations leave off, providing better projections of future trends in freezing and thawing indices.

Plots similar to Figs. 16.3 and 16.4 showing observed and projected freezing and thawing indices for the 21 stations in Table 16.3 are reported by Instanes A. and Mjureke (2002b).

16.2.2.5. Engineering concerns

The physical and mechanical properties of frozen soils are generally temperature-dependent, and these dependencies are most pronounced at temperatures within 1 to 2 °C of the melting point. Esch and Osterkamp (1990) summarize most of the engineering concerns related to permafrost warming as follows.

- Warming of permafrost body at depth.
 - a. Increase in creep rate of existing piles and footings.
 - b. Increased creep of embankment foundations.
 - c. Eventual loss of adfreeze bond support for pilings.
- Increases in seasonal thaw depth (active layer).
 - a. Thaw settlement during seasonal thawing.
 - b. Increased frost-heave forces on pilings.
 - c. Increased total and differential frost heave during winter.
- Development of residual thaw zones (taliks).
 - a. Decrease in effective length of piling located in permafrost.
 - b. Progressive landslide movements.
 - c. Progressive surface settlements.

Frozen-ground behavior

A constant rate of surface temperature increase due to projected climate change is very likely to lead to an increase in active-layer thickness. Woo et al. (1992), Kane et al. (1991), and Nakayama et al. (1993) attempted to simulate numerically the increase in active-layer thickness projected to result from climate change. Comparable simulations have been performed for three locations in the Mackenzie Basin, Canada (Burgess et al., 2000a).

In contrast to frozen rocks and dense gravels, whose strength depends mainly on mineral bonds and internal friction, the bulk of the mechanical strength of fine-grained frozen soils is due to ice bonding. Rising surface temperatures are likely to increase the unfrozen water content of fine-grained soils and decrease the ice bonding (cohesion) of soil particles, resulting in a gradual loss of strength in these soils.

Soil and rocks can be classified by their sensitivity to climate change, similar to the classification normally used in permafrost engineering. In order of increasing sensitivity (defined by the potential impacts of climate change on strength and thaw settlement), geological materials are classified as follows.

1. Rocks
 - dense, with ice only in pores; and
 - shattered, with ice filling cracks and fissures (an existing rock mass classification system can be used for evaluating the degree of fragmentation and fissures).
2. Gravels and sands (according to their density and moisture content).
3. Silts (according to their density and moisture content).
4. Clays (according to their density and moisture content).
5. Organic soils and peat.
6. Ground ice.

Andersland and Ladanyi (1994) provided a more detailed classification of frozen soils.

Frozen soil will settle to a certain extent when completely thawed. For a given soil type, the amount of thaw settlement can be related to the increase in active-layer thickness, the soil bulk or dry density, and its ice saturation or total water content. Several correlations between the unit thaw settlement and the physical properties of frozen soils have been published (Haas and Barker, 1989; Johnson et al., 1984; Johnston, 1981; Ladanyi, 1994; McRoberts et al., 1978; Nixon, 1990a; Speer et al., 1973). One such correlation relates the percentage of thaw settlement to the frozen bulk density and is the preferred methodology for engineering purposes (first published by Speer et al., 1973, and completed by Johnston, 1981). In the last

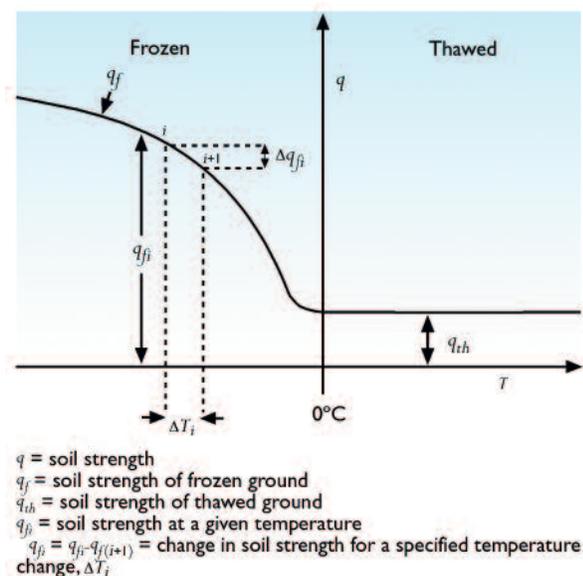


Fig. 16.5. Variation in frozen-soil strength with temperature (Ladanyi, 1996).

20 years, several such correlations between thaw settlement and frozen bulk density for a wide range of frozen soils have been published (Haas and Barker, 1989; Leroueil et al., 1990; Nelson R. et al., 1983), and some have also been expressed by empirical equations. “Thaw sensitivity maps” for specific permafrost regions can be created using information from climate models, surficial geology maps, organic soil maps, ground temperature data, and the above-mentioned correlations. Smith S. et al. (2001), Smith S. and Burgess (1998, 1999, 2004) and Nelson F. et al. (2002) have constructed such maps for Canada and the circumpolar Arctic.

The strength of frozen soil depends not only on temperature, but also on soil density, ice content, and salinity. It is also affected by the degree of confinement and the applied strain rate.

The sensitivity of frozen-soil strength to a temperature increase can be expressed by the ratio:

$$S_T = \frac{\Delta q_{fi}}{q_{fi}} \quad \text{Eqn. 16.1}$$

where q_{fi} is the strength at temperature $\theta_i = -T_i$, and Δq_{fi} is its variation due to a temperature increase ΔT_i (see Fig. 16.5). The strength sensitivity index can also be expressed in terms of frozen soil creep parameters (Ladanyi, 1995, 1996, 1998).

The strength sensitivity index, S_T , defined in equation 16.1, may be a useful measure for evaluating the loss of strength in frozen soils in regions where climate change is not projected to cause complete permafrost thawing. The index requires information about the temperature sensitivities of strength and creep in typical arctic soils. Although some information already exists, further laboratory and field tests of permafrost soils are required. By combining information about permafrost occurrence, soil types and characteristics, and projected climate change, it may be possible to construct maps of projected effects on permafrost. Such maps would show not only the projected trends in active-layer depth and permafrost thawing, but also the projected reduction in permafrost strength. Permafrost sensitivity maps of this kind would be useful for projecting the effects of climate change on existing facilities in the Arctic, and for establishing guidelines for the design of new facilities. Vyalov et al. (1988) proposed the delineation of permafrost sensitivity zones in the Arctic, based on the mean annual ground temperature of permafrost (often measured at the level of negligible annual temperature amplitude, 10 to 20 m below the surface).

Frost heave is the result of ice lenses developing as soils freeze. Temperatures below 0 °C and frost-susceptible soils are required for frost heave to occur, while the availability of water and the freezing rate determine the degree of frost heave. The first two

conditions generally do not differ much between permafrost and seasonal freezing regions. However, the availability of groundwater for ice accumulation in the active layer is different in the two regions. The active layer is generally thinner in permafrost regions, thus the freezing rate is rapid and there is less time available for ice lens growth. In addition, the presence of nearly impermeable permafrost below the active layer may limit the water available for lens formation in permafrost areas, so that for comparable soil conditions there is less frost heave in permafrost regions than in regions of seasonal freezing. An increase in the mean annual air temperature is very likely to increase the thickness of the layer subjected to freeze-thaw cycles and subsequent frost heave.

Thaw settlement and pile creep

An increase in the mean annual air temperature in permafrost regions is very likely to lead to an increase in the thickness of the active layer, resulting in increased thaw settlement during seasonal thawing; and is very likely to lead to a decrease in frozen-ground creep strength (long-term strength of frozen soil), resulting in an increase in the creep settlement rate of existing piles and footings.

Numerical simulations that assume a specific rate of warming have been used to project the degree of settlement effects on existing and future structures in the Arctic. Nixon (1990a,b, 1994) used a one-dimensional geothermal model and assumed a mean surface temperature increase of 0.1 °C/yr for 25 years to examine the effects on thaw depth and pile creep settlement. The simulation of thaw depth below insulated surfaces in discontinuous permafrost projects a doubling of thaw depth after 25 years compared to a case with no temperature increase.

Thawing of permafrost soils can result in subsidence of the surface, thermokarst, and activation of freeze-thaw related processes such as solifluction. Parmuzin and Chepurinov (2001) projected soil subsidence in sandy loam soils by 2100 given different rates of warming and different soil ice content (Table 16.7). Other studies have projected the thaw settlement potential for Mackenzie Basin soils (Aylsworth et al., 2000; Burgess et al., 2000a; Burgess and Smith, 2003).

Such projections of the possible consequences of climate change may help inform the design of future facilities in permafrost regions.

16.2.2.6. Areas south of the permafrost border

In the Arctic and subarctic, there are large land areas south of the permafrost border that experience frost action during winter. Annual freezing of the top soil layer commonly causes frost heave of foundations and structures. Highway structures and embankments located above the frost-heave zone usually experience increased surface roughness and bumps (Andersland and Ladanyi, 1994). During the spring thaw, the bearing capacity of the structure may be considerably reduced, causing breakup of the pavement structure and failure of the embankment. It is possible that projected climate change will reduce the problems associated with winter frost action in these areas.

16.2.2.7. Summary

It is possible that projected climate change will be a factor in engineering projects if its effects go beyond those anticipated within the existing conservative design approach. Therefore, engineering design should take into account projected climate change where

Table 16.7. Projected soil subsidence between 2000 and 2100 due to the thawing of frozen deposits in sandy loam soils (Parmuzin and Chepurinov, 2001).

Initial (2000) permafrost soil temperature (°C)	Volumetric ice content of soil (%)	Air temperature increase (°C/yr)		
		0.06	0.03	0.01
Subsidence by 2100 (m)				
-7 to -9	>40	no subsidence	no subsidence	no subsidence
	>40	<1.5		
-5 to -7	20–40	0.4–0.7	no subsidence	no subsidence
	<20	<0.5		
-3 to -5	>40	1.5–3.5	0.5–1.0	
	20–40	0.7–1.5	<0.5	no subsidence
	<20	<0.7	<0.1	
-1 to -3	>40	3.5–6.0	1.0–1.5	
	20–40	1.5–3.5	0.5–1.0	no subsidence
	<20	<1.5	<0.5	
0 to -1	>40	5.5–6.5	3.5–5.0	<0.5
	20–40	3.5–5.5	1.5–3.5	<0.3
	<20	<3.5	<0.5	<0.1

appropriate and where the potential effects represent an important component of the geothermal design.

The sensitivity of permafrost soil strength to projected climate change can be mapped using a simple strength sensitivity index, such as the one proposed in this section. A risk-based procedure for analyzing structures based on their sensitivity to the potential consequences of climate change is a reasonable approach to incorporating climate change concerns into the design process (section 16.4.1). The project-screening tool developed and currently in use in Canada is a very good guideline for such an approach (Bush et al., 1998).

16.2.3. Natural hazards

In some regions of the Arctic, climate change is projected to lead to increasing temperature and precipitation (sections 4.4.2, 4.4.3, and 6.2.3) and increasing storm frequency (Hanssen-Bauer and Forland, 1998). The type of precipitation is very likely to change as the temperature increases. Where the average winter temperature is close to 0 °C, a higher frequency of precipitation falling as rain instead of snow is expected. Runoff from the arctic river basins is likely to increase due to greater snow depth resulting from increased winter precipitation and to increased thawing of permafrost resulting from surface warming in summer. Greater winter snow depth coupled with rapid melting caused by higher spring temperatures is likely to increase the possibility of floods in the arctic river basins and increase erosion in thawing permafrost riverbanks. Thawing permafrost and increasing depth of the thawed layer are likely to make slopes vulnerable to slides caused by erosion, increasing pore water pressure, and earthquakes.

Floods and slides in soil, rock, and snow are directly or indirectly connected to weather phenomena. Slides in soil and rock can also be triggered by earthquakes. Most structures in the Arctic are located and designed based on historic observations of extreme weather events to meet defined criteria for acceptable risk. Climate change is very likely to change the probability of natural hazard occurrences. This implies that criteria for the location and design of infrastructure must be revised to keep risks at defined levels.

16.2.3.1. Infrastructure and natural hazards

Settlements are often located in areas of low hazard risk to avoid floods, mudflows, slides, and avalanches. River embankments are designed to control rivers during extreme flood events. The location and design of communities and structures are determined based on the risk of hazard occurrence (e.g., permanent settlements in Norway are only permitted in areas where the annual probability of natural hazards is less than 1×10^{-3}). Highways and railways crossing steep terrain are located where the risk of closure and accidents due to natural hazards is acceptable, or can be mitigated by protection facilities (e.g., snow sheds).

Houses, highways, roads, railways, transmission lines, and other infrastructure are sometimes located in areas exposed to snow accumulation and drifting. Highways and railways may be subjected to traffic restrictions or closure by high wind velocities and related snow drifting. To avoid dangerous snow accumulation, regulations in some areas dictate that houses and transmission lines are located in terrain where snow depths are acceptable or appropriate protection has been installed. At present, regulations governing the design of these facilities are based on acceptable risks of extreme snow depth, ice loads, wind forces, and storm frequencies.

16.2.3.2. Factors affecting slope stability and failure

Acceptable risk is directly related to the probability of slides and avalanches. Factors important to slope stability include the groundwater regime, and erosion caused by surface water flow, freeze–thaw processes, and human activity. The groundwater regime is affected by precipitation and meltwater infiltration. For a specific slope, the probability of slides can often be related to threshold values for water infiltration caused by the intensity and duration of rain and snowmelt.

Snow accumulation in avalanche release areas in mountainous regions of the Arctic (Scandinavia, Iceland, Russia, and North America) is dependent on wind velocity and duration in addition to the intensity of snowfall. Avalanche probability depends primarily on the rate of snow accumulation in the release area. The probability of slush avalanches (where water-saturated snow releases as a slide) is related to the porosity and permeability of the snow, which play a key role in snow stability. Slush avalanches release when the rate of water infiltration by rain and snowmelt reaches a threshold value for the specific type of snow on the slope.

Thawing of permafrost caused by climate change will possibly also influence the stability of a particular site. As shown in section 16.2.2.5, the strength of frozen soil drops rapidly as the temperature rises above 0 °C. The development of a weak saturated layer between frozen and unfrozen material can trigger landslides; slopes along arctic rivers are particularly sensitive to failure due to erosion of the toe of the slope (Dyke et al., 1997; Dyke, 2000). Such landslides are known as active-layer detachment slides or skin flows, which can also be triggered by forest fires that burn away the insulating organic layer, leading to increased absorption of solar radiation and more rapid thaw of the active layer.

Reservoirs are used to control flooding in some watersheds, but most arctic watersheds are unregulated. Flood intensity is dependent on precipitation and snowmelt rates and is tempered by the ability of the soil ability to absorb water.

Mudflows and debris flows are triggered as a consequence of a rapid increase in pore water pressure

together with runoff-induced erosion (Sandersen et al., 1996). They occur during periods of intense rainstorms or as a consequence of rapid melting of snow and ice. Severe mudflows can also occur as a result of rapid drainage of glacier-dammed lakes due to glacial melting; examples of this phenomenon include the catastrophes in the Sima Valley (Norway) in 1893 and 1937, and in the city of Tyrnyauz (Caucasus) in 1977 and 1992 (Seinova, 1991; Seinova and Dandara, 1992).

16.2.3.3. Potential impacts of climate change on avalanche and slide activity

The ACIA-designated climate models forced with the B2 emissions scenario project that mean annual arctic temperatures (60°–90° N) will increase 1.2 °C by 2011–2030, 2.5 °C by 2041–2060, and 3.7 °C by 2071–2090 compared to the 1981–2000 baseline (5-model average, see section 4.4.2). The increase is projected to have an uneven spatial distribution, with the greatest increase in the Russian and Canadian Arctic, and the smallest increase in areas close to the Atlantic and Pacific coasts (IPCC, 2001). The changes are also projected to vary seasonally, with the greatest temperature increases occurring in winter.

The Norwegian Meteorological Institute projects that temperatures in Norway will increase by 0.2 to 0.7 °C between 2000 and 2010. The greatest increase is projected to occur in part of the Norwegian Arctic in winter (Haugen and Debenard, 2002). Regional down-scaling of temperature projections for other regions of the Arctic has not been performed, but would be useful for assessing the potential impacts of climate change on natural hazards.

As a consequence of rising temperatures, the ACIA-designated models project average increases in precipitation of 4.3% by 2011–2030, 7.9% by 2041–2060, and 12.3% by 2071–2090 compared to the 1981–2000 baseline (section 4.4.3). Precipitation increases are projected to be greatest in winter, and smallest in summer (when a decrease is projected for some Russian watersheds).

Changes in the extent of snow cover in the Arctic are very likely to be influenced by both temperature and precipitation. Increasing temperature in a region is very likely to lead to earlier spring snowmelt and reduced snow cover extent at the end of the winter. Conversely, increasing precipitation is very likely to lead to greater snow depth in winter, especially in the coldest parts of the region. The ACIA-designated models project decreases in arctic snow-cover extent of 3–7%, 5–13%, and 9–18% by 2011–2030, 2041–2060, and 2071–2090, respectively, compared to the 1981–2000 baseline (section 6.4.3). The decrease in snow extent between the baseline (1981–2000) and 2071–2090 is projected to be greatest in spring ($4.9 \times 10^6 \text{ km}^2$) and winter ($3.8 \times 10^6 \text{ km}^2$), and lowest in summer ($1.1 \times 10^6 \text{ km}^2$) and autumn ($3.3 \times 10^6 \text{ km}^2$).

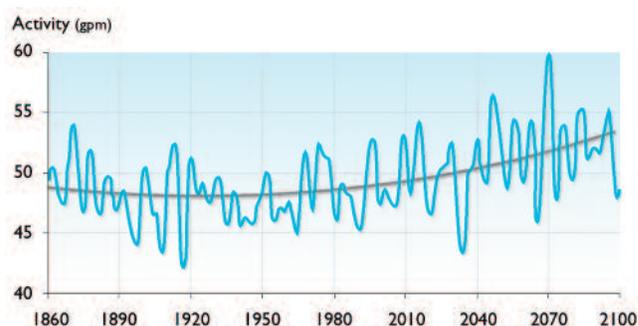


Fig. 16.6. Storm track activity (geopotential meters – gpm) over northwest Europe projected by the ECHAM4/OPYC greenhouse-gas scenario (4-yr running mean). The non-linear climate trend obtained from quadratic curve fitting is marked by the smooth curve (Ulbrich and Christoph, 1999, cited in IPCC, 2001).

Storms also affect avalanche and slide activity, and are projected to increase in frequency (5 to 10%) and amplitude over the 21st century (IPCC, 2001; see Fig. 16.6). For the west coast of Norway, the Norwegian Meteorological Institute projects a higher frequency of storms and greater amplitudes of storm activity over the next 50 years, combined with a 20% precipitation increase and a temperature increase of 2 to 3 °C, with the greatest change occurring in winter (Hackett, 2001; Haugen et al., 1999).

Avalanche activity depends on the rate of snow accumulation, which is dependent on temperature (<0 °C), precipitation rate, and storm frequency. A change in any of these factors is very likely to have an impact on avalanche activity. Increasing snow precipitation is likely to occur in areas with continental climates and high-altitude coastal regions, leading to an increase in avalanche activity. For example, an increase in precipitation rates and storm magnitude is likely to increase snow accumulation intensity in high-altitude avalanche release areas. Because avalanche run-out distance is related to the volume of snow released, it is possible that greater snow accumulation will cause longer run-outs than have historically occurred, resulting in increased risk to settlements and infrastructure.

