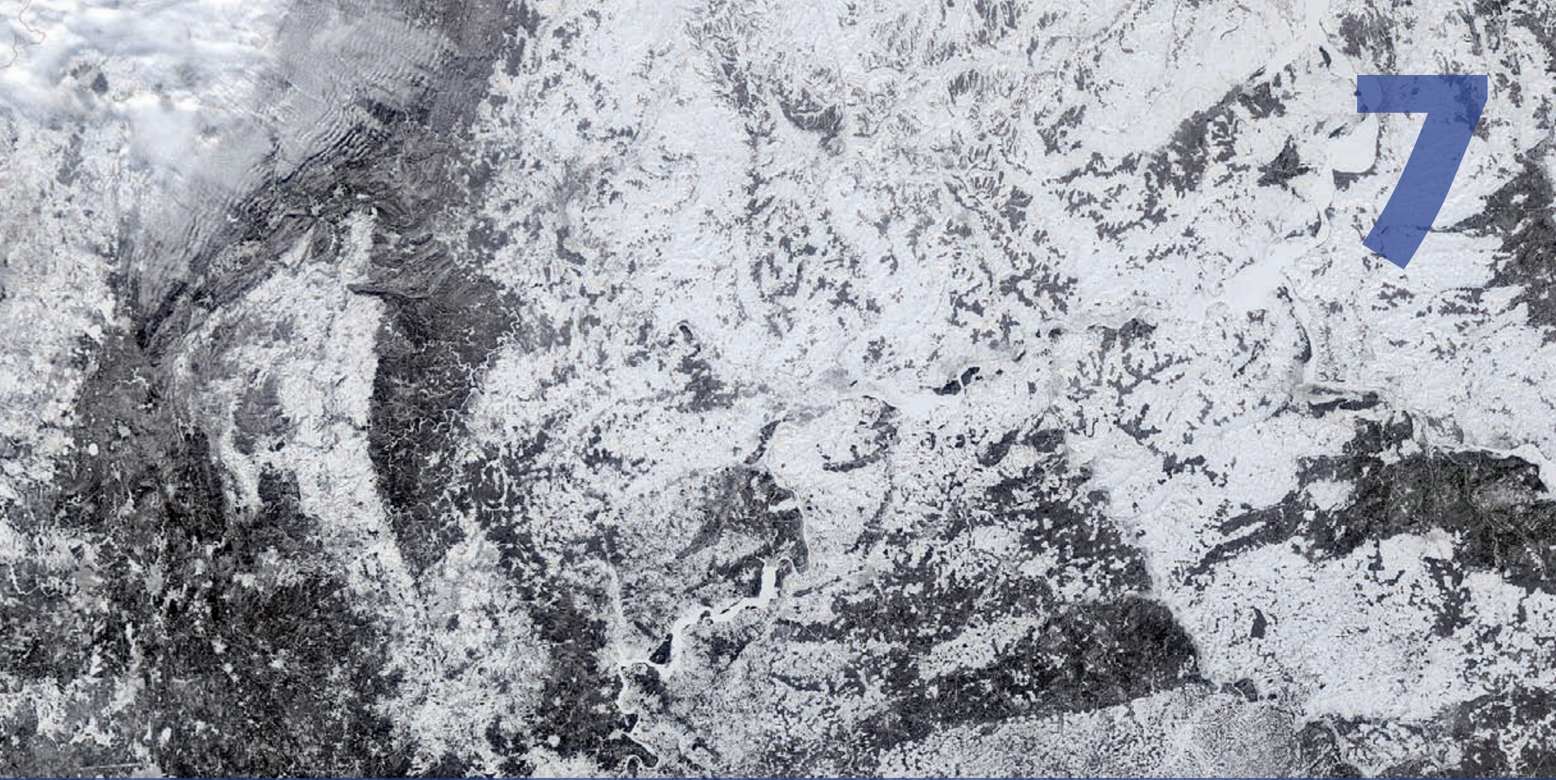

7

Frozen Ground

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Frozen Ground

Permafrost extent within the exposed land areas of the Arctic and Antarctic

Permafrost: perennially frozen ground – rock, sediment or any other earth material with a temperature that remains below 0°C for two or more years.

Permafrost (Northern Hemisphere):	
Area Covered (million square km)	22.8
Ice Volume (million cubic km)	4.5
Potential Sea Level Rise (cm)	~7

Source: IPCC 2007[1a]

Summary

Permafrost temperatures have increased during the last 20–30 years in almost all areas of the Northern Hemisphere. An increase in the depth of the active layer above the permafrost, which thaws in the summer, is less certain. Further increases in air temperatures predicted for the 21st century are projected to initiate widespread permafrost thawing in the subarctic and in mountain regions in both hemispheres. Widespread thawing of permafrost will speed up the decomposition of organic material previously held frozen in permafrost, emitting large amounts of greenhouse gases into the atmosphere. Thawing of ice-rich permafrost may also have serious consequences for ecosystems and infrastructure, and in mountain regions, may reduce the stability of slopes and increase the danger of rock falls and landslides.

Introduction to permafrost

Permafrost zones occupy up to 24 per cent of the exposed land area of the Northern Hemisphere[1] (Figure 7.1). Permafrost is also common within the vast continental shelves of the Arctic Ocean. This subsea permafrost formed during the last glacial period when global sea levels were more than 100 m lower than at present and the shelves were exposed to very harsh climate conditions. Subsea permafrost is slowly thawing at many locations. Permafrost of various temperatures and continuity also exists in mountainous areas, due to the cold climate at high elevations. Permafrost exists throughout ice-free areas of the Antarctic, as well as underneath some areas of the Antarctic Ice Sheet[2].

There are two permafrost zones: continuous permafrost and discontinuous permafrost (Figure 7.1). In the continuous permafrost zone, permafrost lies beneath the entire surface except beneath large rivers and deep lakes. Most continuous permafrost formed during or before the last glacial period. In the discontinuous permafrost zone, permafrost lies beneath 10 to 90 per cent of the surface. Most discontinuous permafrost is much younger and formed within the last several thousand years. Permafrost ranges from very cold (–10° C and lower) and very thick (from 500 to 1400 metres) in the Arctic, to warm (one or two degrees below the melting point) and thin (from several metres or less to 150 metres) in the subarctic.

The main feature that distinguishes permafrost from unfrozen ground is the presence of ground ice. The amount of ground ice in permafrost varies from a few tenths of a per cent to 80 or 90 per cent of the total permafrost volume. The mechanical strength of frozen soil with ice in it is close to the strength of bedrock, while the strength of unfrozen soil is much lower. The stability of ecosystems in permafrost regions depends on the stability of the ground ice; loss of permafrost means a loss of system stability.

Current measurements and climate model projections show that areas in which permafrost occurs are currently and will continue to be among the areas of the world with the largest changes in climate. Current climatic changes and those predicted for the future will inevitably affect the stability of permafrost. The changes that affect permafrost most are increases in air temperature and changes in the hydrological cycle. Ground ice will begin to melt, triggering changes in ecosystems that will make them very vulnerable to natural and anthropogenic influences. The thawing of permafrost will thus alter, if not destroy, ecosystems. These effects of permafrost thaw have already been seen in the mountain areas of Europe, Central Asia, China, and the Andes, where permafrost is generally warm and contains less ice.

Figure 7.1. Permafrost extent in the Northern Hemisphere.

Source: Based on Brown and others 1997[3]

Trends and outlook for high latitude (Arctic) permafrost

There has been a general increase in permafrost temperatures during the last several decades in Alaska[4–6], northwest Canada[7–9], Siberia[10–13], and northern Europe[14,15].

Permafrost temperature records have been obtained uninterrupted for more than 20 years along the International Geosphere-Biosphere Programme Alaskan transect, which spans the entire continuous permafrost zone in the Alaskan Arctic. Records from all locations along the transect show a substantial warming during this period. The permafrost typically warmed by 0.5 to 2°C, depending on location (Figure 7.2). Similar warming trends were observed in the North Slope region of Alaska from long-term monitoring sites[16].

Temperature monitoring in Canada indicates a warming of shallow permafrost over the last two to three decades. Since the mid-1980s, shallow permafrost (upper 20-30 m) has generally warmed in the Mackenzie Valley[7,17,18]. The greatest increases in temperature were 0.3 to 1°C per decade in the cold and thick permafrost of the central and northern valley (Figure 7.3). In the southern Mackenzie Valley, where permafrost is thin and close to 0°C, no significant trend in permafrost temperature is observed[7] (Figure 7.3). This absence of a trend is probably due to the fact that this permafrost is ice-rich; a lot of heat is absorbed to melt the ice before an actual temperature change occurs.

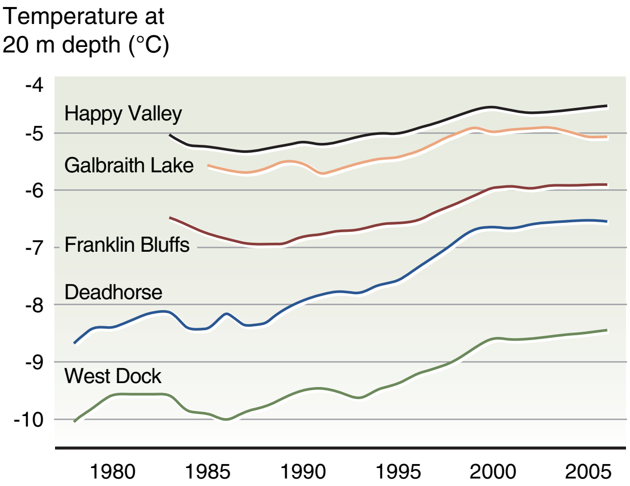


Figure 7.2: Changes in permafrost temperatures during the last 23 to 28 years in northern Alaska. Temperatures are measured at 20 m depth, at which there is no seasonal temperature variation in the permafrost.

Source: V.E. Romanovsky; updated from Osterkamp 2003[5]

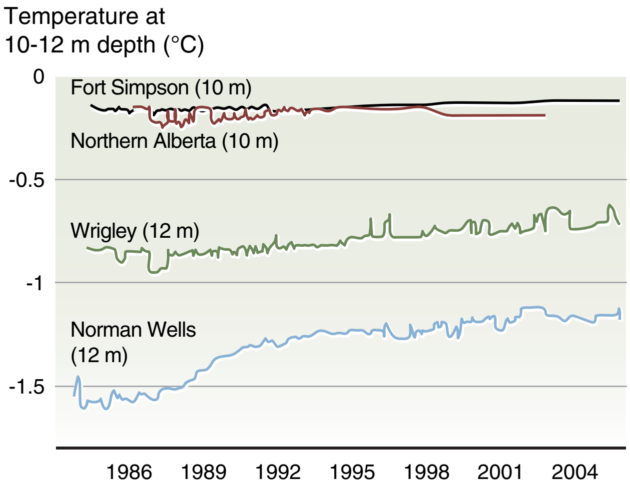


Figure 7.3: Ground temperatures at depths of 10 or 12 m between 1984 and 2006 in the central (Norman Wells and Wrigley) **and southern** (Fort Simpson and Northern Alberta) **Mackenzie Valley,** showing increases of up to 0.3°C per decade.