As snow accumulation primarily occurs at temperatures below 0 °C, snow-cover extent and depth will depend on the duration of the frost period and the precipitation environment in any given area. In regions of the Arctic with long cold periods and low precipitation, changes in temperature and precipitation will have a negligible influence on avalanche activity. Conversely, in regions where winter temperatures are presently close to 0 °C and precipitation rates are high, the snow environment has a high sensitivity to changes in climate. For example, Naryan-Mar in northwest Russia (67.6° N, 53° E) has a typical arctic continental climate, with an average January temperature of -18.9 °C and a snow cover less sensitive to temperature change than Vardø in Norway (70.37° N, 31.1° E), which has a typical maritime climate and an average January temperature of -5.1 °C.

In the continental Russian, Canadian, and Alaskan regions of the Arctic, the winter is long and cold, with few periods of temperature above 0 °C. The coastal areas of Scandinavia and Iceland and the west coast of North America have shorter and warmer winters with a higher frequency of temperature fluctuations around 0 °C. A winter temperature change of a few degrees in cold continental regions of the Arctic is very likely to affect the duration of the winter, but not very likely to affect the snow environment.

As temperature is dependent on altitude, mountain areas with relatively low average temperatures are very likely to be less affected by temperature change than lower-elevation coastal areas. At low altitudes in a warmer maritime climate such as that of Scandinavia, the frequency of precipitation falling as rain is very likely to increase in the future. The frequency of snow avalanches with release areas at low altitudes (below 500 to 1000 m) is likely to be reduced due to this change in precipitation type. Increases in the frequency of rainstorms and intensity of storm precipitation are likely to lead to an increasing frequency of mudflows, as well as an increasing frequency of slush flows where the rate of thaw together with intense rain precipitation is the triggering mechanism (Hestnes, 1994). A higher frequency of winter rain events is very likely to increase the number of wet snow and slush avalanches. However, the duration of slush flow activity in the Arctic is projected to be shorter (Sidorova et al., 2001). The frequency of mudflows and debris flows is projected to increase, as the summer season is projected to be longer, with greater amounts of precipitation and a higher frequency of extreme events such as rainstorms and storm-induced flooding (Glazovskaya and Seliverstov, 1998). For Iceland, storm frequency and precipitation falling as rain are projected to increase along the east coast and decrease along the west coast, owing to a reduction in the ice sheet along the Greenland coast (Olafsson, pers. comm., University of Iceland, Reykjavik, 2003).



Fig. 16.7. Debris slide in a saturated moraine during spring thaw, Lofoten, northern Norway, 1998 (photo: Jan Otto Larsen, Norwegian Public Roads Administration, Oslo).

In maritime climates, the frequency of avalanches with long run-out distances is likely to decrease, owing to a projected change in snow type (from dry-snow to wet-snow and slush avalanches). This is very likely to have a positive effect on transportation routes in some areas. As the frequency of dry-snow avalanches with long run-out distances decreases, the exposure of highways and buildings to avalanches will be reduced.

Increased precipitation is projected to influence groundwater flow. Higher temperatures will probably also increase the thaw rate in spring and summer, increasing groundwater flow and flood potential. In low-altitude areas where snow is presently the predominant form of winter precipitation, an increase in winter rain events is likely to lead to a higher probability of slides in rock and soils (Fig. 16.7). Slopes that are stable under the current precipitation regime are likely to gradually become unstable if the frequency and magnitude of rainstorms increase (Sandersen et al., 1996), leading to a potential increase in rock and soil slide activity until a new equilibrium is established.

A change in the groundwater regime is also likely to affect the pore water pressure in quick clays (materials that can change rapidly from solid to liquid state) that are typical of some fjord districts in the Scandinavian and Canadian Arctic (Bjerrum, 1955; Janbu, 1996; Larsen et al., 1999), and may cause instability of these materials. Quick-clay slides (Fig. 16.8) have caused serious disasters with loss of lives and properties. Together with increased floods and erosion by rivers, higher amounts of groundwater are very likely to increase the risk of quick-clay slides in the future.

As shown in sections 6.6.1.2 and 6.8.2, observed air temperature changes in the Arctic have increased the thaw depth in permafrost areas and increased the discharge of water to the Arctic Ocean from Eurasia (Shiklomanov, et al., 2002). These changes are causing numerous slides in permafrost riverbanks (Fig. 16.9).



Fig. 16.8. Slide in a quick-clay deposit, Verdal, Norway (photo: Jan Otto Larsen, Norwegian Public Roads Administration, Oslo).

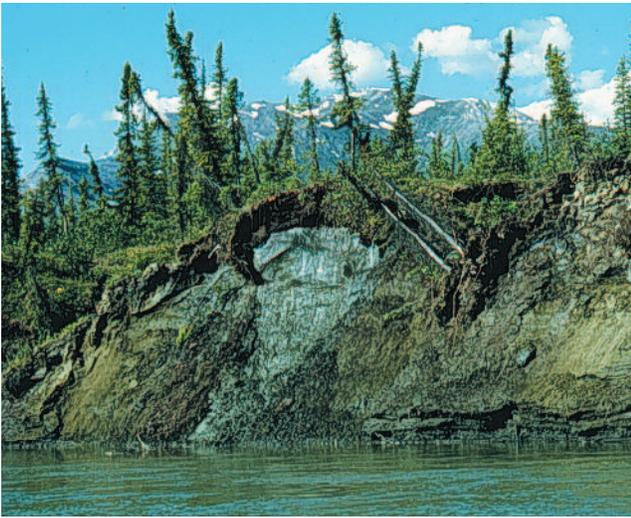


Fig. 16.9. River erosion and slides in a permafrost riverbank with exposed ice wedge (photo: Edward C. Murphy, University of Alaska, Fairbanks).

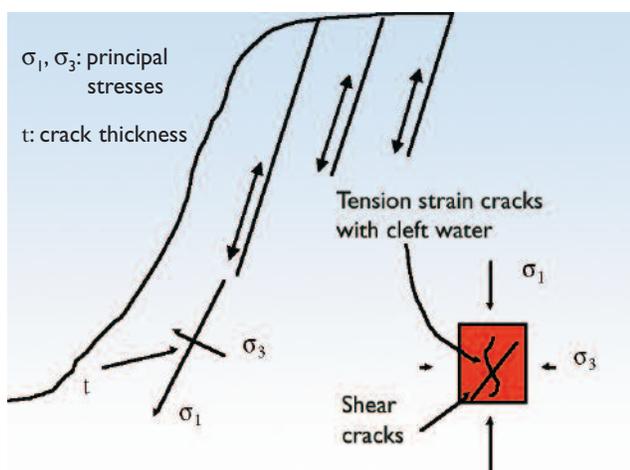


Fig. 16.10. Landslides in hard rock with joints parallel to the slope. Water accumulation in cracks is an important factor triggering failure (figure and photo provided by Jan Otto Larsen, Norwegian Public Roads Administration, Oslo, 2003).

Increasing storm frequencies are very likely to increase closure periods of wind-exposed roads, highways, railroads, and airports, and are likely to affect industries and other human activities dependent on transportation. For example, an increase in the frequency of closed roads is very likely to have an impact on the fishing industry in Norway where immediate transport of fresh fish to the European market is essential.

Greater amounts of precipitation combined with increased rates of snowmelt is likely to increase water infiltration in rock and influence the cleft water pressure in tension cracks in high mountain slopes (Terzaghi, 1963). The cleft water pressure depends on the permeability of the rock and the rate of infiltration; higher cleft water pressures can increase the probability of landslides in hard rock (Fig. 16.10).

16.2.3.4. Summary

Climate change is projected to increase precipitation frequencies and magnitudes, and it is possible that the frequency and magnitude of storms will increase in some regions. An increase in the frequency and magnitude of storms is very likely to lead to increased closures of roads, railways, and airports. Increases in temperature and precipitation together with increases in storm magnitude and frequency are very likely to increase the frequency of avalanches and slides in soil and rock. In some areas, the probability that these events will affect settlements, roads, and railways is likely to increase. Structures located in areas prone to slope failure are very likely to be more exposed to slide activity as groundwater amounts and pore water pressure increase. It is possible that floods of greater magnitude will occur due to greater amounts of precipitation and higher rates of snowmelt. Increased erosion due to higher river flows and thawing permafrost is very likely to initiate slope failure in riverbanks, exposing infrastructure such as buildings, harbors, and communication lines to potential damage. In low-altitude areas with maritime climates, increased temperatures and more precipitation falling as rain are likely to result in a higher frequency of wet-snow avalanches where dry-snow avalanches dominate at present. This is likely to reduce avalanche run-out distance and related problems on exposed traffic routes. The frequency and extent of slush-flow avalanches are likely to increase in the future. An increasing probability of slides coupled with increases in traffic and population concentrations is very likely to lead to expensive mitigation measures to maintain a defined risk level. The best way to address these problems is to incorporate the potential for increasing risk in the planning process for new settlements and transportation routes such as roads and railways.

16.2.4. Coastal environment

The Arctic has approximately 200 000 km of coastline, most of which is uninhabited. However, coastal development is critical to the economy and social well-being

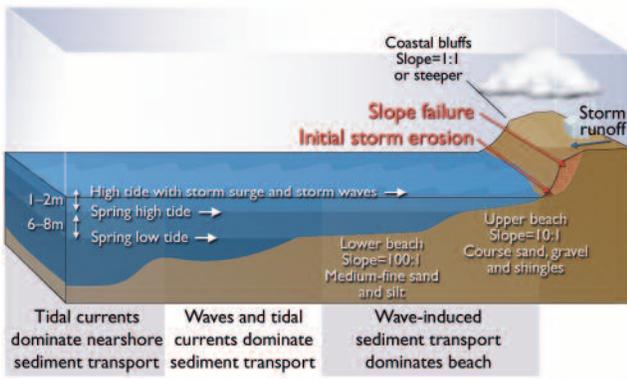


Fig. 16.11. Processes affecting bluff erosion in Cook Inlet, south-central Alaska (redrawn from Smith O. and Levasseur, 2002).

of nearly all arctic residents (see also Chapters 3, 12, and 15). Natural-resource development is concentrated along the coast, and the development of resources in these remote areas is constrained because of challenging transportation routes (Smith O. and Levasseur, 2002).

Arctic coastal dynamics are often affected directly or indirectly by the presence of permafrost. Permafrost coasts are especially vulnerable to erosive processes as ice beneath the seabed and shoreline melts from contact with warmer air and water. Thaw subsidence at the shore allows additional wave energy to reach unconsolidated erodible materials. Low-lying, ice-rich arctic permafrost coasts are the most vulnerable to thaw subsidence and subsequent wave-induced erosion.

The southern half of Alaska has coastal characteristics dominated by erodible glacial deposits and high tides. Cook Inlet, in south-central Alaska, has a 10 m tidal range at its northern extreme and an eroding shoreline of glacially deposited bluffs, as illustrated in Fig. 16.11 (Smith O. and Levasseur, 2002). Freezing of brackish water and ice deposition on broad tidal flats create huge blocks of “beach ice” (Fig. 16.12) that, when set afloat by higher tides, can carry coarse sediments for distances of over a hundred kilometers. Of all Cook Inlet sea ice, these sediment-laden ice blocks present



Fig. 16.12. Beach ice in macro-tidal zones of Alaska (photo provided by Orson Smith, University of Alaska, Anchorage).

the greatest danger to ships in winter. The complex dynamics of bluff erosion and ice-borne sediment transport will become even more difficult to forecast with sea-level rise and a more erratic storm climate.

16.2.4.1. Observed changes in the coastal environment

Coastal erosion rates vary considerably across the Arctic. As indicated in Fig. 16.13, erosion rates are dependent on environmental forcing, sedimentology, geocryology, geochemistry, and anthropogenic disturbance of the coastline. In fine-grained icy silty-clayey sediments, average erosion rates are typically 1 to 3 m/yr, while in silty-sandy sediments with high ice content that are directly exposed to waves and storm surges, erosion rates can be as high as 10 to 15 m/yr under extreme weather conditions. Frozen rock and sediments with low ice content may have erosion rates as low as 0.1 m/yr. Anthropogenic disturbance of the coastline can increase erosion rates, but there are also examples from Varandei in the Pechora Sea indicating that shore protection techniques can slow erosion rates. Table 16.8 presents examples of erosion rates along the arctic coast.

Erosion rates have increased along the arctic coast over the past 30 years. Coastal residents are concerned about the observed changes and the future of arctic coastal communities. However, arctic coastal survey data are often inadequate to reliably quantify accelerating shoreline retreat. Baseline surveys using satellite imagery will help the assessment of erosion rates and systematic planning of future responses significantly. Understanding of circumpolar coastal dynamics is also inadequate. Improved understanding of the physical processes involved in arctic coastal erosion will improve techniques for shore protection and other mitigation measures that may be necessary in the future.

The Arctic Coastal Dynamics project (ACD) is a recent international initiative, sponsored by the International Arctic Sciences Committee and the IPA, to address coastal change in the Arctic (Rachold et al., 2002,

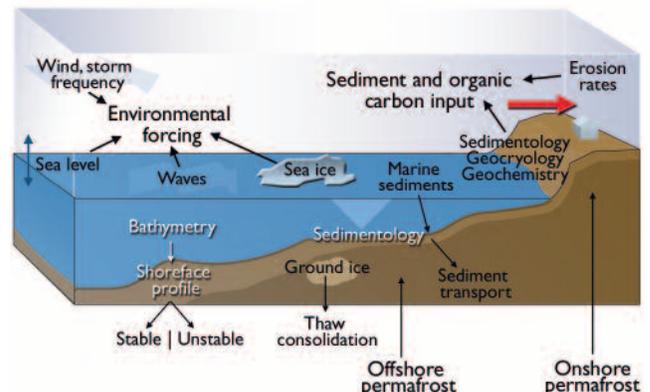


Fig. 16.13. Processes affecting coastal erosion in the Arctic (redrawn from Rachold et al., 2002).

2003). Its objective is to improve the understanding of coastal dynamics as a function of environmental forcing (including climate change), coastal geology and cryology, and changes in landforms (Fig. 16.13). The ACD has proposed:

- to establish the rates and magnitudes of erosion and accumulation along arctic coasts (e.g., Table 16.8);
- to develop a network of long-term monitoring sites including local community-based observation sites; and
- to develop empirical models to assess the sensitivity of arctic coasts to environmental variability and change and human impacts.

Output from studies such as those proposed by the ACD can be used for site-specific evaluation of arctic coastal areas. This type of research and monitoring is essential to document ongoing and future changes and to make policy recommendations.

16.2.4.2. Projected changes in the coastal environment

Arctic coastal conditions are likely to change as climate changes. Thinner, less extensive sea ice is very likely to improve navigation conditions along most northern shipping routes, such as the Northwest Passage and the

Northern Sea Route (see also section 16.3.7). However, decreasing sea-ice extent and thickness is very likely to affect traditional winter travel and hunting where sea ice has been used for these purposes.

Greater expanses and longer periods of open water are likely to result in wave generation by winds over longer fetches and durations. Wave energy is constrained by wind speed, duration of winds, extent of fetch, and water depth. Wave-induced coastal erosion along arctic shores is likely to increase as climate changes. Sea-level rise and thaw subsidence of permafrost shores are projected to exacerbate problems of increased wave energy at the coast. If more frequent and intense storms accompany climate change, these are also likely to contribute to greater wave energy.

Global sea level is rising, although the contribution of various factors to this rise is still being debated (section 6.9.2). The volume of water in the oceans is increasing due to thermodynamic expansion of seawater and melting of ice caps and glaciers. Rising sea level inundates marshes and coastal plains, accelerates beach erosion, exacerbates coastal flooding, and increases the salinity of bays, rivers, and groundwater. Some northern regions, such as the southern coasts of Alaska, have sea-level trends complicated by tectonic rebound of the land resulting from the retreat of continental glaciers at the end of the last glacial period. At Sitka, in south-

Table 16.8. Arctic coastal erosion rates measured at various sites (Brown et al., 2003; Rachold et al., 2002, 2003).

	Country	Time period	Average erosion rate (m/yr)
Yugorsky Peninsula, Kara Sea	Russia	1947–2001	0.6–1 ^a
			1.3–1.6 ^b
Herschel Island, Beaufort Sea	Canada	1954–1970 1970–2000 1954–2000	0.7
			1.0
			0.9
Barrow, Alaska, Chukchi Sea	United States	1948–1997 1948–2000	0.4–0.9
			1–2.5 ^c
Pesyakov Island, Pechora Sea	Russia	2002	0.5–2.5 ^d
Varandei, Pechora Sea	Russia	2002	1.8–2.0 ^e
Varandei Island, Pechora Sea	Russia	1970–1980	7–10
		1980–1990	1.5–2 ^f
		1987–2000	3–4
		1984–1999	4.3
Maly Chukochiy Cape, East Siberian Sea	Russia	1984–1988	3.5
		1988–1990	1.5
		1990–1991	3
		1991–1994	5
		1994–1999	4.4
		projected future	1.8 ^g
Kolguev Island, Barents Sea	Russia	not available	1–2 ^h
		not available	0.1–0.2
Beaufort Sea	Canada	not available	1–5

^ascarp; ^bbluff; ^cElson Lagoon; ^dHolocene terrace; ^ethermoabrasion coast; ^fshore protection; ^gbased on complete melting of ice bodies; ^hincludes thermo-erosion of ice-rich sediments.

east Alaska, the net effect is falling sea level. However, arctic coasts have a wide variation of tectonic trends. Low-lying coastal plains in the Arctic are generally not tectonically active, which is another reason why they are vulnerable to the adverse effects of sea-level rise. Global sea-level rise will possibly allow more wave energy to reach the coast and induce erosion as waves break at the shore.

Reduced sea-ice extent and thickness are very likely to provide opportunities for the export of natural resources and other waterborne commerce over new northern shipping routes. Reduced sea ice in the coastal regions of the Arctic Ocean is very likely to result in longer navigation seasons along the Russian Arctic coast, in the Canadian Arctic, along the eastern and western coasts of Greenland, and around Alaska. Enhanced regional arctic navigation, such between Europe and the Kara Sea, and potential trans-arctic voyages using icebreaking container ships and tankers, is very likely to shorten distances between markets and improve the delivery times for valuable products.

Climate change is also likely to change the use of arctic rivers for transportation routes, water sources, and habitat. Increased precipitation is very likely to result in higher stream flows and more flooding. Conditions for commercial river navigation will possibly improve the transport of minerals and bulk exports to tidewater. Erosion of thawing permafrost banks is very likely to accelerate, threatening the infrastructure of rural arctic river communities. River-ice breakup is very likely to occur earlier and ice jams and flooding risks are likely to be more difficult to project. The projection and prevention of ice-jam flooding warrant further study.

Higher sea levels at the mouths of rivers and estuaries are likely to allow salt to travel further inland, changing riparian habitats. Furthermore, climate change is projected to result in more frequent and intense storms accompanied by stronger winds. These winds are very likely to induce even higher water levels at the coast, accompanied by higher waves. Storms are also

likely to result in more intense rainfall at the coast, increasing runoff-related erosion and the mobile sediment in coastal waters.

Coastal communities are sensitive to climate change. Engineering solutions are available for shore protection (flood barriers, dikes, breakwaters, erosion control) but may not be able to reduce erosion rates sufficiently to save specific settlements. Moreover, while these protective measures may address one problem, they may create another by altering the dynamics of erosion and deposition processes.

16.2.5. Arctic Ocean

16.2.5.1. Observed changes in sea-ice extent

Climatic and environmental changes in the Arctic Basin include changes in air temperature, water temperature and salinity, and the distribution, extent, and thickness of sea ice. There is compelling empirical evidence of consistent environmental changes across the Arctic Ocean, including increases in air temperature, reductions in sea-ice extent, and freshening of the Beaufort Sea mixed layer (Maslanik et al., 1996; McPhee et al., 1998). Data from ice-floe measurements show a slight air temperature increase with statistically significant warming in May and June between 1961 and 1990. Air temperature anomalies in the Arctic Basin have been strongly positive since 1993. Between 1987 and 1997, the mean annual air temperature increased by 0.9 °C (Aleksandrov and Maistrova, 1998), comparable to temperature changes observed in the terrestrial Arctic.

The area of warm Atlantic waters in the polar basin increased by almost 500 000 km² over the past three decades (Kotlyakov, 1997), and the inflowing fresh-water has warmed (Carmack, 2000; Carmack et al., 1995). Measurements from submarines indicate that surface waters in the Arctic Ocean basin warmed by 0.5 to 1 °C from the mid-1970s to the mid-1990s, with maximum warming observed in the Kara Sea (Alekseev et al., 1997).

One of the most valuable and graphic records of sea-ice extent changes in the Northern Hemisphere was produced by Walsh and Chapman (2001). Figure 16.14 shows a 103-year record (1900–2002) of sea-ice extent. A decreasing trend in sea-ice extent, starting in the mid-20th century, is evident for all four seasons. The greatest decreases have occurred in summer and spring: over the past 50 years, summer sea-ice extent has decreased by nearly 3 × 10⁶ km². Although the decrease in sea-ice extent has been unevenly distributed around the coastal margins of the Arctic Ocean, it has provided greater marine access for ships.

Satellites have recorded increasing areas of open water along the Russian Arctic coast and in the Beaufort Sea. Figure 16.15 is a satellite passive microwave image showing the extent of arctic sea ice on 22 September

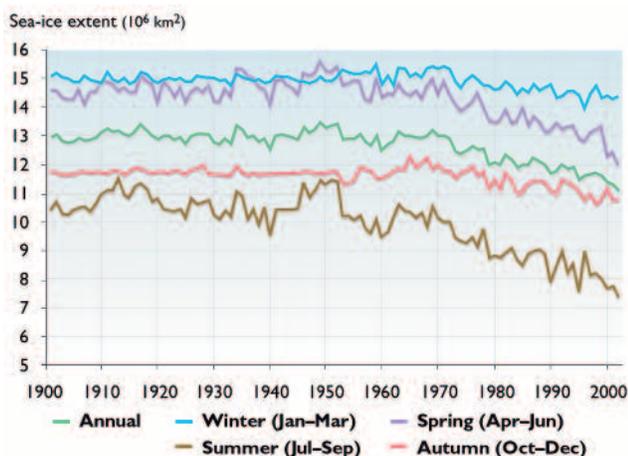
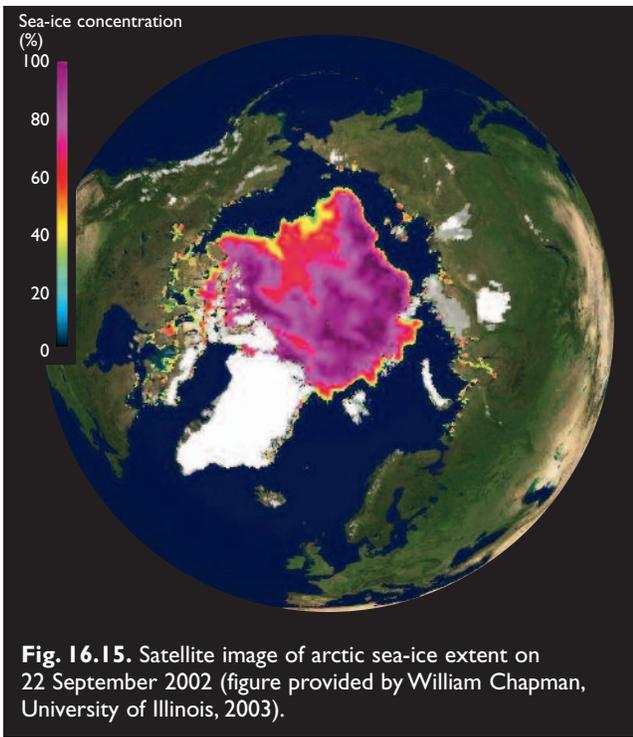


Fig. 16.14. Sea-ice extent in the Northern Hemisphere between 1900 and 2002 (Walsh and Chapman, 2001, updated).



2002 – the date of the minimum observed extent in the 103-year record. This image illustrates the large areas of open water surrounding the Arctic Basin at the summer minimum extent of sea ice. Of significance for the Northern Sea Route, the only pack ice reaching the Russian Arctic coast is along the northern tip of Severnaya Zemlya; the sea ice in this image has also retreated record distances in the Beaufort, Chukchi, and East Siberian Seas.

Sea-ice conditions in the Canadian Arctic are very complex. Observations of minimum sea-ice extent in the

eastern and western regions of the Canadian Arctic between 1969 and 2003 (Fig. 16.16) illustrate the extraordinary interannual variability of the ice conditions. Although the trends in sea-ice extent are negative in both regions over the period shown, the year-to-year variability is extreme and sometimes differs between the two regions. For example, one of the largest observed minimum extents in the western region (for the period shown) occurred in 1991, while in the eastern region the minimum sea-ice extent that year was relatively low. While these observations indicate a recent overall decrease in the extent of sea ice in the Northwest Passage, the interannual and spatial variability is not conducive to planning a reliable marine transportation system.

16.2.5.2. Projected changes in sea-ice extent

Figure 16.17 shows the median of the sea-ice extents projected by the five ACIA-designated climate models for the three ACIA time slices. However, an important limitation of the ACIA-designated models is that they cannot resolve the complex geography of the Canadian Arctic and thus cannot provide adequate sea-ice projections for this region. In summer, the models project a substantial retreat of sea ice throughout the entire Arctic Ocean for each ACIA time slice, except for parts of the Canadian Archipelago and along the northern coast of Greenland. By mid-century (September 2041–2060), most of the alternative routes in the Northwest Passage and Northern Sea Route are projected to be nearly ice-free; three of the five models project open water conditions across the entire lengths of both. By the end of the 21st century, vast areas of the Arctic Ocean are projected to be ice-free in summer, increasing the possibility of shipping across the Arctic Ocean.

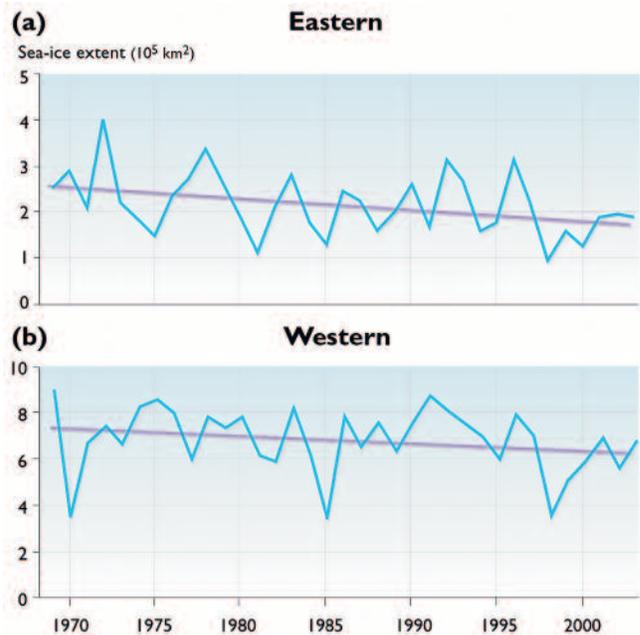
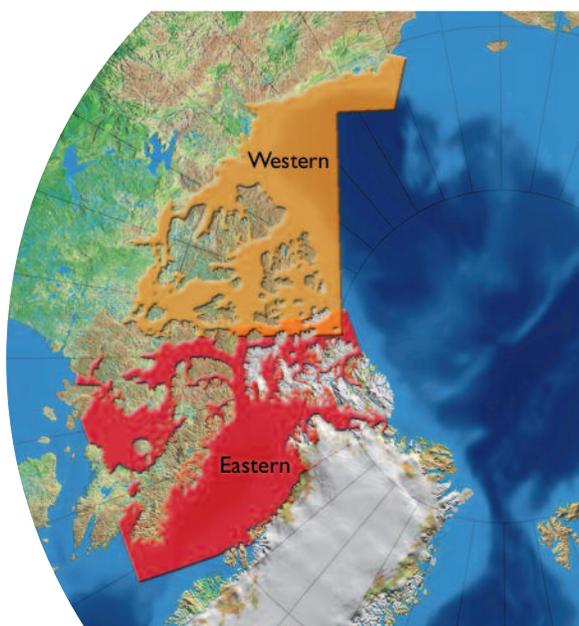
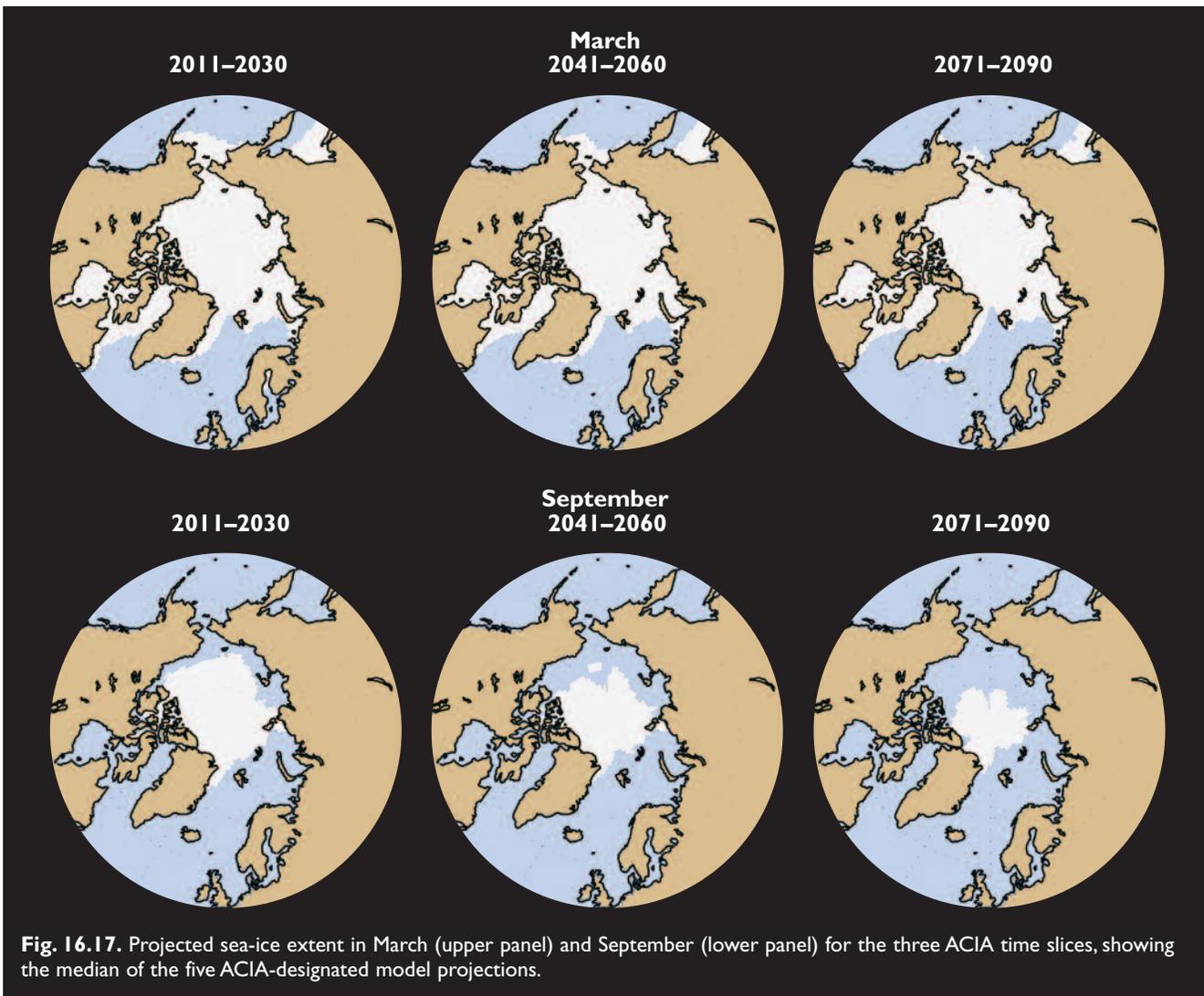


Fig. 16.16. Annual minimum sea-ice extent in (a) the eastern and (b) the western regions of the Canadian Arctic between 1969 and 2003, from a composite of remotely sensed and ground-based measurements. Lavender lines show linear trends (redrawn from figure provided by the Canadian Ice Service, 2004).



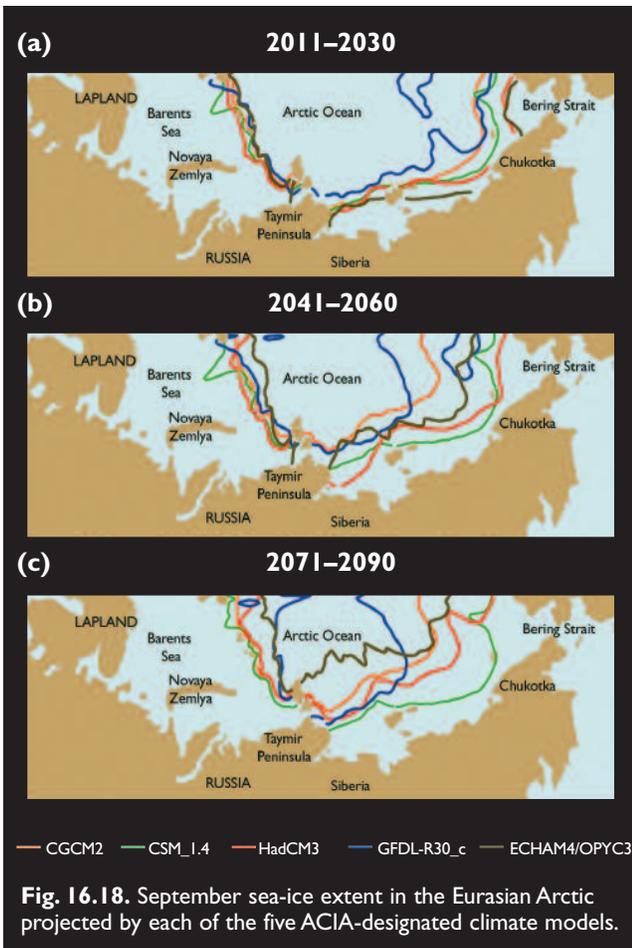
Although there is some projected winter retreat of the sea-ice edge, particularly in the Bering and Barents Seas where ship access is likely to improve throughout the 21st century, most of the Arctic Ocean is projected to remain ice-covered in winter. However, sea-ice cover is likely to be on average thinner, and the area of multi-year sea ice in the central Arctic Ocean is likely to decrease through 2080. Winter navigation (throughout the year to Dudinka since 1978) along the western end of the Northern Sea Route, from the Barents Sea to the mouths of the Ob and Yenisey Rivers, will possibly encounter less first-year sea ice. Full transit of the Northern Sea Route through Vilkitskii Strait to the Bering Sea is very likely to remain challenging and require icebreaker escort. The only improvement in winter sea-ice conditions for the Laptev, East Siberian, and western Chukchi Seas is a possible reduction in the area and frequency of multi-year floes along the navigable coastal routes.

The significant interannual sea-ice variability in the arctic seas is also important to navigation. The projected increase in ice-free areas and reduced sea-ice concentrations will possibly lead to a more dynamic sea-ice cover under the influence of local and regional wind fields. These more variable environmental condi-

tions, combined with an increase in the number of ships making passages in the Arctic Ocean, will possibly lead to a higher demand for sea-ice information, long-range ice forecasting, and increased icebreaker support. While direct (across the North Pole) trans-arctic voyages are unlikely by mid-century, voyages may be possible north of the arctic island groups (such as those along the Russian Arctic coast) and away from shallow continental shelf areas that restrict navigation.

There is likely to be an increased requirement for real-time satellite imagery of sea-ice conditions. Increased ship access to the Arctic Ocean is very likely to require more resources to facilitate marine traffic and to support maritime safety and protection of the arctic marine environment.

The four ACIA regions are not conveniently drawn for assessment of future arctic marine transport routes. Therefore, as a case study, a new “sector” was defined between 60° and 90° N, and between 40° E and 170° W, which includes the coastal region from the eastern Barents Sea to Bering Strait. This sector also encompasses Russia’s Northern Sea Route, defined by regulation as the routes or waterways between Kara Gate (at the southern end of Novaya Zemlya) and Bering Strait.



As shown in Fig. 16.17, the median of the ACIA-designated model projections suggests that, in all the time slices, most coastal waters of the Eurasian Arctic (along the Northern Sea Route) will be relatively ice-free in September. Figure 16.18 illustrates the September sea-ice extents projected by each of the five models for the Eurasian Arctic sector used in this analysis. During September, the month of minimum sea-ice extent in the Arctic Ocean, the models consistently project sea ice in the vicinity of Severnaya Zemlya during each of the ACIA time slices. For ships to travel north of Severnaya Zemlya, highly capable, more expensive icebreaking ships would be necessary. However, it is more likely that ships would sail through the deep waters of Vilkitskii Strait to the south – between the Kara and Laptev Seas north of the Taymir Peninsula – where more open water is very likely to be found. Four of the five models also project open water to the east and north of the New Siberian Islands in September. Ships sailing along the Northern Sea Route are likely to take advantage of these ice-free conditions to avoid the shallow, narrow passages along the Eurasian coast. In addition, if there is a continued reduction in the proportion of winter multi-year sea ice in the Central Arctic Ocean (Johannessen et al., 1999), it is very likely that first-year sea ice will dominate the entire maritime region of the Northern Sea Route throughout the year, with a decreasing frequency of intrusions of multi-year sea ice into the coastal seas. Such changes in sea-ice conditions would have key

implications for ship construction (e.g., potentially lower construction costs) and route selection along the Northern Sea Route in summer and winter.

16.3. Infrastructure in the Arctic

Infrastructure is defined as facilities with permanent foundations or the essential elements of a community. It includes schools; hospitals; various types of buildings and structures; and facilities such as roads, railways, airports, pipelines, harbors, power stations, and power, water, and sewage lines. Infrastructure forms the basis for regional and national economic growth. In the Arctic, the largest population concentrations are located in North America and Russia (Freitag and McFadden, 1997), as is much of the existing infrastructure.

Most arctic facilities are connected with population concentrations, extraction of natural resources, or military activity. In the case of industrial or military developments, facilities typically include industrial buildings and warehouses, crew and worker quarters, embankments (roadway, airport, work pad), pipelines (both chilled and warm), and excavations of different types. Many industrial buildings must be designed to accommodate heavy equipment, increasing demands on the foundation system. In the case of human settlements, infrastructure includes public transportation systems, utility generation and distribution facilities, and buildings associated with residential or business activities. In addition to the complexity presented by the wide range in requirements of the different types of infrastructure, the problems associated with climate change are compounded by the range of environmental conditions over which human activities occur, extending from the sporadic permafrost/seasonal frost zone to the high Arctic with its cold, continuous permafrost layer.

Some of the engineering projects that are likely to be affected by climate change are as follows (see also Bush et al., 1998; Nixon, 1994).