Source: S. Smith; updated from Smith and others 2005[7]

A similar lack of temperature trend is found for warm and thin permafrost in the southern Yukon Territory[19,20].

Warming of permafrost is also observed in the eastern and high Canadian Arctic but this appears to have mainly occurred in the late 1990s. At Alert, Nunavut, a warming of 0.15°C per year occurred between 1995 and 2001 at a depth of 15 m and warming of about 0.06°C per year has occurred since 1996 at a depth of about 30 m[8]. At another high Arctic site, shallow permafrost (upper 2.5 m) temperatures increased by 1°C between 1994 and 2000[21]. At Iqaluit in the eastern Arctic, permafrost cooled between the late 1980s to the early 1990s at a depth of 5 m and warmed by 0.4°C per year between 1993 and 2000[7]. A similar trend was observed in northern Quebec[22,23].

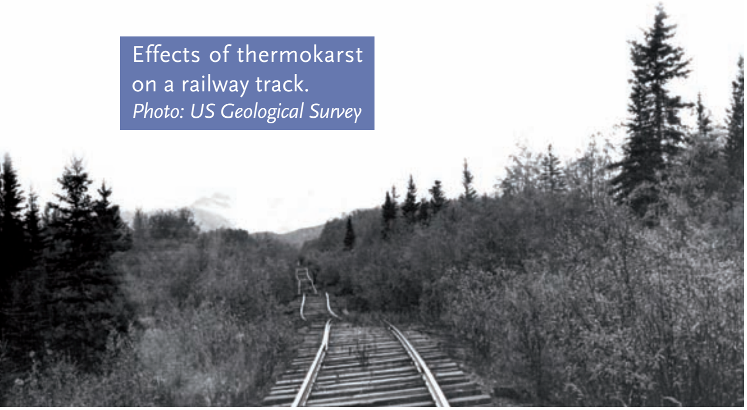
In environments containing permafrost, the top layer (active layer) of soil thaws during the summer and freezes again in the autumn and winter. Trends in the depth of this active layer are less conclusive than trends in permafrost temperature. In the North American Arctic, the depth of the active layer varies strongly from year to year[24–26]. An increase in active-layer thickness was reported for the Mackenzie Valley in Canada[27]. However, after 1998 the active layer began decreasing in thickness at most of the same sites[28]. An increase in thickness of more than 20 cm between the mid-1950s and 1990 was reported for the continuous permafrost regions of the Russian Arctic[29,30]. At the same time, reports from central Yakutia show no significant changes in active-layer thickness[31,32].

Thawing permafrost along the bank of the Kolyma River in Siberia.
Photo: V. Romanovsky

Outlook

Permafrost warming has not yet resulted in widespread permafrost thawing on a landscape or regional scale. Long-term thawing of permafrost starts when the active layer of soil above the permafrost, which thaws during the summer, does not refreeze completely even during the most severe winter. Year-round decomposition of organic matter can then occur, and permafrost continues to thaw from the top down. Predicted further changes in climate will eventually force high latitude natural systems to cross this very important threshold.

When permafrost starts to thaw from the top down, many processes, some of them very destructive, can be triggered or intensified. These changes may impact ecosystems, infrastructure, hydrology and the carbon cycle, with the largest impacts in areas where permafrost is rich in ground ice. One of the most significant consequences of ice-rich permafrost degradation is the formation of thermokarst, land forms in which parts of the ground surface have subsided[33]. Thermokarst forms when ground ice melts, the resulting water drains and the remaining soil collapses into the space previously occupied by ice. In addition to its impacts on ecosystems and infrastructure, thermokarst often leads to the formation of lakes and to surface erosion, both of which can significantly accelerate permafrost degradation.