- Northern pipelines are likely to be affected by frost heave and thaw settlement. Slope stability is also likely to be an issue in discontinuous permafrost (Nixon et al., 1990).
- The settlement of shallow pile foundations in permafrost could possibly be accelerated by temperature increases over the design life of a structure (~20 years). However, over the same period, there is very likely to be less of an effect on the deeper piles used for heavier structures (Nixon et al., 1990).
- Large tailings disposal facilities might be affected (negatively or positively) by climate change, due to the long-term effects on tailings layers. There is some chance that layers that freeze during winter deposition in northern seasonal-frost or permafrost areas would thaw out many years later, releasing excess water and contaminants into groundwater. There is some chance that

increasing temperature would significantly change the rate of thawing of such layers.

- The availability of off-road transportation routes (e.g., ice roads, snow roads) is likely to decrease owing to a reduction in the duration of the freezing season. The effect of a shorter freezing season on ice and snow roads has already been observed in Alaska and Canada (section 16.3.6).
- Climate change is likely to reduce ice-cover thickness on bodies of water and the resulting ice loading on structures such as bridge piers. However, until these effects are observed, it is unlikely that engineers will incorporate them into the design of such structures.
- The thickness of arctic sea-ice cover is also likely to change in response to climate change, and it is possible that this will affect the design of off-shore structures for ice loadings, and the design of ice roads used to access structures over land-fast ice in winter.
- Precipitation changes are very likely to alter runoff patterns, and possibly the ice–water balance in the active layer. It is very difficult to assess the potential effects of these changes on structures such as bridges, pipeline river crossings, dikes, or erosion protection structures.
- The stability of open-pit mine walls will possibly be affected where steep slopes in permafrost overburden have been exposed for long periods of time. The engineering concerns relate to increased thaw depth over time, with consequent increased pore pressures in the soil and rock, and resulting loss of strength and pit-wall stability (Szymanski et al., 2003; Bush et al., 1998).
- The cleanup and abandonment of military and industrial facilities throughout the Arctic sometimes involves storage of potentially hazardous

materials in permafrost or below the permafrost table. There is some chance that permafrost degradation associated with climate change will threaten these storage facilities. AMAP (1998) provides a detailed review of arctic pollution issues.

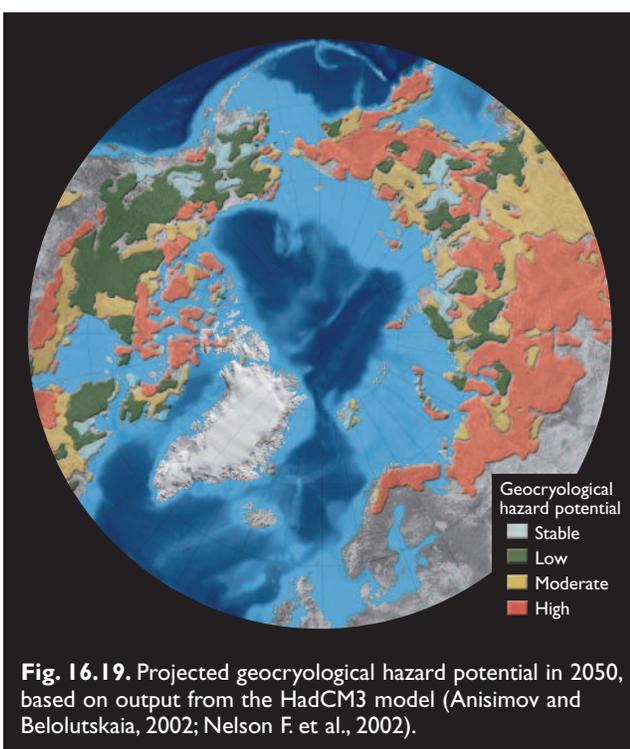
For all types of arctic infrastructure, the key climate-related concern is changes in the thermal state of the supporting soil layers. As described in section 16.2.2.5, changes in soil temperature can induce large variations in soil strength and bearing capacity and may also cause thaw settlement or frost heave. Many facilities and structures were designed for current climatic conditions, and it is possible that appreciable warming will introduce differential settlement beneath them. The susceptibility of permafrost to environmental hazards associated with thermokarst, ground settlement, and several other destructive cryogenic processes can be crudely evaluated using the geocryological hazard index, which is the combination of the projected percentage change in active-layer thickness and the ground ice content:

$$I_s = \Delta z_{al} \cdot V_{ice} \quad \text{Eqn. 16.2}$$

where Δz_{al} is the percentage increase in active-layer thickness, and V_{ice} is the volumetric proportion of near-surface soil occupied by ground ice. The index provides a qualitative representation of relative risk, with lower values representing lower risk and vice versa.

Future geocryological hazards were projected using several scenarios of climate change (including those from the ACIA-designated models) as input to a permafrost model that included information about existing permafrost and ground ice distributions from the IPA. Figure 16.19 presents the geocryological hazard potential with respect to engineered structures projected for 2050, calculated using the HadCM3 scenario (Anisimov and Belolutskaia, 2002; Nelson F. et al., 2002). The map shows areas projected to have low, moderate, and high susceptibility to thaw-induced settlement, as well as areas where permafrost is projected to remain stable.

A zone of high and moderate risk potential is projected to extend discontinuously around the Arctic Ocean, indicating high potential for coastal erosion. North American population centers (e.g., Barrow, Inuvik) and river terminals on the arctic coast of Russia (e.g., Salekhard, Igarka, Dudinka, and Tiksi) fall within this zone. Transportation and pipeline corridors traverse areas of high projected hazard potential in northwestern North America. The area containing the Nadym-Pur-Taz natural gas production complex and associated infrastructure in northwest Siberia also falls in the projected high-risk category. Large portions of central Siberia, particularly the Sakha Republic (Yakutia) and the Russian Far East, have moderate or high projected hazard potential. These areas include several large population centers (Yakutsk, Noril'sk, and Vorkuta), an extensive network of roads and trails, and the Trans-



Siberian and Baikal–Amur mainline railroads. The Bilibino nuclear power station and its grid occupy an area of projected high hazard potential in the Russian Far East. Areas of lower projected hazard potential are associated with mountainous terrain and cratons (geologically stable interior portions of continents) where bedrock is at or near the surface.

Three main design approaches are employed when using permafrost soils as foundations for structures and infrastructure (Andersland and Ladanyi, 1994):

- to maintain the existing ground thermal regime (referred to as Principle I in Russia, and the passive method in North America);
- to accept changes in the ground thermal regime caused by construction and operation, or to modify foundation materials prior to construction (referred to as Principle II in Russia, and the active method in North America); and
- to use conventional foundation methods if the soils are thaw stable.

With the first two methods, it is necessary to estimate the maximum active-layer thickness and the maximum permafrost temperature as a function of depth that the structure will be subjected to in its lifetime. The air thawing index can be used to calculate active-layer thickness and maximum permafrost temperatures as a function of depth and time of year (see section 16.2.2.2). Other approaches can also be used to calculate active-layer thickness (e.g., using a full surface energy balance).

A significant consequence of permafrost degradation is likely to be a change in the maintenance conditions of many structures, especially for those that were designed without consideration of potential climate change. Projections of the change in bearing capacity and durability of foundations as temperatures change illustrate the potential for damage as a result of climate change. The results of such calculations for Yakutsk are presented in Table 16.9.

For structures utilizing Principle I (permafrost conservation), the table illustrates that foundation failures will possibly begin when the mean annual air temperature increases by a small amount (a few tenths of a

Table 16.9. Projected decrease in the bearing capacity and durability of foundations in Yakutsk for different increases in air temperature (Khrustalev, 2000).

	Increase in mean annual air temperature (°C)				
	0	0.5	1.0	1.5	2.0
Bearing capacity of structures built using Principle I (%)	100	93	85	73	50
Foundation durability of structures built using Principle II (%)	100	68	46	42	23

degree), and extend to all foundations when the increase exceeds 1.5 °C. This indicates that there is little margin for safety in the bearing capacity related to changes in air temperature. For structures utilizing Principle II (permafrost thawing), design is based on allowable deformations. As with structures utilizing Principle I, no factor of safety is included in the design. However, foundation failures will occur a relatively long time after the temperature changes. This means that the change in temperature affects only the durability of the foundations. Table 16.9 shows that a small increase in air temperature substantially affects the stability of the building, and the safety of the foundation decreases sharply with rising temperatures.

Temperature increases can result in a significant decrease in the lifetime and potential failure of the structure (Khrustalev, 2000, 2001). Permafrost engineers, therefore, face the problem of preserving infrastructure under projected future climate conditions. The compensation method (putting new buildings into operation as existing ones are damaged and abandoned) appears to be one of the possible ways to address this problem. However, Khrustalev (2000, 2001) states that this method will be inadequate, since the required rate of new construction rises exponentially from 5% per decade in 1980–1990 to 108% per decade in 2030–2040 (assuming a linear increase in mean annual temperature of 0.075 °C/yr).

Various methods have been suggested to address temperature-related foundation problems. Techniques to reduce warming and thawing, such as heat pumps, convection embankments, thermosyphons, winter-ventilated ducts, and passive cooling systems, are already common practice in North America, Scandinavia, and Russia (Andersland and Ladanyi, 1994; Couture et al., 2003; Goering and Kumar, 1996; Instanes, B., 2000; Khrustalev and Nikiforov, 1990; Smith S. et al., 2001).

16.3.1. Ultraviolet radiation and construction materials

Ultraviolet (UV) radiation adversely affects many materials used in construction and other outdoor applications. Exposure to UV radiation can alter the mechanical properties of synthetic polymers used in paint and plastics, and natural polymers present in wood. Increased exposure to UV radiation due to stratospheric ozone depletion is therefore likely to decrease the useful life of these materials (Andrady et al., 1998).

The impact of UV radiation on infrastructure in the Arctic is influenced by two compounding factors: the high surface reflectivity of snow or ice and long hours of sunlight. Both factors have strong seasonal components, generally resulting in increased UV radiation levels in the late spring. While the level of UV radiation incident on a horizontal surface (e.g., a flat roof) may be considerably lower in the Arctic than at mid-latitudes, the level

of UV radiation incident on a vertical surface (e.g., a south-facing wall) may be higher than that on a horizontal surface at some times of the year, when reflection from snow augments the direct UV radiation incident on the surface. Materials degradation is often related to the total accumulated UV radiation exposure.

Long days during the arctic summer can result in large daily doses of UV radiation, even when noon levels remain moderate. If UV radiation levels increase as a result of ozone depletion or changes in cloud cover, the impacts on materials are likely to include earlier degradation and significant discoloration.

For natural polymers found in wood, exposure to UV radiation can lead to a decrease in the useful lifetime of the product. Even small doses of UV radiation may darken wood surfaces. Other effects of increased exposure to UV radiation on wood are less certain. The damage to finished wood products is limited primarily by protective surface coatings, but increased UV radiation levels will possibly lead to increased costs for more frequent painting or other maintenance.

The construction industry is increasingly turning to synthetic polymers for use in building materials. In the United States and Western Europe, the building sector uses 20 to 30% of the annual production of plastics (Mader, 1992). Plastics and other synthetic polymer products are used for a number of applications, including irrigation, water distribution and storage, and in fishing nets and agricultural films.

During the manufacture of virtually all polymer products, impurities can be introduced that make the end product susceptible to photodegradation by UV radiation. Although stabilizers may be added to retard photodegradation effects, their inclusion can substantially increase the cost of the final product. Unfortunately, much of the research on UV-induced degradation has been conducted on pure polymer resins, leading to problems in extrapolating the findings to processed products of the same polymer.

The effects of UV radiation on materials are closely tied to other environmental factors, including ambient temperatures. Polar regions have experienced the greatest ozone depletion and therefore the greatest potential increases in UV-B radiation levels. However, the cooler temperatures in these locations can help prevent rapid degradation of materials. Materials have different sensitivities that can depend on wavelength and dose. Some materials contain stabilizers designed to mitigate degradation, but the efficacy of those stabilizers under spectrally altered (e.g., higher than normal UV) conditions is not always known (Andrady, 1997).

UV-induced polymer deterioration has been widely observed. Polyvinyl chloride tends to undergo discoloration or yellowing, and to lose impact strength. This loss of impact strength can eventually lead to

cracking and other irreversible damage. Another polymer, polycarbonate, undergoes a rearrangement reaction when exposed to UV-B or UV-C radiation. When irradiated at longer wavelengths, including visible wavelengths, polycarbonates undergo oxidative reactions that result in yellowing (Factor et al., 1987).

Polystyrene, used as expanded foam in both building and packaging applications, also undergoes light-induced color changes. In polyethylene and polypropylene, which are used extensively in agricultural mulch films, greenhouse films, plastic pipes, and outdoor furniture, the loss of tensile properties and strength is a particular concern (Hamid and Pritchard, 1991; Hamid et al., 1995).

The cost of more frequent replacement of woods and polymers is likely to be higher in the Arctic than at lower latitudes because of the increased cost of shipping and placement. Environmental stresses in the Arctic, including high winds and repeated freezing and thawing, will possibly exacerbate minor materials problems that develop as a result of UV radiation damage.

16.3.2. Buildings

Several foundation systems are currently in use for industrial, commercial, and residential structures situated in the Arctic and subarctic. When building sites are underlain by permafrost, the foundation system must ensure that any warmth emanating from the structure does not induce thawing of the permafrost layer. For many structures, this is accomplished by elevating the building above the ground surface on a pile or adjustable foundation system. The resulting air space ensures that heat from the structure will not induce permafrost warming. Thousands of structures ranging from single-family residences to large living quarters and apartment blocks are currently supported on pile foundations, including many residential structures in the permafrost zones of Alaska, Canada, and Scandinavia, and many apartment buildings in Siberia. In most of these areas, existing structures are performing well, and there has been little evidence that climate change is inducing failures. However, as noted in section 16.3.8 many Siberian buildings are experiencing significant rates of structural failure that may be connected to increasing temperatures.

The bearing capacity of piles embedded in permafrost depends on the type of frozen soil (clay, silt, or sand), its temperature, and the length of pile embedment in the permafrost layer. A safe pile design is usually based on the calculated maximum temperatures of the frozen soil along the embedded pile length, determined from data on the mean annual temperature of the site and the seasonal temperature variation. Pile foundations are particularly sensitive to permafrost temperatures because of the large increase in creep rates as temperatures approach 0 °C (see section 16.2.2.5). For this reason, extra cooling measures, such as the use of thermopiles (thermosyphon-cooled pilings), are some-

times taken in the warmer discontinuous permafrost zone in order to lower temperatures and ensure a stable permafrost–piling bond.

An increase in ground temperature along an existing pile is very likely to reduce its bearing capacity or increase the rate of its settlement for two reasons: an increase in the active-layer thickness will reduce the effective embedment length of the pile; and increased temperature will reduce the strength of the frozen soil. As a result, if soil warming occurs, an existing structure founded on piles will experience an increasing settlement rate that is likely to lead to uneven settlement and damage to the structure.

The design of all future structures founded on piles embedded in permafrost soils should take into account projected future temperature increases. Depending on the estimated useful lifetime of the structure, the pile design should preferably be based on projected temperature conditions at the end of its lifetime. For any particular pile type, unless bearing on rock, this will result in longer pile length and increased cost.

Very light buildings in permafrost areas are often established directly on the ground surface and supported by a system of adjustable mechanical jacks providing a sufficient crawl space below the heated and insulated floor of the building and the ground surface. Although such buildings will not produce thaw settlement of underlying permafrost, they are likely to be subject to the effects of regional thaw settlement due to rising temperatures and the resulting increase in active-layer thickness. Although settlement in these types of buildings can be adjusted by the jacking system, the differential settlement of water supply and sewage evacuation pipes attached to the building must also be addressed.

Depending on local meteorological conditions, the foundation soils of buildings constructed on elevated foundation systems (either pile or adjustable supports) are likely to be less prone to temperature increases as climate change occurs. This is due to the combined influence of shielding the surface from solar radiative input (due to shading by the structure) and elimination of snow cover at the surface beneath the building, both of which have a significant cooling effect on ground-surface temperatures.

For industrial and equipment buildings that must support large floor loads, pile foundations are sometimes too costly. These buildings often have a slab-on-grade foundation with insulation installed beneath the floor to help protect the underlying permafrost. In addition to the insulation, some sort of cooling system under the slab is required to remove heat from beneath the structure. Both active and passive refrigeration systems have been employed for this purpose, but passive systems are generally preferred due to their lower operational and maintenance costs. Passive systems are based on either thermosyphon or air-duct cooling systems, and utilize

low ambient temperatures during winter to refreeze a buffer layer of non-frost-susceptible material beneath the building. The buffer layer typically consists of a pad of granular material that is placed before building construction and sized to contain the seasonal thaw that develops beneath the building during summer months when the passive cooling system is inactive.

Increasing air temperature is very likely to have a detrimental effect on the operation of these foundation systems for two reasons. Higher air temperatures are likely to lengthen the thaw season and place increased requirements on the thickness of the buffer layer and/or the insulation system, and reduced air freezing indices (section 16.2.2.4) are very likely to decrease the capacity of the passive cooling system to refreeze the buffer layer material during winter.

As a result, existing buildings built on slabs are likely to experience an increasing failure rate as air temperatures rise and produce either significantly longer thaw seasons or a reduced freezing index. Future designs for such buildings will need to take into account temperature increases projected for the lifetime of the structure. This is very likely to increase costs due to the need for additional buffer layer material and higher cooling capacities.

16.3.3. Road and railway embankments and work pads

Transportation routes are likely to be particularly susceptible to destructive frost action under conditions of changing climate. Garagulya et al. (1997) developed a map showing areas with various probabilities of natural hazards. This map indicated that the regions of highest susceptibility to frost heave and thaw settlement are located along the Arctic Circle.

The design of road and railway embankments in the Arctic is complicated by the presence of underlying permafrost, due to the possibility of thaw settlement and significant permanent embankment deformation if thermal disturbance occurs. The situation is exacerbated by complex thermal interactions between the embankment and the surrounding environment. Embankment construction often produces a significant alteration of the surface microclimate that results in an increase in mean annual surface temperature of several degrees as compared to natural conditions. Precise temperature increases are a complex function of embankment surface conditions, maintenance operations (e.g., snow clearing patterns), and the pre-existing natural vegetation, and are sometimes difficult to project.

In the continuous permafrost zone, where the permafrost layer and surface conditions are generally colder, surface warming due to embankment construction can usually be accommodated using well-established design practices. In this case, the embankment thickness is adjusted to ensure that seasonal thawing is contained

within the embankment itself, thus avoiding thawing of the underlying permafrost. The required embankment thickness is sensitive to climatic conditions, tending to increase significantly with warmer conditions.

In the discontinuous permafrost zone, permafrost and ground-surface temperatures are warmer, often within a few degrees of the melting point. In this zone, it is more difficult to accommodate surface warming due to embankment construction since the resulting mean surface temperatures are often above the melting point. In this case, long-term thaw of the permafrost layer can be expected and cost-effective design strategies are currently unavailable. In a limited number of cases, techniques such as thermosyphon, air duct, or convection cooling systems have been used to mitigate these problems (Andersland and Ladanyi, 1994; Goering, 2003; Goering and Kumar, 1996; Instanes, B., 2000; Phukan, 1985), however, the expense associated with these systems severely limits their utility. In practice, even under current climatic conditions, many road and railway embankments located in regions of warm discontinuous permafrost experience high failure rates and resulting high maintenance costs. Typical problems include differential thaw settlement and shoulder failure due to thawing permafrost, resulting in an uneven, cracked embankment surface (Fig. 16.20). The timescales associated with permafrost thaw beneath embankments are of the order of the embankment lifetime (20 to 30 years), thus necessitating a continuous maintenance program.

Increasing temperatures are very likely to affect embankment performance in both the continuous and discontinuous permafrost zones and should be considered in the design of future projects. In the discontinuous permafrost zone, the problems associated with permafrost thaw described above are very likely to increase as increasing air temperature adds to the warming influence of embankment construction. This is very likely to result in increased failure rates and higher maintenance costs. As climate change reduces permafrost extent in the southern discontinu-



Fig. 16.20. Typical embankment cracking and differential thaw settlement in the discontinuous permafrost zone of Interior Alaska (Photo: Larry Hinzman, University of Alaska, Fairbanks).

ous permafrost zone, some reduction in these embankment problems is possible, although the timescales for projected warming and thaw are much longer than typical project lifetimes.

In the continuous permafrost zone, increasing temperatures are likely to have negative impacts on embankment performance for two reasons:

- increased surface temperatures will necessitate greater embankment thicknesses in order to contain the seasonal thaw depth. This is very likely to have a large impact on project costs due to the difficulty and expense associated with obtaining appropriate granular material for embankment construction; and
- as air and surface temperatures increase, a design regime shift will possibly occur in association with the northward movement of the boundary between the discontinuous and continuous permafrost zones. It is possible that increasing embankment thickness alone will no longer be sufficient to protect underlying permafrost and greater failure rates will occur, similar to those seen in the discontinuous permafrost zone.

As a result, it is likely that existing road, rail, or airport embankments will experience increasing failure rates both in the continuous and discontinuous permafrost zones. Future embankment designs should incorporate the effects of projected temperature increases over the lifetime of the project, which is likely to increase construction costs.

16.3.4. Pipelines

Many of the earth's remaining oil and gas reserves are located in regions of the Arctic far from population centers. These areas include the North Slope of Alaska, the Canadian Arctic, northwestern Russia, and Siberia. The limited exploitation of these resources to date has relied primarily on pipeline systems to transport products to market. Future expansion of these pipeline networks is likely given the increasing demand for fossil fuels worldwide. Examples include the large gas pipeline projects currently under consideration to connect natural gas reserves in the Alaskan and western Canadian Arctic to southern Canada and the continental United States. Many of the current and anticipated pipeline routes cross extensive areas of continuous and discontinuous permafrost and require special design considerations.

Oil and gas pipelines differ in their interactions with the surrounding environment because of variations in operating temperature. Transmission of oil through pipelines usually takes place at high temperatures because of high oil-well production temperatures and reduced pumping losses. Conversely, natural gas transmission through pipelines often takes place at temperatures below freezing in order to increase gas density

and throughput. High- or low-temperature pipelines present different challenges to designers and will react in different ways to increased air temperatures.

Gas and oil pipelines are normally constructed below the ground surface, as this reduces construction costs and provides other benefits. In the case of warm-oil pipelines, this becomes problematic in areas where permafrost is encountered. The desire to keep the oil warm to limit viscosity and pumping costs is in direct conflict with the requirement to maintain the frozen state of the surrounding soil. If the pipeline is buried, no practical amount of insulation will prevent the warm oil from thawing surrounding permafrost, thus resulting in loss of strength, thaw settlement, and probable line failure. As a result, designers have relied on one of two methods to avoid permafrost degradation:

- an elevated oil pipeline that is supported above the ground surface on some sort of pile foundation, thus limiting the possibility of permafrost thaw; or
- a more conventional buried pipeline design, with the oil chilled to near-permafrost temperatures (typically below 0 °C for a large part of the year).

A major shortcoming of both methods, particularly with regard to potential climate change, is their reliance on the permafrost layer for structural support. In the first case, the piles are embedded in the permafrost, as for a building foundation, and the adfreeze bond between the pile and the permafrost supports the load. In the second case, the integrity of the pipe trench and support of the pipeline are dependent on the structural integrity of the underlying permafrost. Both methods result in increased cost; the first due to the large expense of constructing an elevated line, and the second due to the high pumping costs associated with moving chilled oil and related problems with potential wax formation in the line.

The best-known example of an existing elevated arctic oil pipeline is the Trans Alaska Pipeline System (TAPS), which stretches 1280 km from Prudhoe Bay to the ice-free port of Valdez in southern Alaska. This pipeline is elevated for just over half of its length in order to avoid potential permafrost problems. The northern sections, where permafrost temperatures are cold (lower than approximately -5 °C), utilize non-refrigerated pile supports and a work-pad embankment designed to protect underlying permafrost. In the more southerly sections, where warmer discontinuous permafrost is encountered, the piles utilize a passive refrigeration system consisting of pairs of thermosyphons installed in each piling. More than 120 000 thermosyphons are used (Sorensen et al., 2003). The thermosyphons are designed to ensure that any excess heat transported downward from the pipeline or entering the ground surface due to construction disturbance will not cause thawing of the permafrost where the piles are embedded.

Owing to the extensive use of pile supports, elevated oil pipelines are sensitive to increasing air and soil temperatures, as are building-support pilings. Increased soil temperatures are very likely to reduce the bearing capacity of these systems because of the reduction in the strength of the adfreeze bond between the frozen soil and the pile. In addition, increased air temperatures are very likely to result in a greater active-layer depth, which will reduce the effective embedment length of the pile in the frozen zone. Some of these effects can be countered by the use of refrigerated piles, as in the case of TAPS; however, increased air temperatures are also very likely to reduce the ability of these systems to provide adequate cooling. It is also possible that the pipeline right-of-way and work-pad embankment will begin to experience increased problems with thaw settlement due to the combination of surface disturbance and increasing air temperature. These factors should be considered during the design stage of future projects.

The Norman Wells Pipeline, which runs 896 km through the western Canadian Arctic from Norman Wells, Northwest Territories, to Zama City, Alberta, is an example of a chilled pipeline that is buried in permafrost terrain. The oil is chilled by a refrigeration system before it enters the line at Norman Wells, and operates at near-ambient permafrost temperatures. Even though the oil is chilled to minimize permafrost disturbance, the designers anticipated a significant amount of thaw settlement and/or frost heave along the route (Nixon et al., 1984). To resist the anticipated loading due to thaw strain or frost heave, a relatively high-strength system consisting of a small-diameter thick-wall pipe was used. Two major design/performance issues were identified as the most significant for this project: adequate thermal conditions must be maintained such that design loads due to thaw settlement or frost heave are not exceeded; and permafrost thaw within the pipeline trench and right-of-way must be limited in order to avoid slope instability (and potential landslides) in areas of sloped terrain.

Variations in line operating conditions have resulted in significant movement of the pipe due to thaw settlement and frost heave. In some places, thaw settlement near the pipeline trench has exceeded the design projections of 1 m (Burgess and Smith, 2003), and increases in thaw depth have reduced the factor of safety for slope stability (Oswell et al., 1998).

Many of the difficult operational issues identified above for buried ambient-temperature pipelines result from the thermal interaction between the pipe and the surrounding ground. These difficulties are likely to be exacerbated if air temperatures also change over time. Increased air temperatures are likely to aggravate problems with thaw settlement along the right-of-way and decrease slope stability. To some extent, it may be possible to reduce the severity of these problems by decreasing the operational temperatures of the pipeline,

however this is not desirable because of the high pumping cost and wax formation issues mentioned previously. New projects should take projected temperature increases into account during the design stage and may have to increase measures designed to prevent slope instability and settlement associated with permafrost thaw.

Unlike oil pipelines, gas pipelines benefit from low-temperature operation and are often operated at temperatures significantly below the freezing point. When these pipelines are buried in continuous permafrost, they aid the maintenance of the permafrost layer and design is straightforward. On the other hand, where chilled buried pipelines must traverse zones of discontinuous permafrost, problems can be expected. In this case, the chilled pipeline will cause freezing of the thawed soil present along the route, some of which may be susceptible to frost. The resulting frost-heave loads on the pipe can be large and must be accounted for carefully. Previous studies have suggested that line operation temperatures should be kept only moderately below freezing in these areas in order to minimize frost-heave problems while, at the same time, avoiding thaw settlement in the permafrost portions of the route (Jahns and Heuer, 1983). Increased air temperatures will possibly expand the problematic portion of these pipeline routes as the boundary between continuous and discontinuous permafrost moves northward. However, the ability to control pipeline operating temperatures may help to adapt to changing climatic conditions.

16.3.5. Water-retaining structures

Water-retaining embankments in permafrost are discussed in detail by Andersland and Ladanyi (1994), and are generally one of two types: unfrozen embankments or frozen embankments. With unfrozen embankments it is assumed that the permafrost foundation will thaw during the lifetime of the structure. This type is limited to sites with thaw-stable foundation materials or bedrock, or cases where the water is retained for a short period of time. With frozen embankments it is assumed that the permafrost foundation will remain frozen during the lifetime of the structure. This type is suitable for continuous permafrost areas and other areas where the foundation materials are thaw-unstable.

The embankment design for a particular site must combine the principles of soil mechanics for unfrozen soils and the mechanical behavior of permafrost. The design should always include thermal and stability considerations, and for permanent structures, potential climate change should be taken into account. Sayles (1984, 1987) and Holubec et al. (2003) have summarized the factors that are relevant to embankment design.

Problems associated with water-retaining dams include seepage, frost heave (in areas of seasonal frost), settlement, slope stability, slope protection, and construction methods. Increased air temperatures are not likely to affect unfrozen embankments because the perma-

frost foundation is thaw stable. Frozen embankments usually require supplementary artificial freezing to ensure that the foundation and embankment remain frozen (Andersland and Ladanyi, 1994). Increased air temperatures are likely to increase the construction and operational costs of frozen embankments due to the increased energy demand required to keep the embankment frozen.

16.3.6. Off-road transportation routes

In recent years, temporary winter transportation routes have played an increasingly important role for community supply and industrial development in the permafrost zones of North America. These transportation corridors consist of ice roads that traverse frozen lakes, rivers, and tundra. In some cases, ice roads are constructed for one-time industrial mobilizations, such as oil and gas exploration activities. In other cases, permanent ice-road corridors have been established and are reopened each winter season. Winter ice roads offer important advantages that include low cost and minimal impact to the environment. Oil and gas exploration can be conducted from these road structures with very minimal ecological effects, and costs associated with construction and eventual removal of more permanent gravel roads or work pads can be avoided.

Winter ice-road construction is affected by a number of climatic factors, including air temperature, accumulated air freezing index, and snowfall. These roads depend on the structural integrity of the underlying frozen base material and, thus, a significant period of freezing temperature must occur each autumn before ice-road construction can begin. For water crossings, the critical factor influencing the start of the winter-road season is the rate and amount of ice formation. Ice thickness must reach critical minimum values before vehicles and freight can be supported safely. For tundra areas (particularly where temporary transportation routes are needed), a critical issue is protection of the existing vegetative cover. In this case, the active layer must be frozen to a depth that is sufficient to support anticipated loads and avoid damage to vegetation. Once a sufficient frozen layer has been established, the surface is covered with snow and water is applied and allowed to freeze in place. The result is a durable driving surface that can support significant loads without harming the underlying vegetation.

In North America, winter-road use and construction is regulated to avoid environmental damage to the tundra. Various inspection techniques are used to ensure adequate freezing before the winter-road season is opened. One technique employs a penetrometer that is pushed into the frozen active layer to measure the strength and thickness of the frozen zone. Based on these measurements, regulatory agencies make decisions regarding opening and closing dates for winter-road travel.

Climatic conditions play a strong role in determining the opening and closing dates for winter-road travel, although inspection techniques and load requirements, among other factors, are also important. Increased air temperature and reductions in the annual air freezing index are very likely to have a negative impact on the duration of the winter-road season. This will possibly become particularly problematic for oil and gas exploration because of the time needed at the beginning and end of the ice-road season for mobilization and demobilization.

Hinzman et al. (in press) present historic data for the opening and closing dates for tundra travel on the North Slope of Alaska that show a substantial reduction in the duration of the winter-road season (from over 200 days in the early 1970s to just over 100 days in 2002). The rate of reduction has been fairly consistent over the intervening years and is due primarily to delayed opening dates (from early November in the 1970s to late January in the 2000s), although closing dates have also been occurring earlier in the spring. Reductions in the duration of the winter-road season have also occurred in the Canadian Arctic, however the reductions are much smaller than those observed in Alaska, and in some cases the season length has increased.

Fig. 16.21 shows historic data for opening and closing dates of winter roads on the North Slope of Alaska and in Canada's Northwest Territories. The data for the North Slope are for temporary winter roads used primarily for oil and gas exploration, whereas the data for the Northwest Territories are for the winter roads between Inuvik and Tuktoyaktuk (187 km) and between the Yellowknife Highway and Wha Ti (103 km). The figure illustrates the reduction in season length for the North Slope of Alaska, and a trend of later opening

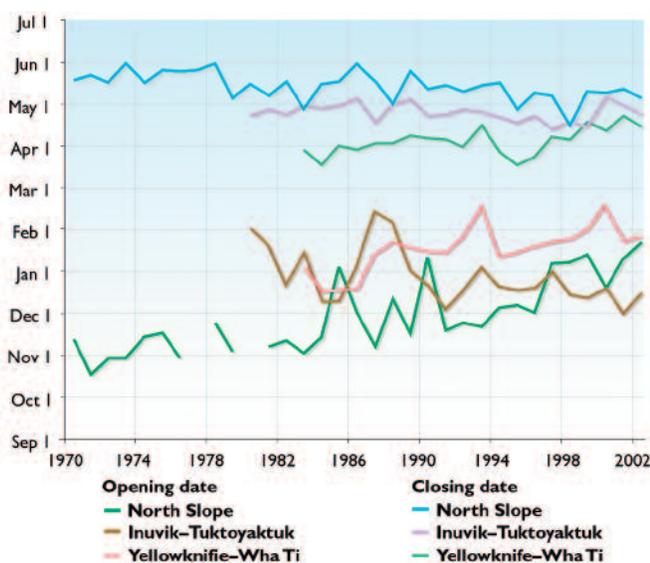


Fig. 16.21. Opening and closing dates for winter roads on the North Slope of Alaska and the Inuvik–Tuktoyaktuk and Yellowknife Highway–Wha Ti winter roads in western Canada (North Slope data after Hinzman et al., in press; Canadian data from the Government of the Northwest Territories, Department of Transportation, www.hwy.dot.gov.nt.ca/highways/, 2003).

dates for the Wha Ti road. Data for the Inuvik–Tuktoyaktuk road, however, indicate an increased season length.

The observed trend in Alaska shows that climate change is likely to lead to decreased availability of off-road transportation routes (ice roads, snow roads, etc.) due to reduced duration of the freezing season.

16.3.7. Offshore transportation routes

The global economy of the 21st century will need the natural resources of the Arctic and subarctic. Air transport remains unprofitable for mineral payloads and attention to arctic shipping is growing as a result. Road, rail, and pipeline routes are complicated in the far north by tectonically active glacier-contorted landscapes, low-lying frozen ground, and fragile ecosystems. Shorter routes from resource to tidewater minimize terrestrial complications only if a port can be built at the coast. New ice-breaking ship designs are continually improving the efficiency of arctic shipping. Growing evidence of climate change indicates that ice-free navigation seasons will probably be extended and thinner sea ice will probably reduce constraints on winter ship transits (section 16.2.5). Additional northern port capacity is critical to the success of arctic shipping strategies associated with northern resource development and potential climate change. Difficulties related to freezing temperatures, snow accumulation, and extended darkness compound the challenges of geotechnical, structural, architectural, mechanical, electrical, transportation, and coastal engineering in designing and operating sea and river ports.

The International Northern Sea Route Programme was a six-year (June 1993 – March 1999) international research program designed to create an extensive knowledge base about the ice-infested shipping lanes along the coast of the Russian Arctic, from Novaya Zemlya in the west to the Bering Strait in the east. This route was previously named the Northeast Passage, but is now more often known by its Russian name – the Northern Sea Route.

Projected reductions in sea-ice extent are likely to improve access along the Northern Sea Route and the Northwest Passage. Projected longer periods of open water are likely to foster greater access to all coastal seas around the Arctic Basin. While voyages across the Arctic Ocean (over the pole) will possibly become feasible this century, longer navigation seasons along the arctic coasts are more likely. Development of the offshore continental shelves and greater use of coastal shipping routes will possibly have significant social, political, and economic consequences for all residents of arctic coastal areas.

Output from the five ACIA-designated climate models was used to project the length of the navigation season along the Northern Sea Route based on the amount of

sea ice present. Figure 16.22 shows the five-model mean for three conditions: 25, 50, and 75% open water across the Northern Sea Route. If ships sailing along the Northern Sea Route are designed for and capable of navigating in waters with 25% open water (75% sea-ice cover), the projected length of the navigation season is considerably longer than that for ships that are minimally ice-capable and can only navigate in 75% open water (25% sea-ice cover).

There are few days when, even at mid-century, the Northern Sea Route is covered by 75% open water (25% sea-ice cover). When days on which navigation is possible are defined by a higher ice-cover percentage, the length of the navigation season increases. In 2050, Fig. 16.22 shows a projected navigation season length of 125 days under conditions of 25% open water (75% sea-ice cover); conditions very favorable for the transit of ice-strengthened cargo ships. However, the ACIA-designated model projections provide no information on sea-ice thickness, a critical factor for ice navigation. Section 16.2.5.2 provides additional projections of future sea-ice conditions.

With increased marine access to arctic coastal seas, national and regional governments are likely to be called upon for increased services such as icebreaking assistance, improved sea-ice charts and forecasting, enhanced emergency response capabilities for sea-ice conditions, and greatly improved oil-ice cleanup capabilities. The sea ice, although thinning and decreasing in extent, will possibly become more mobile and dynamic in many coastal regions where fast ice was previously the norm. Competing marine users in newly open or partially ice-covered areas in the Arctic are likely to require increased enforcement presence and regulatory oversight.

A continued decrease in arctic sea-ice extent this century is very likely to increase seasonal and year-round

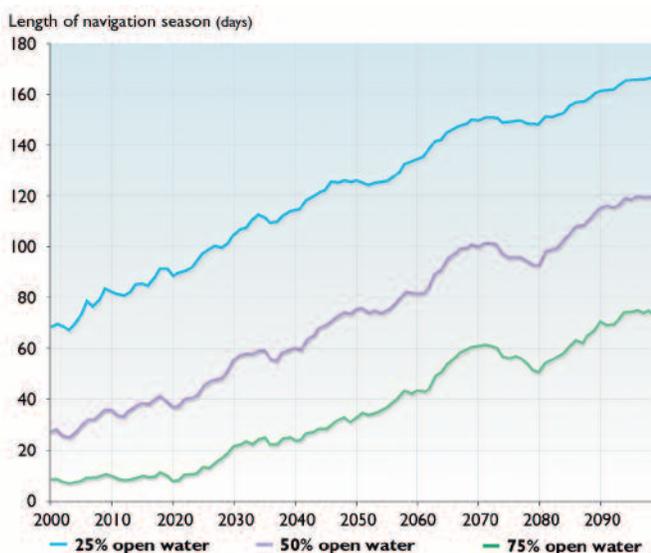


Fig. 16.22. Length of the navigation season along the Northern Sea Route projected by the ACIA-designated climate models (five-model mean).

access for arctic marine transportation and offshore development. New and revised national and international regulations, focusing on marine safety and marine environmental protection, are likely to be required as a result of these trends. Another probable outcome of changing marine access will be an increase in potential conflicts between competing users of arctic waterways and coastal seas.

Based on the scenarios presented in this section and in section 16.2.5.2, a longer navigation season along the arctic coast is very likely and trans-arctic (polar) shipping is possible within the next 100 years.