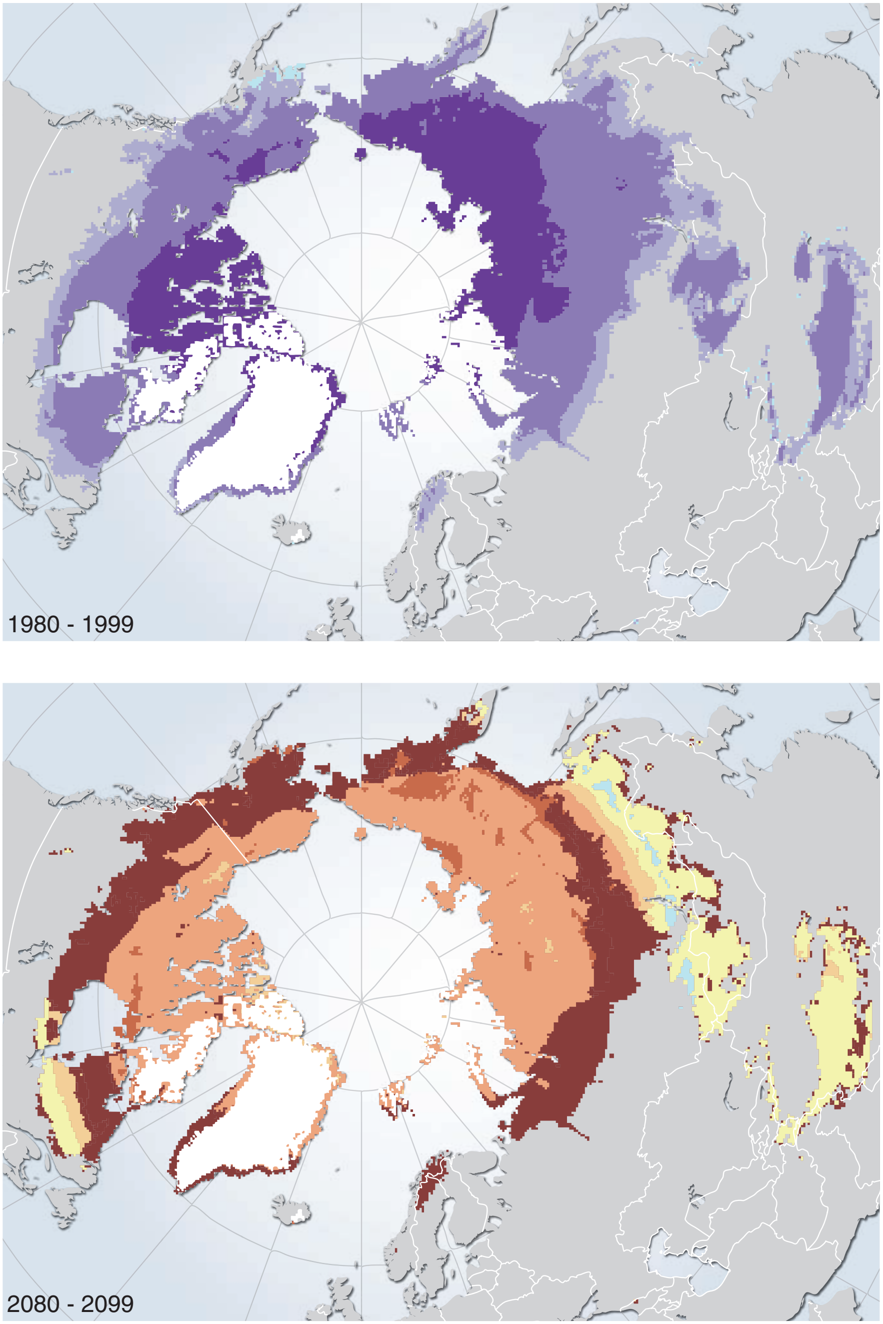
Effects of thermokarst on a railway track.
Photo: US Geological Survey

The form and rate of permafrost degradation will differ between regions, depending on geographical location and on specific environmental settings. On the Arctic tundra, the ground temperatures are generally cold and no widespread permafrost thawing is expected during the 21st century, with the possible exception of the European tundra where temperatures are closer to zero. However, location of ground ice close to the surface makes the Arctic tundra surfaces extremely sensitive to thawing, as only a small amount of thawing can lead to development of thermokarst. In contrast, in boreal forests ground ice is typically located at a greater depth below the surface. Thus, although warming of permafrost will soon lead to extensive permafrost thawing because of the relatively high temperature of permafrost in boreal forests, the thawing will not immediately lead to destructive processes.

Future changes in permafrost will be driven by changes in climate (primarily by air temperature and precipitation changes), changes in surface vegetation and changes in surface and subsurface hydrology. At present, there is no coupled climate model that takes into account all of these driving forces. However, by choosing a future climate scenario and assuming certain changes in vegetation and/or hydrology, it is possible to specify and apply an equivalent forcing to a permafrost model in order to project future permafrost dynamics on a regional or

Figure 7.4: Modelled permafrost temperatures (mean annual temperature at the permafrost surface) for the Northern Hemisphere, derived by applying climatic conditions to a spatially distributed permafrost model[34,35].
(a) Present-day: temperatures averaged over the years 1980–1999. Present-day climatic conditions were based on the CRU2 data set with 0.5° x 0.5° latitude/longitude resolution[36].
(b) Future: projected changes in temperatures in comparison with 1980–1999, averaged over the years 2080–2099. Future climate conditions were derived from the MIT 2D climate model output for the 21st century[37].

Source: Permafrost Laboratory of the Geophysical Institute, University of Alaska Fairbanks



(a)

Mean annual temperature at the permafrost surface (°C)

-25 - -8
-8 - -2.5
-2.5 - -0.5
-0.5 - 0

(b)

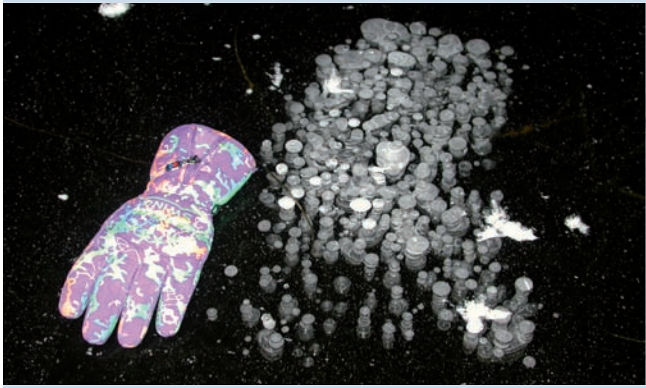
Projected change in mean annual temperature at the permafrost surface (°C)

-3 - -0
0 - +2
+2 - +4
+4 - +6
+6 - +8
thawing permafrost

even circumpolar scale. Figure 7.4 shows a projection of future permafrost temperatures for the entire Northern Hemisphere. According to this model, by the end of the 21st century permafrost that is presently discontinuous with temperatures between 0 and –2.5° C will have crossed the threshold and will thus be actively thawing. The most significant permafrost degradation is expected in North America, where permafrost will be thawing in practically all areas south of the Brooks Range in Alaska and in most of subarctic Canada. This is probably due to the fact that permafrost within continental North America is generally warmer and thinner than in Siberia. In Russia the most severe permafrost degradation is projected for northwest Siberia and the European North.