16.3.8. Damage to infrastructure

Instanes A. (2003) pointed out that for structures on permafrost it is often difficult to differentiate between the effect of temperature increases and other factors that may affect a structure on permafrost. For example: the site conditions are different from the assumed design site conditions; the design of the structure did not take into account appropriate load conditions, active-layer thickness, and permafrost temperature; the contractor did not carry out construction according to the design; the maintenance program was not carried out according to plan; and/or the structure is not being used according to design assumptions. In addition, it is very difficult to find cost-effective engineering solutions for foundations or structures on warm ($T > -1^{\circ}\text{C}$), discontinuous permafrost.

Kronik (2001) summarized reports on damage to infrastructure in Russian permafrost areas from the 1980s to 2000. The reported deformations of foundations and structures were caused not only by climate change, but also by other factors such as those listed above, particularly the low quality and inadequate maintenance of structures. Unfortunately, it is difficult to distinguish between these factors. The analysis of deformation causes performed by Kronik (2001) for industrial and civil complexes showed that 22, 33, and 45% of the deformations were due to mistakes by designers, contractors, and maintenance services, respectively (see also Panova, 2003). Out of 376 buildings surveyed, 183 (48.4%) did not meet building code requirements in 1992, including 21 buildings (8.5%) that were unfit for use (Kronik, 2001). The percentage of dangerous buildings in large villages and cities in 1992 ranged from 22% in the village of Tiksi to 80% in the city of Vorkuta, including 55% in Magadan, 60% in Chita, 35% in Dudinka, 10% in Noril'sk, 50% in Pevek, 50% in Amderma, and 35% in Dikson.

The condition of land transportation routes in Russia is not much better. In the early 1990s, 10 to 16% of the subgrade in the permafrost areas of the Baikal-Amur railroad line was deformed because of permafrost thawing; this increased to 46% in 1998. The majority of runways in Noril'sk, Yakutsk, Magadan, and other cities may be closed for shorter or longer periods due to lack

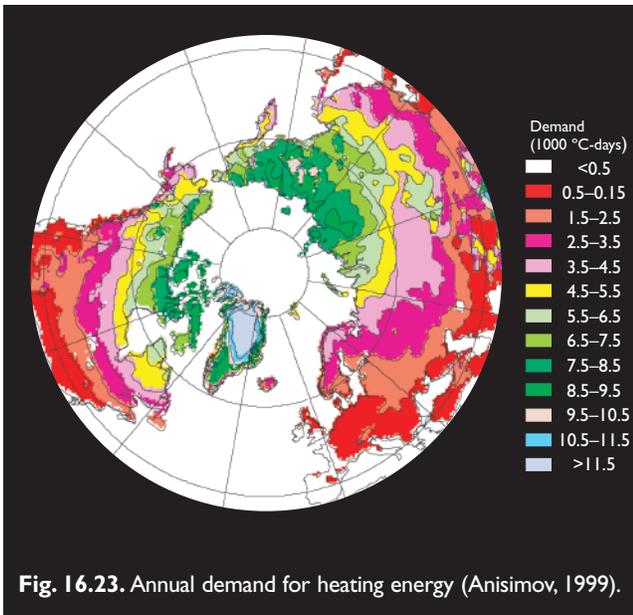


Fig. 16.23. Annual demand for heating energy (Anisimov, 1999).

of maintenance. The main gas and oil transmission lines in the permafrost region have also suffered damage related to permafrost thawing: 16 breaks were recorded on the Messoyakha–Noril’sk pipeline in 2000.

16.3.9. Energy consumption for heating

A reduction in the demand for heating energy is a potential positive effect of climate change in the Arctic and subarctic. The air-temperature threshold that defines the beginning of the cold period, when additional heating of living facilities, businesses, and industrial buildings is necessary, varies within and between countries. In North America and Western Europe, most civil buildings, private houses, apartment complexes, and even most buildings in large cities have local heating systems. In the United States the temperature threshold for heating is defined as 65 °F (17.8 °C), but because the local systems are very flexible and can be manipulated individually, evaluation of energy consumption is complex.

In Eastern Europe and Russia, most urban buildings have centralized heating systems. Under standard con-

ditions, such systems operate when the mean daily air temperature falls below 8 °C (47 °F). Because of the large thermal inertia of these centralized heating systems, comfortable indoor temperatures (e.g., 18 °C) are usually maintained throughout the winter.

Figure 16.23 shows the annual demand for heating energy (in 1000 °C-days) when building heating is required (mean daily air temperature below 8 °C) calculated for current climatic conditions. Annual heating degree-day totals characterize the demand for heating over the entire cold period. Daily heating degree-days are calculated by subtracting the mean daily temperature from the 8 °C threshold (e.g., a day with a mean daily temperature of 5 °C would result in three heating degree-days); days with a mean temperature at or above 8 °C result in zero heating degree-days.

Anisimov (1999) used the GFDL, ECHAM-1 (Max-Planck Institute for Meteorology), and HadCM transient climate scenarios for 2050 to calculate the reduction in the duration of the heating period and changes in the number of heating degree-days relative to 1999. Projected reductions in the number of heating degree-days (Fig. 16.24) can be used as a metric for the reduction in heating energy consumption. Figure 16.25 shows the percentage reduction in the duration of the heating period between 1999 and 2050; this decrease is projected to vary from a few weeks to more than a month, depending on the regional effects of climate change.

The energy savings from decreased demand for heating in northern regions are likely to be offset by increases in the temperature and duration of the warm period, leading to greater use of air conditioning.

16.3.10. Natural resources

The Arctic has large oil and natural gas reserves. Most are located in Russia: oil in the Pechora Basin, natural gas in the Lower Ob Basin, and other potential oil and gas fields along the Siberian coast. Canadian oil and gas fields are concentrated in two main basins in

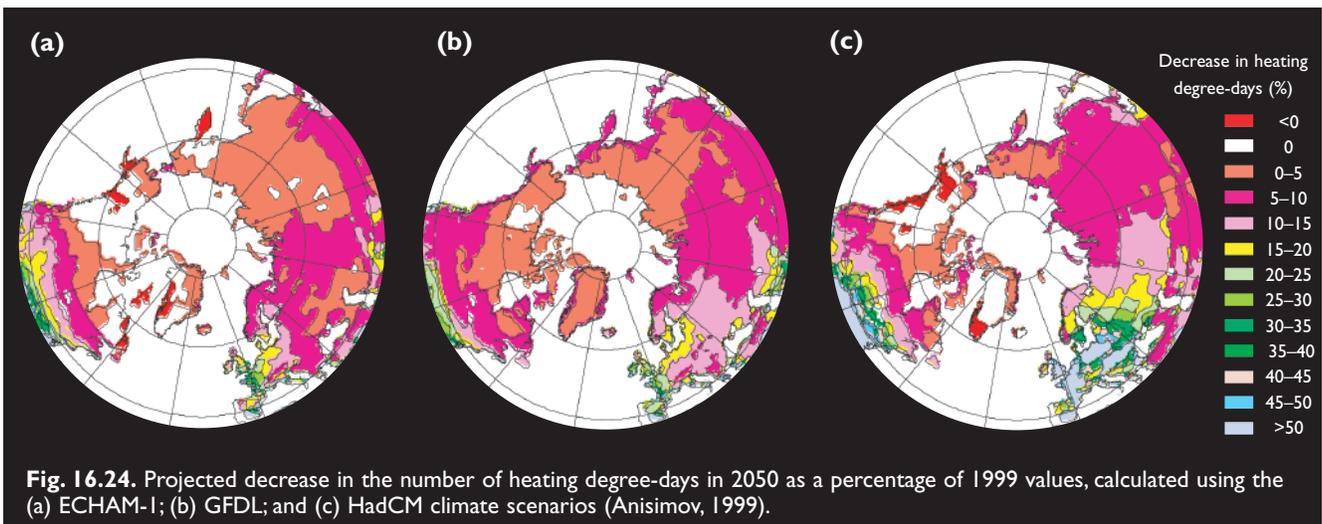


Fig. 16.24. Projected decrease in the number of heating degree-days in 2050 as a percentage of 1999 values, calculated using the (a) ECHAM-1; (b) GFDL; and (c) HadCM climate scenarios (Anisimov, 1999).

the Mackenzie Delta–Beaufort Sea region and in the high Arctic. Prudhoe Bay (Alaska) is the largest oil field in North America, and other fields have been discovered or are likely to be present along the Beaufort Sea coast. Oil and gas fields also exist in other arctic waters, for example, the Barents Sea and off the west coast of Greenland. The Arctic is an important supplier of oil and gas to the global market, and it is possible that climate change will have both positive and negative financial impacts on the exploration, production, and transportation activities of this industry.

Climate change impacts on oil and gas development have so far been minor, but are likely to result in both financial costs and benefits in the future. For example, offshore oil exploration and production is likely to benefit from less extensive and thinner sea ice because of cost reductions in the construction of platforms that must withstand ice forces. Conversely, ice roads, now used widely for access to offshore activities and facilities, are likely to be useable for shorter periods and less safe than at present. The thawing of permafrost, on which buildings, pipelines, airfields, and coastal installations supporting oil development are located, is very likely to adversely affect these structures and the cost of maintaining them (Parker, 1998; Weller and Lange, 1999; Weller et al., 1999).

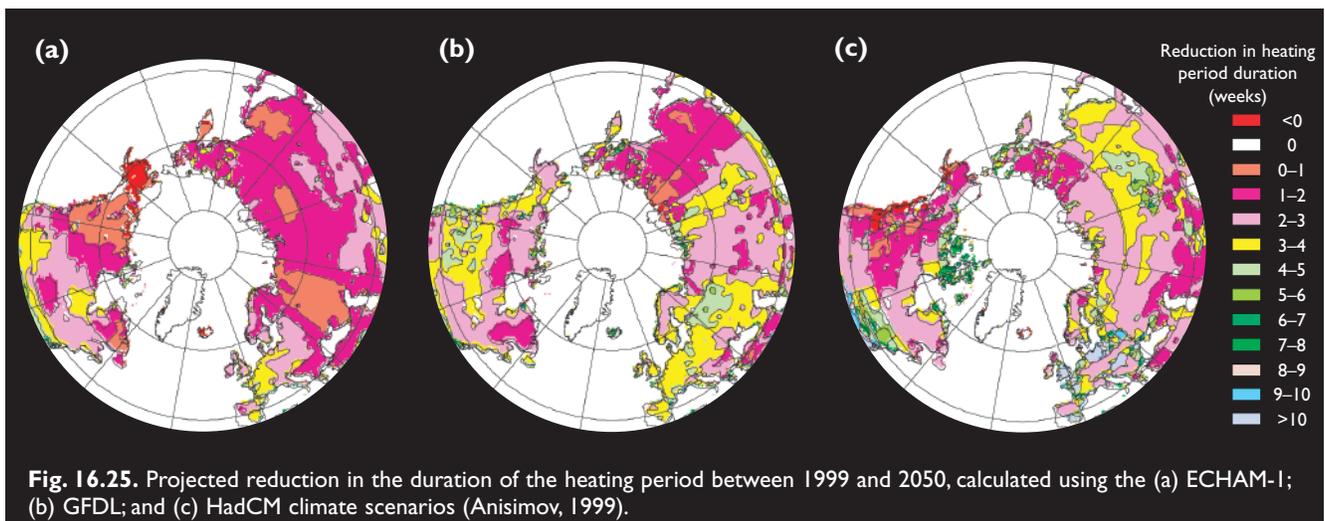
The Arctic holds large stores of minerals, ranging from gemstones to fertilizers. Russia extracts the largest quantities, including nickel, copper, platinum, apatite, tin, diamonds, and gold, mostly on the Kola Peninsula but also in Siberia. Canadian mines in the Yukon and Northwest Territories supply lead, zinc, copper, and gold. Gold mining continues in Alaska, along with extraction of lead and zinc deposits from the Red Dog Mine, which contains two-thirds of US zinc resources. Coal mining also occurs in several areas of the Arctic. Mining activities in the Arctic are an important contributor of raw materials to the global economy and are likely to benefit from improved transportation conditions to bring products to market, due to a longer ice-free shipping season.

The coal and mineral extraction industries in the Arctic are important contributors to national economies, and the actual extraction process is not likely to be much affected by climate change. However, climate change will possibly affect the transportation of coal and minerals. Mines that export their products using marine transport are likely to experience savings due to reduced sea-ice extent and a longer shipping season. Conversely, mining facilities with roads on permafrost are likely to experience higher maintenance costs as the permafrost thaws (Parker, 1998; Weller and Lange, 1999; Weller et al., 1999).

Any expansion of oil and gas activities and mining is likely to require expansion of air, marine, and land transportation systems. The benefits of a longer shipping season in the Arctic, with the possibility of easy transit through the Northern Sea Route and Northwest Passage for at least part of the year, are likely to be significant. Other benefits are likely to include deeper drafts in harbors and channels as sea level rises, a reduced need for ice strengthening of ship hulls and offshore oil and gas platforms, and a reduced need for ice-breaker support. Conversely, coping with greater wave heights, and possible flooding and erosion threats to coastal facilities, is likely to result in increased costs.

16.4. Engineering design for a changing climate

Climate change is likely to affect infrastructure in different ways, as has been described in previous sections of this chapter. Some infrastructure may be relatively insensitive to climate change or easily adaptable to changing conditions. In other cases, a large sensitivity may exist and/or the consequences of any failure may be high (Esch, 1993; Ladanyi et al., 1996; Khrustalev, 2001, 2000). For infrastructure in the first category, a detailed analysis of the potential impacts of climate change may not be important, particularly given the high level of uncertainty associated with local climate trends that will affect individual projects. Conversely, for projects where high sensitivity or large consequences are possible, a detailed analysis may be warranted.



16.4.1. Risk-based evaluation of potential climate change impacts

Bush et al. (1998) presented a methodology for considering the impact of projected climate change within the framework of the engineering design process. They also explained how the same methodology can be utilized to identify and prioritize concerns about existing facilities with respect to climate change impacts. The method involves a multi-step approach that first assesses the sensitivity of a given project to climate change and then the consequences of any potential failures. The relationship between sensitivity and consequences defines the risk that climate change poses to the project. Finally, the degree of sensitivity and the severity of the consequences are used to determine what level of climate-change impact analysis should be carried out for a given project.

The sensitivity of a particular infrastructure project to climate change is determined by a number of factors, including the initial soil and permafrost temperatures, the temperature dependence of the material properties, the project lifetime, and the existing over-design or safety margin that might be included in the design for other reasons. Bush et al. (1998) included a procedure for categorizing these effects and determining the climate sensitivity of a project using a scale of high, medium, or low.

Any analysis of the consequences of failure begins with a determination of all relevant failure scenarios. These scenarios are then evaluated qualitatively using a scale of catastrophic, major, minor, or negligible, considering not only potential physical damage to the infrastructure but also socioeconomic or cultural impacts.

The final step in the screening process involves the determination of the level of climate-change impact analysis required at the design stage. Bush et al. (1998) included a table that suggests a level of analysis as a function of the degree of risk indicated by the project sensitivity and failure consequences. Level A requires a detailed quantitative analysis relying on numerical geotechnical models with refined input parameters, independent expert review, and a field-monitoring program with periodic evaluation of performance. Level B requires more limited quantitative analysis and also suggests a field-monitoring program. Level C suggests the use of qualitative analysis based on professional judgment, and Level D does not require any analysis of climate change impacts. This framework provides an organized approach to incorporating projected climate change into the design of arctic infrastructure projects.

16.4.2. Design thawing and freezing indices

Section 16.2.2.2 introduced the concept of air thawing and freezing indices. For design purposes, the design air thawing index (ATI) is commonly defined as the

average ATI for the three warmest summers in the latest 30 years of record, or the warmest summer in the latest 10 years of record if 30 years of record are not available (Andersland and Anderson, 1978; Andersland and Ladanyi, 1994).

In Norway, statistical analysis of historic meteorological data is used to determine design air freezing indices (AFIs) with varying probabilities of occurrence (Heiersted, 1976). A similar approach can be used for determining design ATIs in permafrost areas (Instanes, A., 2003).

Table 16.10 shows different design ATIs and their probability of occurrence. The two-year design ATI (ATI_2) is approximately equal to the 30-year mean of the ATI. The average ATI for the three warmest summers in the latest 30 years of record usually lies somewhere between ATI_{20} and ATI_{50} . The magnitude of potential thawing incorporated in a design is dependent on the type of foundation or structure and the consequences of differential settlement or failure. For road embankments, ATI_2 to ATI_{10} is commonly used, while for buildings, ATI_{50} to ATI_{100} is used. For more sensitive structures, such as power plants and oil or gas pipelines, higher design ATIs should be considered.

In thermal analyses using advanced methods such as finite-element models, the design ATI is usually represented by a time series or sine curve that combines an average winter (AFI_2) and a design summer. Maximum thaw depth and permafrost temperature are usually caused by a combination of warm winters and summers. Therefore, combinations of warm winters (low AFI) and warm summers (high ATI) should also be considered.

Section 16.2.2.4 describes projected changes in freezing and thawing indices calculated using output from the ACIA-designated climate models. Figures 16.26 and 16.27 present an example of projected design freezing and thawing indices for Kugluktuk (Coppermine), Canada. The values from 1940 to 2000 are based on observations, while those from 2000 to 2100 are based on output from the CGCM2 model. The figures show curves for the 30-year mean value (probability of occurrence 50%); the mean of the warmest 3 years during the last 30 years; the warmest year during the last 10 years; AFI_{20}/ATI_{20} (probability of occurrence

Table 16.10. Design air thawing indexes (ATIs).

Magnitude of thawing	Probability of occurrence in any given year (%)	Predicted number of occurrences
ATI_2	50	once in 2 years
ATI_{10}	10	once in 10 years
ATI_{20}	5	once in 20 years
ATI_{100}	1	once in 100 years
ATI_{1000}	0.1	once in 1000 years
ATI_{10000}	0.01	once in 10000 years

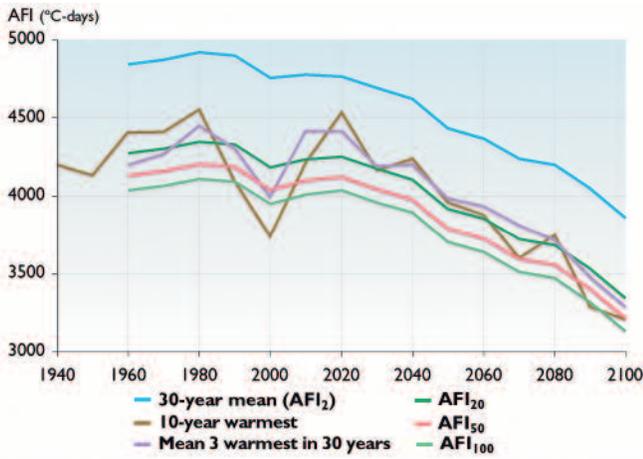


Fig. 16.26. Projected air freezing index (AFI) design levels for Kugluktuk (Coppermine), Canada (Instanes A. and Mjureke, 2002b).

5%); AFI_{50}/ATI_{50} (probability of occurrence 2%); and AFI_{100}/ATI_{100} .

Figure 16.26 shows that the 30-year mean design AFI is projected to decrease from approximately 4850 degree-days in 1960 to 3850 degree-days in 2100. This represents an increase in winter (October–March) temperatures of approximately 5 to 6 °C. Figure 16.27 shows that the 30-year mean design ATI is projected to increase from approximately 720 degree-days in 1960 to 1430 degree-days in 2100. This represents an increase in summer (April–September) temperatures of approximately 4 °C. Instanes A. and Mjureke (2002b) presented similar plots of design freezing and thawing indices for the 21 stations listed in Table 16.3.