Methane emissions from thermokarst lakes

Depressions in the irregular thermokarst topography caused by thawing of ice-rich permafrost are usually occupied by lakes called thermokarst lakes, as meltwater cannot drain away due to the underlying permafrost. Active thawing of the permafrost beneath these lakes releases organic matter into the oxygen-deficient lake bottoms, which produces methane as it decomposes. Ninety-five per cent of the methane emitted from these lakes is released through bubbling[46]. Many of these methane-rich bubbles become trapped in lake ice in the winter as the lake surfaces freeze. Extremely high rates of bubbling from distinct points in lake sediments, known as bubbling hotspots, can maintain open holes in lake ice even during winter, releasing methane to the atmosphere year-round. Recently, scientists quantified methane emissions from thermokarst lakes in Siberia by studying the pattern of bubbles in the lake ice, and found that the amount of methane emission from lakes in this region may be five times higher than previously estimated[46] (Figure 7.5). The methane emitted from the thawing edges of the lakes in this region was 36 000–43 000 years old, showing that organic matter previously stored in permafrost for tens of thousands of years is now contributing to methane emissions when permafrost thaws[46]. High rates of methane production and emission have also been observed in thermokarst lakes in other regions of the Arctic. The formation of new thermokarst lakes and expansion of existing ones observed during recent decades has increased methane emissions in Siberia[46,47]. If significant permafrost warming and thawing occurs as projected, tens of thousands of teragrams of methane could be emitted from lakes, an amount that greatly exceeds the 4850 teragrams[48] of methane currently in the atmosphere[49].



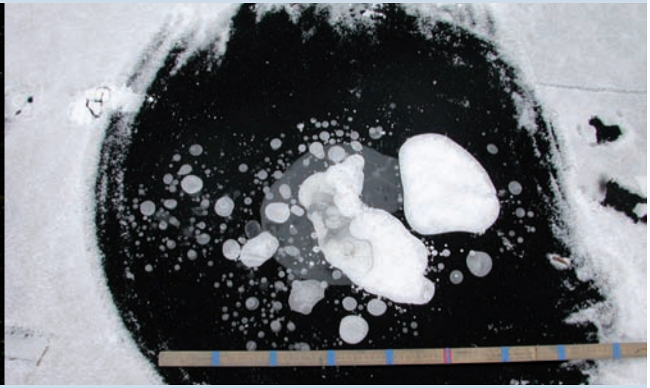


Figure 7.5: Methane bubbles trapped in lake ice form distinct patterns as a result of differing rates of methane bubbling. Methane emissions from the entire lake are estimated, taking into account the patchiness of bubbling, by surveying the distribution of bubble patterns in lake ice in early winter.
Photos: Katey Walter

Almost all permafrost in Europe, as well as permafrost along the southern coasts (below 70° N) of Greenland, will also be thawing by the end of the 21st century. The model predicts permafrost cooling in some regions, due to a combination of predicted increase in air temperatures with predicted decrease in snow depth and duration in these regions.

Impacts on the carbon cycle – feedback mechanisms

The largest global impact of changes in permafrost is due to its role in the global carbon cycle. Permafrost soils gradually accumulate organic carbon as they form because carbon which has been removed from the atmosphere through photosynthesis is stored in the form of organic matter, as soils freeze and decomposition slows or stops. The upper part of permafrost (1–25 m below the surface) in boreal and Arctic ecosystems is estimated to contain ~750–950 gigatonnes of organic carbon[38–40], a quantity that exceeds the 750 gigatonnes of organic carbon currently in the atmosphere. This figure does not include carbon contained in deeper permafrost, in hydrates within or under the permafrost, or other non-permafrost soil carbon pools. The amounts of carbon stored in some of these locations are still poorly defined, but an assessment of current understanding was recently provided through a workshop hosted by the Arctic Council's Arctic Monitoring and Assessment Programme[41]. Yedoma, an extremely carbon-rich type of permafrost found mostly in northern and central Siberia, contains roughly half of the organic carbon in the upper part of permafrost[38,42].

When permafrost thaws, decomposition of organic matter leads to production and emission of the greenhouse gases, carbon dioxide and methane, to the atmosphere. If thawing occurs in the presence of oxygen, decomposition produces carbon dioxide. For yedoma, which contains labile bioavailable organic material, this decomposition process occurs particularly rapidly[43,44]. When thawing occurs in the absence of oxygen, for example, when the permafrost thaws under a lake, decomposition of organic matter produces methane[45] (see box on thermokarst lakes). The warming potential (relative greenhouse effect) of methane is 23 times stronger than that of carbon dioxide, though methane does not persist in the atmosphere for as long as carbon dioxide. Thus, permafrost thawing acts as a positive feedback to global warming that is projected to intensify with further permafrost degradation in the future[34,46].

Impacts on ecosystems

Northern ecosystems depend on permafrost and ground ice conditions. Soil temperature, active-layer thickness, moisture content, presence of unfrozen water, and sur-


Effects of thawing of ice-rich permafrost on a forest in Alaska. *Photo: V. Romanovsky*

face hydrology as they relate to permafrost all affect plant communities and productivity of ecosystems. The observed changes in permafrost temperatures and active-layer thickness can affect diversity and biomass of plant communities[50]. Thawing of ice-rich permafrost can result in the replacement of boreal forest with wetlands[51,52]. This reduces the habitat area for caribou and other terrestrial mammals and birds, while it increases the area favourable for aquatic birds and mammals. The thawing of permafrost with little ground-ice may result in replacement of the boreal forest ecosystems with steppe-like habitats. Long-term permafrost degradation will continuously increase subsurface water drainage, especially in sandy soils, which will increase dryness of soils and place significant stress on vegetation. Increased drainage will also shrink ponds in the degrading permafrost area, dramatically affecting aquatic ecosystems[47,53,54].