Using such projections, it is possible to estimate the potential impacts of climate change on specific structures in the Arctic while also including the effect of natural variability. Such an analysis has been carried out

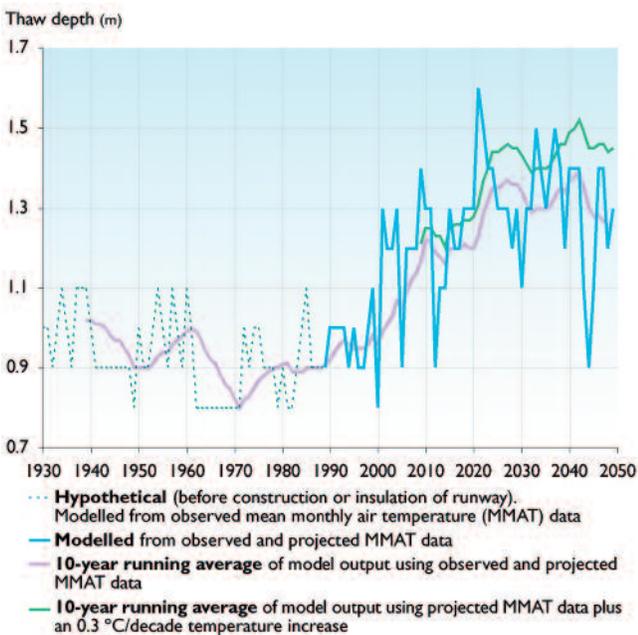


Fig. 16.28. Projected thaw depths below the runway at Svalbard Airport (Instanes A. and Mjureke, in press)

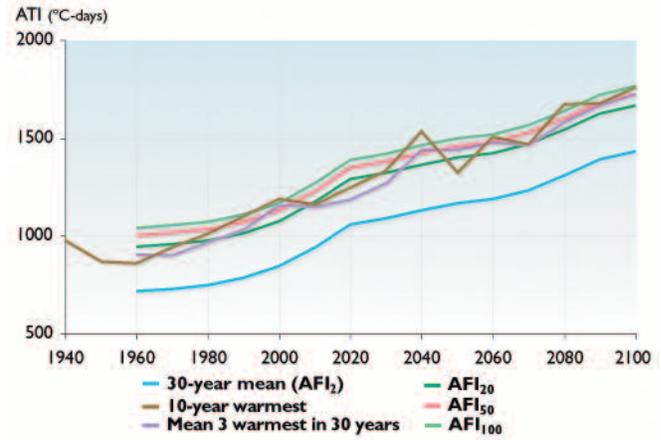


Fig. 16.27. Projected air thawing index (ATI) design levels for Kugluktuk (Coppermine), Canada (Instanes A. and Mjureke, 2002b).

for Svalbard Airport (Instanes A. and Mjureke, in press), using observed air temperature data for 1930 to 2000 and future temperature projections obtained by statistical downscaling of output from the ECHAM4/OPYC3 GSDIO integration (Hanssen-Bauer et. al, 2000, see also section 4.6.2). Figures 16.28 and 16.29 show the results of the analysis. Figure 16.28 shows that average thaw depths are projected to increase by as much as 50% between 2000 and 2050. As Fig. 16.29 shows, March ground temperatures at 2 m depth are projected to undergo the greatest increase (~4 °C) between 2000 and 2050, while the corresponding September temperatures are projected to increase by only 1 °C. At 40 m depth, mean annual temperatures are projected to increase by approximately 2 °C by 2050. At depths of 10 m and more, seasonal temperature variations are small. The climate scenario used in this study projects greater air temperature increases in winter than summer, which contributes to the strong positive trend in March temperatures at 2 m depth. The weak trend in September temperatures at 2 m is largely explained by the proximity of the 0 °C isotherm and the latent heat of the associated phase change. At shorter timescales, the large fluctuations in March ground temperatures reflect variable projected winter conditions, while summer conditions are

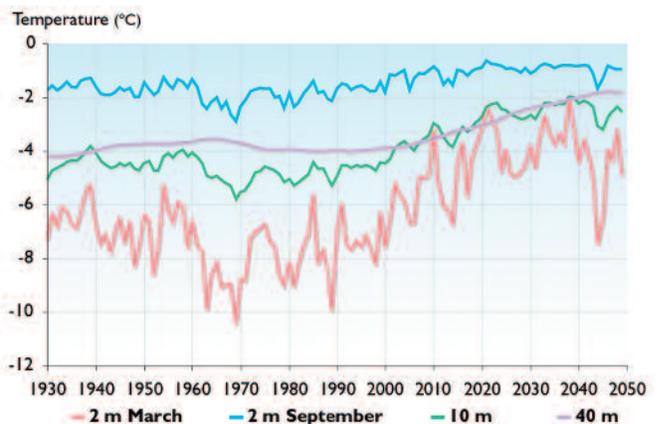


Fig. 16.29. Projected ground temperature changes at depths of 2, 10, and 40 m below the Svalbard Airport runway (Instanes A. and Mjureke, in press)

projected to be more uniform. This analysis suggests that the design of structures sensitive to thaw settlement should utilize the risk-based method described in section 16.4.1.

Instones A. (2003) reported that the design lifetime for structures in permafrost regions is typically 30 to 50 years. Within this time frame, the structure should function according to design with normal maintenance costs. Total rehabilitation, demolition, and replacement of old structures must be expected and are part of sensible infrastructure planning and engineering practice. The effects of climate change on arctic infrastructure are, as previously indicated, difficult to quantify. Structural damage is often blamed on climate change, when a thorough investigation and case history indicates that the cause is either human error or the design lifetime being exceeded.

16.4.3. Coastal areas

Numerous arctic communities face the challenge of increased coastal erosion and warming of permafrost. The combined problems of increased wave action, sea-level rise, and thermal erosion have no simple engineering solutions. Two examples of erosion problems threatening communities and industrial facilities in Canada and Russia are discussed in the following sections. Coastal erosion is discussed in detail in section 6.9.

16.4.3.1. Severe erosion in Tuktoyaktuk, Canada

Tuktoyaktuk is the major port in the western Canadian Arctic and the only permanent settlement on the low-lying Beaufort Sea coast. The location of Tuktoyaktuk makes it highly vulnerable to increased coastal erosion due to decreased extent and duration of sea ice, accelerated thawing of permafrost, and sea-level rise. The Tuktoyaktuk Peninsula is characterized by sandy spits, barrier islands, and a series of lakes that have resulted from collapsed ground due to permafrost thawing ("thermokarst" lakes). Erosion is already a serious problem in and around Tuktoyaktuk, threatening cultural and archeological sites and causing the abandonment of an elementary school, housing, and other buildings. Successive shoreline protection structures have been rapidly destroyed by storm surges and accompanying waves.

As climate change proceeds and sea-level rise accelerates, impacts are likely to include further landward retreat of the coast, erosion of islands, more frequent flooding of low-lying areas, and breaching of freshwater thermokarst lakes and their consequent conversion into brackish or saline lagoons. The current high rates of cliff erosion are projected to increase due to higher sea levels, increased thawing of permafrost, and the increased potential for severe coastal storms during the extended open-water season. Attempts to control erosion at Tuktoyaktuk will become increasingly expensive as the surrounding coastline continues to retreat, and the site could ultimately become uninhabitable.

16.4.3.2. Erosion threatens Russian oil storage facility

The oil storage facility at Varandei on the Pechora Sea was built on a barrier island. Damage to the dunes and beach due to construction and use of the facility accelerated natural rates of coastal erosion. The Pechora Sea coasts are considered to be relatively stable, except where disturbed by human activity. Because this site has been perturbed, it is more vulnerable to damage from storm surges and the accompanying waves that will become a growing problem as climate continues to warm. As with the other sites discussed here, the reduction in sea-ice extent and duration, thawing coastal permafrost, and rising sea level are projected to exacerbate the existing erosion problem. This provides an example of the potential for combined impacts of climate change and other anthropogenic disturbances. Sites already threatened due to human activity are often more vulnerable to the impacts of climate change.

16.4.4. Summary

In areas of continuous permafrost, projected climate change is not likely to pose an immediate threat to infrastructure if the correct permafrost engineering design procedures have been followed; the infrastructure has not already been subjected to one of the factors mentioned at the beginning of this section or strains exceeding design values; and the infrastructure is not located on ice-rich terrain or along coastlines susceptible to erosion. Maintenance costs are likely to increase relative to those at present, but it should be possible to gradually adjust arctic infrastructure (through replacement and changing design approaches over time) to a warmer climate.

Projected climate change is very likely to have a serious effect on existing infrastructure in areas of discontinuous permafrost. Permafrost in these areas is already at temperatures close to thawing, and further temperature increases are very likely to result in extremely serious impacts on infrastructure. However, considerable engineering experience with discontinuous permafrost has been accumulated over the past century. Human activities and engineering construction very often lead to extensive thawing of both continuous and discontinuous permafrost. Techniques to address warming and thawing are already commonly used in North America and Scandinavia.

If the projections and trends presented in this assessment do occur over the next five to ten years, this is very likely to have a serious impact on the future design of engineering structures in permafrost areas. However, engineering design should still be based on actual meteorological observations and a risk-based method.

The most important engineering considerations related to projected climate change include: that risk-based methods should be used to evaluate projects in terms

of potential climate change impacts; that design air thawing and freezing indices should be updated annually to account for observed climate variations and change; and that mitigation techniques such as artificial cooling of foundation soils should be considered as situations require.

In coastal areas, shore protection measures have to some extent reduced local erosion rates. However, thawing and erosion of ice-rich coastal sediments is a process that has been ongoing since the last glaciation and cannot be reversed given present climate trends.

16.5. Gaps in knowledge and research needs

The main gaps in knowledge are the lack of site-specific scenarios providing the probability of occurrence of various meteorological conditions (temperature, precipitation, wind, snow and sea-ice thickness and extent, waves, and erosion rates). Monitoring of infrastructure and the coastal environment is essential, as are climate sensitivity analyses.

It is also important to combine engineering knowledge with socioeconomic development scenarios and environmental impact assessments (see Chapters 3, 12, and 15) to evaluate how projected climate change may affect human lives in the Arctic in the future. Studies examining impacts and socioeconomic assessments have been performed in Canada (Couture et al., 2001). Studies are also underway for other regions of the Arctic, including Alaska (University of Alaska, Institute of Social and Economic Research) and northwest Russia (Centre for Economic Analysis, Oslo; Norwegian Institute of International Affairs, Oslo; and the Fridtjof Nansen Institute, Bergen).

References

- Alekseev, G.V., Z.V. Bulatov, V.F. Zakharov and V.P. Ivanov, 1997. Influx of very warm water in the Arctic basin. *Doklady Akademii Nauk SSSR*, 356:401–403.
- Aleksandrov, Ye.I. and V.V. Maistrova, 1998. Comparison of the air temperature measurements for the polar regions. *The Antarctica*, 34:60–72.
- AMAP, 1997. Arctic Pollution Issues: A State of the Arctic Environment. Arctic Monitoring and Assessment Programme, Oslo, 188pp.
- AMAP, 1998. AMAP Assessment Report: Arctic Pollution Issues. Arctic Monitoring and Assessment Programme, Oslo, xii+859pp.
- Andersland, O.B. and D.M. Anderson, 1978. *Geotechnical Engineering for Cold Regions*. McGraw-Hill.
- Andersland, O.B. and B. Ladanyi, 1994. *An Introduction to Frozen Ground Engineering*. Chapman & Hall, 352pp.
- Andrady, A.L., 1997. Wavelength sensitivity in polymer photo-degradation. *Advances in Polymer Science*, 128:49–94.
- Andrady, A.L., S.H. Hamid, X. Hu and A. Torikai, 1998. Effects of increased solar ultraviolet radiation on materials. *Journal of Photochemistry and Photobiology B*, 46:96–103.
- Anisimov, O.A., 1999. Impacts of anthropogenic climate change on heating and air conditioning of buildings. *Meteorology and Hydrology*, 6:10–17. (In Russian)
- Anisimov, O.A. 2001. Predicting patterns of near-surface air temperature using empirical data. *Climatic Change*, 50:297–315.
- Anisimov, O.A. and M.A. Belolutskaia, 2002. Effects of changing climate and degradation of permafrost on infrastructure in northern Russia. *Meteorology and Hydrology*, 9:15–22. (In Russian)
- Anisimov, O.A. and B. Fitzharris, 2001. Polar Regions (Arctic and Antarctic). In: J. McCarthy, O. Canziani, N.A. Leary, D.J. Dokken and K.S. White (eds.). *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, pp. 801–841. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- Anisimov, O.A., N.I. Shiklomanov and F.E. Nelson, 1997. Effects of global warming on permafrost and active-layer thickness: results from transient general circulation models. *Global and Planetary Change*, 61:61–77.
- Aylsworth, J.M., M.M. Burgess, D.T. Desrochers, A. Duk-Rodkin, T. Robertson and J.A. Traynor, 2000. Surficial geology, subsurface materials, and thaw sensitivity of sediments. In: L.D. Dyke and G.R. Brooks (eds.). *The Physical Environment of the Mackenzie Valley, Northwest Territories: a Baseline for the Assessment of Environmental Change*. Geological Survey of Canada Bulletin, 547:41–47.
- Bjerrum, L., 1955. Stability of natural slopes in quick clay. *Geotechnique*, 5(1):101–119.
- Borzenkova, I.I., 1999a. Environmental indicators of recent global warming. In: Yu.A. Pykh (ed.). *Environmental Indices*, pp. 455–465. EOLSS Publishing.
- Borzenkova, I.I., 1999b. About natural indicators of the present global warming. *Meteorology and Hydrology*, 6:98–116.
- Brown, J., O.J. Ferrians, J.A. Heginbottom and E.S. Melnikov, 1997. International Permafrost Association Circum-Arctic Map of Permafrost and Ground Ice Conditions. Circum-Pacific map series, CP-45. U.S. Geological Survey.
- Brown, J., K.M. Hinkel and F.E. Nelson, 2000. The circumpolar active layer (CALM) program: research designs and initial results. *Polar Geography*, 24:163–258.
- Brown, J., M.T. Jorgenson, O.P. Smith and W. Lee, 2003. Long-term rates of erosion and carbon input, Elson Lagoon, Barrow, Alaska. In: M. Phillips, S.M. Springman and L.U. Arenson (eds.). *Permafrost: Proceedings of the Eighth International Conference on Permafrost*, pp. 101–106. A.A. Balkema.
- Burgess, M.M. and S.L. Smith, 2003. 17 years of thaw penetration and surface settlement observations in permafrost terrain along the Norman Wells pipeline, Northwest Territories, Canada. In: M. Phillips, S.M. Springman and L.U. Arenson (eds.). *Permafrost: Proceedings of the Eighth International Conference on Permafrost*, pp. 1073–1078. A.A. Balkema.
- Burgess, M.M., D.T. Desrochers and R. Saunders, 2000a. Potential changes in thaw depth and thaw settlement for three locations in the Mackenzie Valley. In: L.D. Dyke and G.R. Brooks (eds.). *The Physical Environment of the Mackenzie Valley, Northwest Territories: a Baseline for the Assessment of Environmental Change*. Geological Survey of Canada Bulletin, 547:187–195.
- Burgess, M.M., S.L. Smith, J. Brown, V. Romanovsky and K. Hinkel, 2000b. Global terrestrial network for permafrost (GTNet-P): Permafrost monitoring contributing to global climate observations. Geological Survey of Canada, Current Research 2000-E14, 8pp.
- Bush, E., D.A. Etkin, D. Hayley, E. Hivon, B. Ladanyi, B. Lavender, G. Paoli, D. Riseborough, J. Smith, and M. Smith, 1998. *Climate Change Impacts on Permafrost Engineering Design*. Environment Canada, Environmental Adaptation Research Group, Downsview, Ontario.
- Carmack, E.C., 2000. Review of the Arctic Ocean's freshwater budget: sources, storage and export. In: E.L. Lewis, E.P. Jones, P. Lemke, T.D. Prowse and P. Wadhams (eds.). *The Freshwater Budget of the Arctic Ocean*. Kluwer Academic Publishers.
- Carmack, E.C., R.W. Macdonald, F.A. Perkin, F.A. McLaughlin and R.J. Pearson, 1995. Evidence for warming of Atlantic water in the southern Canadian basin of the Arctic Ocean: Results from the Larsen-93 Exhibition. *Geophysical Research Letters*, 22:1061–1064.
- Chapman, W.L. and J.E. Walsh, 2003. Observed climate change in the Arctic, updated from Chapman and Walsh, 1993. Recent variations of sea ice and air temperatures in high latitudes. *Bulletin of the American Meteorological Society*, 74(1):33–47. <http://arctic.atmos.uiuc.edu/CLIMATESUMMARY/2003/>
- Couture, R., S.D. Robinson and M.M. Burgess, 2001. Climate change, permafrost degradation and impacts on infrastructure: two cases studies in the Mackenzie Valley. *Proceedings of the 54th Canadian Geotechnical Conference*, 4–9 September 2001, Calgary, 2:908–915.
- Couture, R., S. Smith, S.D. Robinson, M.M. Burgess and S. Solomon, 2003. On the hazards to infrastructure in the Canadian North associated with thawing of permafrost. In: *Proceedings of Geohazards 2003. Third Canadian Conference on Geotechnique and Natural Hazards*, pp. 97–104.