Impacts on infrastructure

Impacts of predicted global climatic changes on Arctic infrastructure are of increasing concern[39,55]. Warming and thawing of permafrost may pose a threat to human lives as well as to infrastructure. Construction activity and existing infrastructure usually increase the heat flow into the ground, due to heating of buildings and build-up of snow, and can result in warming of permafrost. This ongoing permafrost degradation, which can cause instability of building foundations, may be accelerated by increasing air temperatures. In addition, projected increases in air and soil temperatures, 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 may increase due to warming and thawing of permafrost. Structures located on sites

Figure 7.6: Effects of thawing permafrost on infrastructure.
(a) Permafrost thawing caused differential settlement in the foundation of this apartment building in the Russian republic of Yakutia. The building partially collapsed only days after the first cracks appeared in the walls.
(b) A thermokarst depression in Fairbanks, Alaska. Ground ice melted, creating a void within the ground.
Photos: V. Romanovsky

prone to slope failure are more likely to be exposed to slide activity.

It is important to note that in permafrost regions the lifetime of structures, during which they should function according to design with normal maintenance costs, is typically 30 to 50 years. Total renovation, or demolition and replacement, of old structures should be expected and is part of responsible infrastructure planning. For this reason the effect of climate change on northern infrastructure is difficult to quantify. However, damage to structures is often blamed on climate changes while in reality it is due to human error, poor construction, or simply old age.

It is nevertheless necessary to prepare for and adapt to the effects of permafrost changes on infrastructure. In colder, continuous permafrost the predicted climate changes do not pose an immediate threat to infrastructure. Maintenance costs will probably increase, but it should be possible to gradually adjust Arctic infrastructure to a warmer climate. However, transportation infrastructure such as roads, railways and airstrips that are on ice-rich permafrost will generally require relocation or replacement using different construction methods. The predicted warming may have a serious effect on infrastructure in warmer, discontinuous permafrost zones, where permafrost is already close to thawing[56]. These areas, together with coastal areas where the thawing of ice-rich permafrost is combined with the problem of sea-level rise, present the greatest challenges in a changing climate (Figure 7.6). However, many engineering approaches have already been developed over the last century to prevent and to cope with effects of permafrost warming. Such approaches are common practice in North America and Scandinavia[57–59] (Figure 7.7). These techniques can be adapted to handle the permafrost changes predicted in the future (see box on building on permafrost in northern Canada).

Figure 7.7: Examples of good engineering practices which prevent permafrost thawing.
(a) A house built on concrete blocks to allow cold air under the house during the winter, north of Fairbanks, Alaska.
(b) The Trans-Alaskan Oil Pipeline is built on pile-refrigerators to prevent thawing of permafrost underneath.
Photos: (a) V. Romanovsky; (b) Roger Asbury/iStockphoto.com

Building on permafrost in northern Canada

Permafrost and its ground ice present challenges to infrastructure development in northern Canada. Development of infrastructure disturbs the ground surface and changes the heat flow in the ground, causing thawing of ice-rich permafrost which in turn de-stabilizes the ground[9,60]. Current engineering practices consider permafrost and aim to minimize the impacts of thaw. Climate change, however, presents an additional challenge as warmer conditions may enhance the impacts of infrastructure development on the heat flow in the ground. The design of existing structures may not account for additional permafrost thaw resulting from climate changes. It is hard to tell if recent warming has already had an impact on existing infrastructure in Canada. It is difficult to separate the effects of climate change from the effects of construction and operation of a structure, which tend to be of greater magnitude[61].

Climate change, however, is now recognized as a concern over the lifetime of major development projects in northern Canada and has been included in engineering designs since the late 1990s. A screening tool has been developed by a working group of scientists and engineers[62] to assess the level of analysis on climate change needed for a particular project. It is also required to consider climate change in the environmental assessment for major projects, especially long-term ones[63,64]. For example, climate change was recognized as a concern for the Ekati Diamond Mine which opened in 1998, and potential climate change impacts were considered in the design of the mine's waste storage[65]. The proposed Mackenzie Gas Pipeline has considered climate change in both its design and environmental assessment.

Mountain permafrost exists in different forms. Rock glaciers such as this one in the Northern Tien Shan Mountains of Central Asia are a phenomenon of actively creeping, ice-rich mountain permafrost under a cover of debris.
Photo: S. Marchenko

Trends and outlook for high altitude (mountain) permafrost

Europe

Significant amounts of mountain permafrost exist in Svalbard, Fennoscandia, the Urals, the Caucasus, the Pyrenees, the Alps, and Iceland. Data from a north-south line of boreholes, 100 m or more deep, extending from Svalbard to the Alps show a long-term regional warming of permafrost of 0.5–1.0 °C[66] during recent decades. In Scandinavia and Svalbard, monitoring over 5–7 years shows warming

down to 60 m depth and present warming rates at the permafrost surface of 0.04–0.07° C/year[67]. In Switzerland, a warming trend and increased active-layer depths were observed in 2003, but results varied strongly between borehole locations[68]. The warming signals from alpine boreholes are difficult to interpret due to the conflicting factors of topography and the heat released or absorbed during melting or evaporation[69]. However, observations of European mountain permafrost degradation are consistent with climate trends and with the major changes in permafrost and ground ice conditions observed globally. These changes are expected to continue in the near future.

Human activity and permafrost affect each other, especially in the densely populated Alps. The speed of most monitored alpine rock glaciers, a form of mountain permafrost in which frozen debris and/or ice underlie a layer of debris and which move downslope, has increased significantly during recent years. This acceleration is likely due to a reduction in viscosity of the underlying permafrost as a result of warming[70]. Warming of permafrost also affects infrastructure in alpine permafrost regions. An increase of instability problems has motivated the development of technical solutions to improve design lifetime, maintenance costs and safety[71]. Warming can reduce the stability of permafrost in steep areas and thus cause increased rock falls[72–75]. At least four large events involving rock volumes over 1 million m^3 took place in the Alps during the last decade. In 2002, the Kolka Glacier rock and ice slide killed 125 people in the Karmadon Valley of the Caucasus[76], illustrating the potentially catastrophic consequences of such events (see Figure 6B.8).

Central Asia

The Central Asian region is the largest area of widespread mountain permafrost in the world. Mountain permafrost in Central Asia occupies approximately 3.5 million square kilometers and makes up about 15 per cent of the total permafrost area in the Northern Hemisphere. The climatic variations during the 20th century and especially during the last two decades have impacted current permafrost temperatures. In the Tien Shan Mountains, Qinghai-Tibet Plateau, and western Mongolian sector of the Altai Mountains, observations over the last 30 years show that permafrost warmed by 0.3°C in undisturbed systems and by up to 0.6°C in areas affected by human activities (Figure 7.9). In the northern Tien Shan Mountains and the Mongolian Altai Mountains, the average active-layer thickness increased by 20–25 per cent in comparison with the early 1970s[77–79].

Mountain permafrost

At high elevations in mid-latitude mountains, permafrost is widespread where the mean annual air temperature is below –3°C. It often exists far below the altitudes to which glaciers extend, and even below the tree line in continental areas. Mountain permafrost exists in different forms – in steep bedrock, in rock glaciers, in debris deposited by glaciers or in vegetated soil, and contains variable amounts of ice. Since topography causes large variability in local climate, snow cover, and ground and surface properties through the processes of erosion, transport and deposition, mean annual ground temperatures in mountain regions can vary by 5–8 °C over distances as small as 100 m (Figure 7.8). For this reason, the distribution and characteristics of permafrost in mountain regions are very patchy.

Permafrost influences the evolution of mountain landscapes and affects human infrastructure and safety. Permafrost warming or thaw affects the potential for natural hazards such as rock falls, debris flows and secondary events triggered by them and also affects the topography itself in steep terrain. As in Arctic permafrost regions, construction in mountain permafrost regions requires special precautions and warming permafrost poses problems to infrastructure. Mountain permafrost also contains valuable information on climate change. The presence of permafrost, in an actively moving rock glacier for example, indicates a relatively cold climate, therefore inactive or fossil rock glaciers point to past colder climates. Measurements of permafrost temperature, as well as providing information on present-day permafrost stability, offer data on past climate changes.

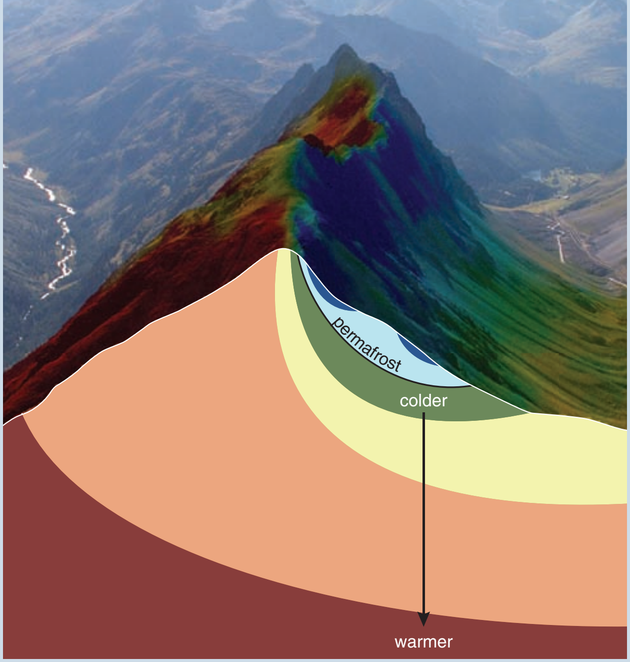


Figure 7.8: Temperatures in a mountain range containing permafrost (blue colours bordered by the black line), ranging from colder (blue) to warmer (red). Steep terrain and strong variability in surface temperatures are typical of mountain permafrost. The cross section in the foreground shows the complex distribution of subsurface temperatures characteristic of mountains, with the isotherms (lines linking points of equal temperature) nearly vertical in the ridge of the mountain. In the background, the colours on the mountain surface illustrate the strong variability in ground temperatures caused by differences in elevation, exposure to the sun, snow cover and ground properties. In the far background, one can only guess at this complex pattern of permafrost distribution because permafrost is invisible at the ground surface.

Source: S. Gruber, photo from Christine Rothenbühler

Mountain permafrost contains large quantities of stored fresh water in the form of ice. Mountain permafrost within debris deposited by glaciers, or in rock glaciers and other coarse blocky material has especially high ice content (up to 80 per cent of the total volume). The total volume of surface ice has been reported at about 462 km^3 while the estimate of ground ice volume is about 280 km^3 for one area of the Tien Shan Mountains[80,81]. Considering the continued glacier recession in Central Asia (see Chapter 6B), the melt waters from permafrost could become an increasingly important source of fresh water in this region in the near future.