- Dyke, L.D. 2000. Stability of permafrost slopes in the Mackenzie valley. In: L.D. Dyke and G.R. Brooks (eds.). *The Physical Environment of the Mackenzie Valley, Northwest Territories: a Baseline for the Assessment of Environmental Change*. Geological Survey of Canada Bulletin, 547:177–186.
- Dyke, L.D., J.M. Aylsworth, M.M. Burgess, F.M. Nixon and F. Wright, 1997. Permafrost in the Mackenzie Basin, its influences on land-altering processes and its relationship to climate change. In: Cohen, S.J. (ed.). *Mackenzie Basin Impact Study (MBIS): Final report*, pp. 112–117. Environment Canada.
- Esch, D.C., 1993. Impacts of northern climate changes on Arctic engineering practice. In: *Impacts of Climate Change on Resource Management in the North, 4th Canada-U.S. Symposium & Biennial AES/DIAND Meeting on Northern Climate*, pp. 185–192.
- Esch, D.C. and T.E. Osterkamp, 1990. Cold regions engineering: Climate warming concerns for Alaska. *Journal of Cold Regions Engineering*, 4(1):6–14.
- Factor, A., W.V. Ligon, R.J. May and F.H. Greenburg, 1987. Recent advances in polycarbonate photodegradation. In: A.V. Patsis (ed.). *Advances in Stabilization and Controlled Degradation of Polymers II*, pp. 45–58. Technomic, Lancaster, Pennsylvania.
- Freitag, D.R. and T. McFadden, 1997. *Introduction to Cold Regions Engineering*. ASCE Press, 738pp.
- Garagulya, L.S., G.I. Gordeeva and L.N. Khrustalev, 1997. Zoning of the permafrost area by the impact of human-induced geocryological processes on environmental conditions. *Kriosfera Zemli*, 1(1):30–38.
- Glazovskaya, T.G. and Yu.G. Seliverstov, 1998. Long-term forecasting of changes of snowiness and avalanche activity in the world due to the global warming. In: *25 Years of Snow Avalanche Research*, Publ. No. 203. pp. 113–116. Norwegian Geotechnical Institute, Oslo.
- Goering, D.J., 2003. Passively cooled railway embankments for use in permafrost areas. *Journal of Cold Regions Engineering*, 17(3):119–133.
- Goering, D.J. and P. Kumar, 1996. Winter-time convection in open-graded embankments. *Cold Regions Science and Engineering*, 24:57–74.
- Haas, W.M. and A.E. Barker, 1989. Frozen gravel: A study of compaction and thaw settlement behaviour. *Cold Regions Engineering*. Fifth International Conference, St. Paul, Minnesota, 6–8 February, 1989.
- Hackett, B., 2001. Surge climate scenarios in the northern North Sea and along the Norwegian coast. Research Report No. 123. Norwegian Meteorological Institute, 51pp.
- Hamid, S.H. and W. Pritchard, 1991. Mathematical modeling of weather-induced degradation of polymer properties. *Journal of Applied Polymer Science*, 43:651–678.
- Hamid, S.H., M.B. Amin and A.G. Maadhah, 1995. Weathering degradation of polyethylene. In: S.H. Hamid, M.B. Amin and A.G. Maadhah (eds.). *Handbook of Polymer Degradation*. Marcel Dekker.
- Hanssen-Bauer, I. and E.J. Forland, 1998. Long term trends in precipitation and temperature in the Norwegian Arctic: can they be explained by changes in atmospheric circulation patterns? *Climate Research*, 102:1–14.
- Hanssen-Bauer, I., O.E. Tveit and E.J. Forland, 2000. Temperature scenarios for Norway: Empirical downscaling from the ECHAM4/OPYC3 GSDIO integration. Norwegian Meteorological Institute, report no. 24/00 KLIMA.
- Harris, S.A., 1986. Permafrost distribution, zonation and stability along the eastern ranges of the Cordillera of North America. *Arctic*, 39:29–38.
- Haugen J.E. and J. Debenard, 2002. Climate scenario for Norway in 2050 for the transportation sector. Internal document. Norwegian Meteorological Institute, Oslo, Norway (In Norwegian).
- Haugen, J.E., D. Bjørge and T.E. Nordeng, 1999. A 20-year climate change experiment with HIRHAM, using MPI boundary data. RegClim Technical Report, 3:37–43. Norwegian Institute for Air Research.
- Heiersted, R.S., 1976. Frost Action in Ground. Committee on Frost Action in Soils, Royal Norwegian Council for Scientific and Industrial Res., No. 17, Oslo. (In Norwegian)
- Hestnes, E., 1994. Weather and snowpack conditions essential to slush flow release and down slope propagation. Norwegian Geotechnical Institute, Publication no. 582000-10.
- Hinzman, L.D., N. Bettez, F.S. Chapin, M. Dyurgerov, C. Fastie, B. Griffith, R.D. Hollister, A. Hope, H.P. Huntington, A. Jensen, D. Kane, D.R. Klein, A. Lynch, A. Lloyd, A.D. McGuire, F. Nelson, W.C. Oechel, T. Osterkamp, C. Racine, V. Romanovsky, D. Stow, M. Sturm, C.E. Tweedie, G. Vourlitis, M. Walker, D. Walker, P.J. Webber, J. Welker, K. Winker and K. Yoshikawa, in press. Evidence and implications of recent climate change in terrestrial regions of the Arctic. *Climatic Change*.
- Holubec, I., X. Hu, J. Wonnacott, R. Olive and D. Delarosbil, 2003. Design, construction and performance of dams in continuous permafrost. In: M. Phillips, S.M. Springman and L.U. Arenson (eds.). *Permafrost: Proceedings of the Eighth International Conference on Permafrost*, pp. 425–430. A.A. Balkema.
- Instanes, A., 2003. Climate change and possible impact on Arctic infrastructure. In: M. Phillips, S.M. Springman and L.U. Arenson (eds.). *Permafrost: Proceedings of the Eighth International Conference on Permafrost*, pp. 461–466. A.A. Balkema.
- Instanes, A. and D. Mjureke, 2002a. Design criteria for infrastructure on permafrost. SV4242-1. Instanes Svalbard AS (Report submitted to the Norwegian ACIA Secretariat, Norwegian Polar Institute, Tromsø).
- Instanes, A. and D. Mjureke, 2002b. Design criteria for infrastructure on permafrost based on future climate scenarios. SV4242-2. Instanes Svalbard AS (Report submitted to the Norwegian ACIA Secretariat, Norwegian Polar Institute, Tromsø).
- Instanes, A. and D. Mjureke, in press. Svalbard Airport runway - performance during a climate warming scenario 2000–2050. In: *Proceedings of the International Conference on Bearing Capacity of Roads and Airfields*, Trondheim, Norway, 27–29 June 2005.
- Instanes, B., 2000. Permafrost engineering on Svalbard. In: *Proceedings of the International workshop on Permafrost Engineering*, Longyearbyen, Svalbard, 18–21 June, 2000, pp. 3–23. Tapir Publishers.
- IPCC, 2001. *Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell and C.A. Johnson (eds.). Cambridge University Press, 881pp.
- Jahns, H.O. and C.E. Heuer, 1983. Frost heave mitigation and permafrost protection for a buried chilled-gas pipeline. In: *Proceedings of the Fourth International Conference on Permafrost*, Fairbanks, Alaska, July 1983, pp. 531–536. National Academy Press.
- Janbu, N., 1996. Slope stability evaluation in engineering practice. In: *Proceedings of the Seventh International Symposium on Landslides*, Trondheim, Norway. Vol. 1, pp. 17–34. Balkema.
- Johannessen, O., E. Shalina and M. Miles, 1999. Satellite evidence for an Arctic sea ice cover in transformation. *Science*, 286:1937–1939.
- Johnson, T.C., E. McRoberts and J.F. Nixon, 1984. Design implications of subsoil thawing. In: R.L. Berg and E.A. Wright (eds.). *Frost Action and its Control*, pp. 45–103. American Society of Civil Engineers.
- Johnston, G.H. (ed.), 1981. *Permafrost, Engineering Design and Construction*. J. Wiley & Sons, 352pp.
- Jones, P.D., M. New, D.E. Parker, S. Martin and I.G. Rigor, 1999. Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics*, 37:173–199.
- Kane, D.L., L.D. Hinzman and J.P. Zarling, 1991. Thermal response of the active layer to climate warming in permafrost environment. *Cold Regions Science and Technology*, 19:111–122.
- Khrustalev, L.N., 2000. Allowance for climate change in designing foundations on permafrost grounds. In: *International Workshop on Permafrost Engineering*, Longyearbyen, Norway, 18–21 June, 2000, pp. 25–36. Tapir Publishers.
- Khrustalev, L.N., 2001. Problems of permafrost engineering as related to global climate warming. In: R. Paepe and V.P. Melnikov (eds.). *NATO Advanced workshop on Permafrost Response on Economic Development, Environmental Security and Natural Resources*, Novosibirsk, Russia, 12–16 November 1998, pp. 407–423. Kluwer Academic Publishers.
- Khrustalev, L.N. and V.V. Nikiforov, 1990. *Permafrost Stabilization in the Construction Basements*. Nauka, Novosibirsk, 353pp.
- Kotlyakov, V.M., 1997. Quickly warming Arctic basin. *The Earth and the World*, 4:107.
- Kronik, Ya.A., 2001. Accident rate and safety of natural–anthropogenic systems in the permafrost zone. In: *Proceedings of the Second Conference of Russian Geocryologists*, vol. 4, pp. 138–146.
- Ladanyi, B., 1994. La conception et la réhabilitation des infrastructures de transport en régions nordiques. RTQ-94-07. Ministère des transports du Québec.
- Ladanyi, B., 1995. Civil engineering concerns of climate warming in the Arctic. *Transactions of the Royal Society of Canada*, 6:7–20.
- Ladanyi, B., 1996. A strength sensitivity index for assessing climate warming effects on permafrost. In: *Proceedings of the Eighth International Conference on Cold Regions Engineering*, Fairbanks, Alaska, 12–16 August 1996, pp. 35–45.
- Ladanyi, B., 1998. Geotechnical microzonation in the Arctic related to climate warming. In: *Proceedings of the Eleventh European Conference on Soil Mechanics and Geotechnical Engineering*, Porec, Croatia, 25–29 May 1998, pp. 215–221. Balkema Publishers.

- Ladanyi, B., M.W. Smith and D.W. Riseborough, 1996. Assessing the climate warming effects on permafrost engineering. In: Proceedings of the 49th Canadian Geotechnical Conference of the Canadian Geotechnical Society, St. John's, Newfoundland, 23–25 September 1996, pp. 295–302.
- Larsen, J.O., L. Grande, S. Matsuura, S. Asano, T. Okamoto and S.G. Park, 1999. Slide activity in quick clay related to pore water pressure and weather parameters. In: Proceedings of the Ninth International Conference and Field Trip on Landslides, pp. 81–88.
- Leroueil, S., G. Dionne and M. Allard, 1990. Tassement et consolidation au dégel d'un silt argileux à Kangiqsualujjuak. Fifth Canadian Permafrost Conference, Collection Nordicana No. 54, pp. 309–316. Laval University, Quebec.
- Linell, K.A., 1973. Long-term effects of vegetative cover on permafrost stability in an area of discontinuous permafrost. In: North American contribution, Second International Conference on Permafrost, Yakutsk, USSR, pp. 688–693. National Academy of Sciences.
- Mader, F.W., 1992. Plastics waste management in Europe. *Macromolecular Symposia*, 57:15–31.
- Maslanik, J.A., M.C. Serreze and R.G. Barry, 1996. Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. *Geophysical Research Letters*, 23:1677–1680.
- McPhee, M.G., T.P. Stanton, J.H. Morison and D.G. Martinson, 1998. Freshening of the upper ocean in the Central Arctic: Is perennial sea ice disappearing? *Geophysical Research Letters*, 25:1729–1732.
- McRoberts, E.C., T.C. Law and E. Moniz, 1978. Thaw settlement studies in the discontinuous permafrost zone. Proceedings of the Third International Conference on Permafrost, Edmonton, Alberta, pp. 700–706.
- Nakayama, T., T. Sone and M. Fukuda, 1993. Effects of climate warming on the active layer. In: Proceedings of the Sixth International Conference on Permafrost, Beijing, pp. 488–493.
- Nelson, F.E., O.A. Anisimov and N.I. Shiklomanov, 2002. Climate change and hazard zonation in the circum-Arctic permafrost regions. *Natural Hazards*, 26(3):203–225.
- Nelson, R.A., U. Luscher, R.W. Rooney and A.A. Stramler, 1983. Thaw strain data and thaw settlement predictions for Alaskan silts. In: Proceedings of the Fourth International Conference on Permafrost, Fairbanks, Alaska, pp. 912–917. National Academy Press.
- Nixon, J.F., 1990a. Effect of climate warming on pile creep in permafrost. *Journal of Cold Regions Engineering*, ASCE, 4(1):67–73.
- Nixon, J.F., 1990b. Seasonal and climate warming effects on pile creep in permafrost. In: Proceedings of the Fifth Canadian Permafrost Conference, Québec, July, 1990, pp. 335–340.
- Nixon, J.F., 1994. Climate Change as an Engineering Design Consideration. Report prepared by Nixon Geotech Ltd. for the Canadian Climate Centre, Environment Canada, Downsview, Ontario, 11 pp.
- Nixon, J.F., J. Stuchly and A.R. Pick, 1984. Design of Norman Wells pipeline for frost heave and thaw settlement. In: Proceedings of the Third International Offshore Mechanics and Arctic Engineering Symposium, American Society of Mechanical Engineers, New Orleans, Louisiana.
- Nixon, J.F., N.A. Sortland and D.A. James, 1990. Geotechnical aspects of northern gas pipeline design. Collection Nordicana No. 54. Laval University, Québec, Canada, Proceedings of the Fifth Canadian Permafrost Conference, pp. 299–307.
- Osterkamp, T.E. and A.H. Lachenbruch, 1990. Thermal regime of permafrost in Alaska and predicted global warming. *Journal of Cold Regions Engineering*, 4(1):38–42.
- Osterkamp, T.E. and V.E. Romanovsky, 1999. Evidence of warming and thawing of discontinuous permafrost in Alaska. *Permafrost and Periglacial Processes*, 10:17–37.
- Oswell, J.M., A.J. Hanna and R.M. Doblanko, 1998. Update on the performance of slopes on the Norman Wells Pipeline Project. In: Proceedings of the Seventh International Conference on Permafrost, Yellowknife, North West Territories.
- Panova, Y.V., 2003. Permafrost processes inducing disastrous effects in engineering constructions, Medvezhje gas-field, Western Siberia. In: M. Phillips, S.M. Springman and L.U. Arenson (eds.). *Permafrost: Proceedings of the Eighth International Conference on Permafrost*, pp. 121–122. A.A. Balkema.
- Parker, W.B., 2001. Effect of permafrost changes on economic development, environmental security and natural resource potential in Alaska. In: R. Paepé and V.P. Melnikov (eds.). *NATO Advanced workshop on permafrost response on economic development, environmental security and natural resources*, Novosibirsk, Russia, 12–16 November 1998, pp. 293–296. Kluwer Academic Publishers.
- Parmuzin, S.Yu. and M.B. Chepurnov, 2001. Prediction of permafrost dynamics in the European North of Russia and Western Siberia in the 21st century. *Moscow University Geology Bulletin*, no. 4. (In Russian)
- Pavlov, A.V., 1997. Cryological and climatic monitoring of Russia: methodology, observation results, and prediction. *Kriosphera Zemli*, 1(1):47–58.
- Phukan, A., 1985. *Frozen Ground Engineering*. Prentice-Hall Inc. 336pp.
- Rachold, V., J. Brown and S. Solomon (eds.), 2002. *Arctic Coastal Dynamics*. Report of an International Workshop, Potsdam, Germany, 26–30 November 2001. Reports on Polar Research 413, 103pp.
- Rachold, V., J. Brown, S. Solomon and J.L. Sollid (eds.), 2003. *Arctic Coastal Dynamics - Report of the Third International Workshop*. Oslo, 2–5 December 2002. Reports on Polar and Marine Research 443, 127pp.
- Riseborough, D.W., 1990. Soil latent heat as a filter of the climate signal in permafrost. Collection Nordicana No. 54, Laval University, Québec, Proceedings of the Fifth Canadian Permafrost Conference, pp. 199–205.
- Sandersen, F., S. Bakkehoi, E. Hestnes and K. Lied, 1996. The influence of meteorological factors on the initiation of debris flows, rockslides and rockmass stability. In: Proceedings of the Seventh International Symposium on Landslides, Trondheim, Norway, pp. 97–114. Balkema.
- Sayles, F.H. 1984. Design and performance of water-retaining embankments in permafrost. In: North American Contribution, Second International Conference on Permafrost, Fairbanks, Alaska, July 17–22 1983. Final Proceedings, pp. 31–42. National Academy Press.
- Sayles, F.H. 1987. Embankment dams on permafrost: design and performance summary. US Army Cold Regions Research Engineering Laboratory, Special Report 87–11.
- Seinova, I., 1991. Past and present changes of mudflow intensity in the Central Caucasus. *Mountain Research and Development*, 11(1):13–17.
- Seinova, I. and N. Dandara, 1992. Hydro-technical arrangements for ecologically rational protection of the debris flow hazard. *Internationales Symposium Interpraevent 1992 - Bern*, Tagungspublication, Band 3, pp. 315–326.
- Serreze, M.C., J.E. Walsh, F.S. Chapin III, T.E. Osterkamp, V. Dyrugerov and D.M. Smith, 2000. Recent increase in the length of the melt season of perennial Arctic sea ice. *Geophysical Research Letters*, 25:655–658.
- Shiklomanov, A.I., R.B. Lammers and C.J. Vorosmarty, 2002. Contemporary changes in Eurasian pan-Arctic river discharge. *American Geophysical Union* 83[47]. American Geophysical Union Meeting, 6–10 December 2002, San Francisco.
- Sidorova, T., N. Belaya and V. Perov, 2001. Distribution of slushflows in northern Europe and their potential change due to global warming. *Annals of Glaciology*, 32:237–240.
- Smith, M.W. and D.W. Riseborough, 1983. Permafrost sensitivity to climate change. In: Proceedings of the Fourth International Conference on Permafrost, Fairbanks, Alaska, pp. 1178–1183. National Academy Press.
- Smith, M.W. and D.W. Riseborough, 1985. The sensitivity of thermal predictions to assumptions in soil properties. Proceedings of the Fourth International Conference on Ground Freezing, Sapporo, Japan, Vol. I, pp. 17–23. Balkema.
- Smith, O.P. and G. Levasseur, 2002. Impact of climate change on transportation infrastructures in Alaska. Discussion paper. Department of Transportation Workshop, 1–2 October, 2002, Washington D.C. 11pp.
- Smith, S.L. and M.M. Burgess, 1998. Mapping the response of permafrost in Canada to climate warming. *Current Research 1998-E*, Geological Survey of Canada, pp. 163–171.
- Smith, S.L. and M.M. Burgess, 1999. Mapping the sensitivity of Canadian permafrost to climate warming. In: M. Tranter, R. Armstrong, E. Brun, G. Jones, M. Sharp and M. Williams (eds.). *Interactions between the Cryosphere, Climate and Greenhouse Gases*, pp. 71–80. IAHS Publication No. 256.
- Smith, S.L. and M.M. Burgess, 2004. Sensitivity of Permafrost to Climate Warming in Canada. *Geological Survey of Canada Bulletin* 579, 24 pp.
- Smith, S.L., M.M. Burgess and J.A. Heginbottom, 2001. Permafrost in Canada, a challenge to northern development. In: G.R. Brooks (ed.). *A Synthesis of Geological Hazards in Canada*. Geological Survey of Canada Bulletin 548, pp. 241–264.
- Sorensen, S., J. Smith and J. Zarling, 2003. Thermal performance of TAPS heat pipes with non-condensable gas blockage. In: M. Phillips, S.M. Springman and L.U. Arenson (eds.). *Permafrost: Proceedings of the Eighth International Conference on Permafrost*, pp. 1097–1102. Balkema.
- Speer, T.L., G.H. Watson and R.K. Rowley, 1973. Effects of ground ice variability and resulting thaw settlements on buried warm oil pipelines. In: Proceedings of the Second International Conference on Permafrost, Yakutsk, Russia, pp. 746–752.

- Szymanski, M.B., A. Zivkovic, A. Tchekovski and B. Swarbrick, 2003. Designing for closure of an open pit in the Canadian Arctic. In: M. Phillips, S.M. Springman and L.U. Arenson (eds.). Permafrost: Proceedings of the Eighth International Conference on Permafrost, pp. 1123–1128. A.A. Balkema.
- Terzaghi, K., 1963. Stability of steep slopes on hard unweathered rock. Norwegian Geotechnical Institute, Publication no. 50.
- Ulbrich, U. and M. Christoph, 1999. A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate Dynamics*, 15:551–559 (cited in IPCC, 2001).
- Vyalov, S.S., A.S. Gerasimov, A.J. Zolotar and S.M. Fotiev, 1988. Ensuring structural stability and durability in permafrost ground areas at global warming of the Earth's climate. In: Proceedings of the Sixth International Conference on Permafrost, Beijing, pp. 955–960.
- Walsh, J.E. and W.L. Chapman, 2001. Twentieth-century sea-ice variations from observational data. *Annals of Glaciology*, 33:444–448.
- Weller, G. and M. Lange, 1999. Impacts of climate change in Arctic regions. Report from a workshop on the Impacts of Global Change, Tromsø, Norway, 25–26 April, 1999. International Arctic Science Committee, Oslo, 59pp.
- Weller, G., P. Anderson and B. Wang, 1999. Preparing for a Changing Climate. The Potential Consequences of Climate Variability and Change. A Report of the Alaska Regional Assessment Group for the U.S. Global Change Research Program. Center for Global Change and Arctic System Research, Fairbanks, Alaska.
- Woo, M.K., W.R. Rouse, A.G. Lewkowicz and K.L. Young, 1992. Adaptation of permafrost in the Canadian North: Present and future. Report No. 93-3. Canadian Climate Center, Environment Canada, Downsview, Ontario.