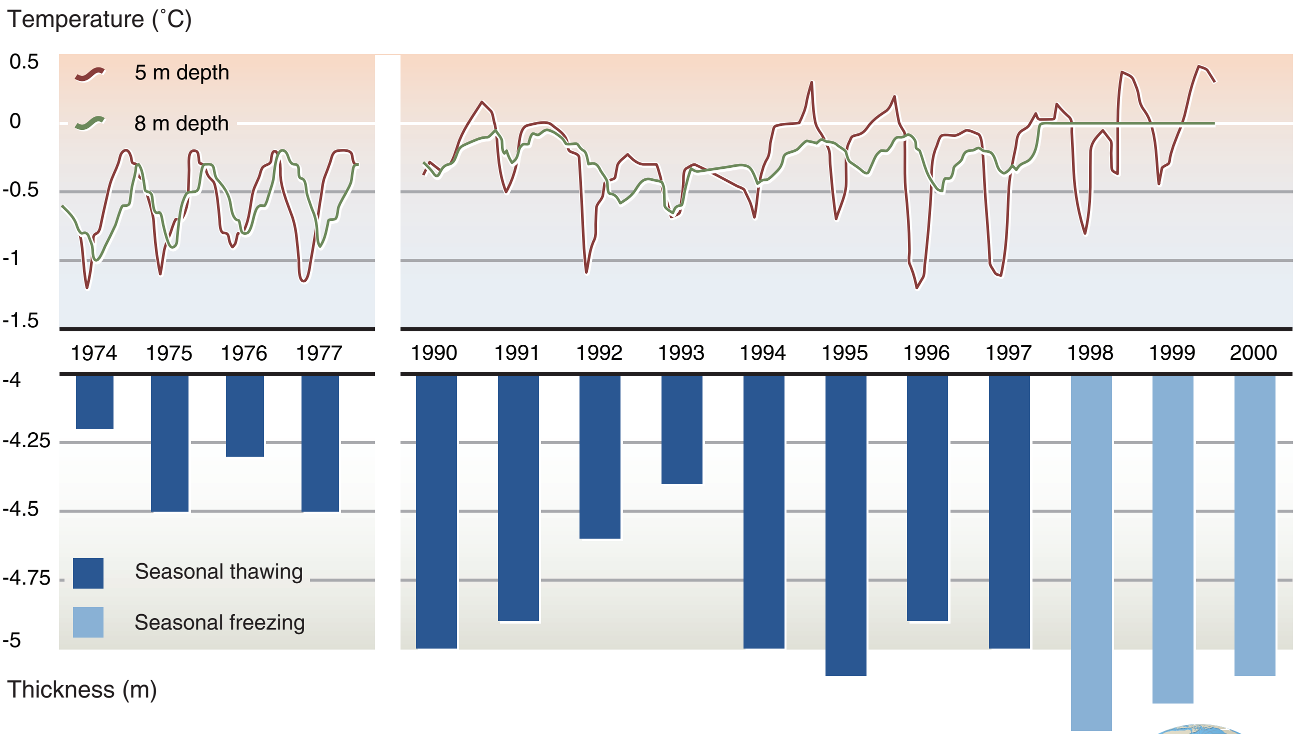


Figure 7.9: Permafrost temperatures and active-layer thickness during 1974–1977 and 1990–2004 measured in a borehole at the "Cosmostation" permafrost observatory, 3300 m above sea level, Northern Tien Shan Mountains in Central Asia.

Source: Based on Marchenko and others 2007[82]

China

Permafrost in China has degraded significantly during the past 40 years[79,83], with changes observed in both permafrost extent and temperature. The area of the southern Qinghai-Tibet highway with underlying permafrost decreased by 35.6 per cent between 1974 and 1996[84], while the permafrost area of the northern Qinghai-Tibet highway decreased by 12 per cent between 1975 and 2003[85]. In the Xing'anling Mountains in northeast China, many patches of permafrost have disappeared[86]. The permafrost area in China is projected to decrease by 30-50 per cent during the 21st century[79,87].

Morenas Coloradas rock glacier in Argentina.
Photo: D. Trombotto

Changing permafrost conditions have already impacted and will continue to strongly impact many infrastructures in China. Design of the Qinghai-Tibet Railway has taken into account the 2.6° C increase in air temperature predicted for the 21st century by using various cooling techniques[88,89]. The impacts of climate changes on stability will also need to be considered in the design of the proposed China-Russia Oil Pipeline.

South America

Most mountain permafrost in South America is found at high elevations in the Andes. The total area of South American permafrost is estimated at 100 000 km^2. Permafrost in the Andes varies significantly in temperature, ice content, and distribution (whether it is continuous or discontinuous). Andean permafrost also varies in its vulnerability to future changes in climate[90]. Continuous permafrost is found at various elevations, in regions where mean annual air temperatures are –2 to –4 °C and mean annual precipitation is 500–900 mm[91]. Continuous permafrost can also exist in areas with air temperatures between –1 °C and –2 °C but much lower amounts of precipitation (300 mm per year), as in the case of the Argentine Puna region. In the central Andes, permafrost appears in groups of rock glaciers. The lower limit of Andean permafrost, which on the Cordón del Plata mountain range occurs at an elevation of 3700–3800 m, is marked by the absence of rock glaciers.

Features indicating permafrost degradation can be seen in some rock glaciers[92]. Ground subsidence in the central Andes is related to warming during the Holocene, six to eight thousand years ago (see timeline on inside back cover). However, there are some signs that permafrost degradation has recently restarted. Since degradation of permafrost in rock glaciers directly affects the discharge volume of Andean rivers[93], permafrost warming could temporarily enhance the regional supply of fresh water. On the other hand, degrading permafrost leads to slope instability, increasing risks of hazards such as rock falls and mud flows, which will affect Andean passes and mountain roads.

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