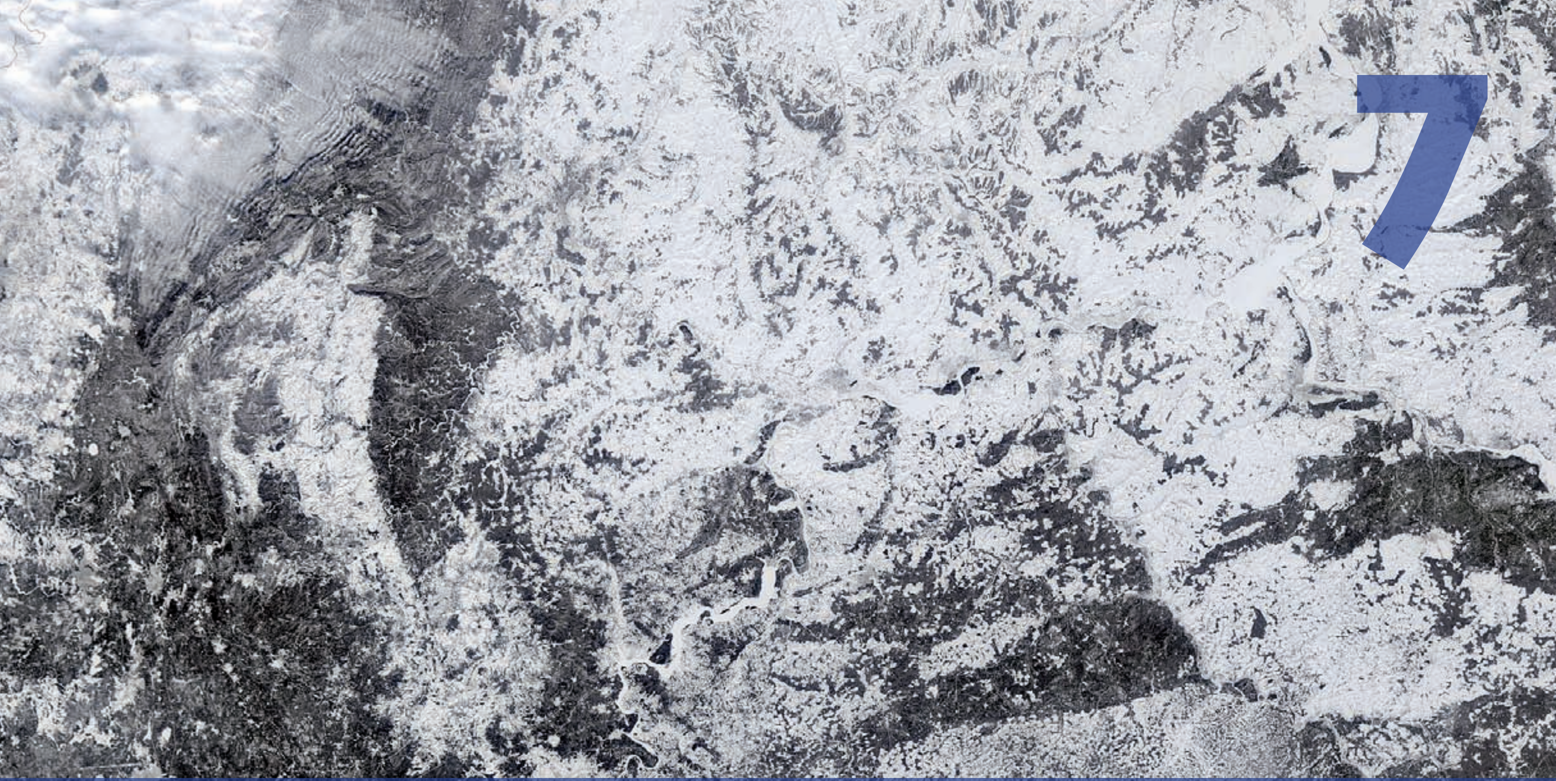

7

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.

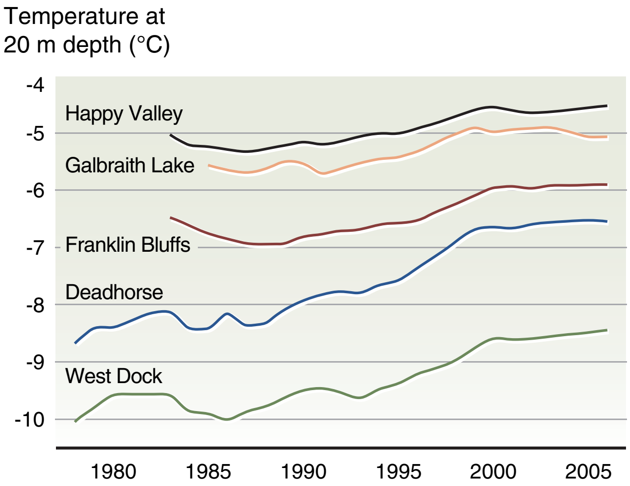


Figure 7.2: Changes in permafrost temperatures during the last 23 to 28 years in northern Alaska. Temperatures are measured at 20 m depth, at which there is no seasonal temperature variation in the permafrost.

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

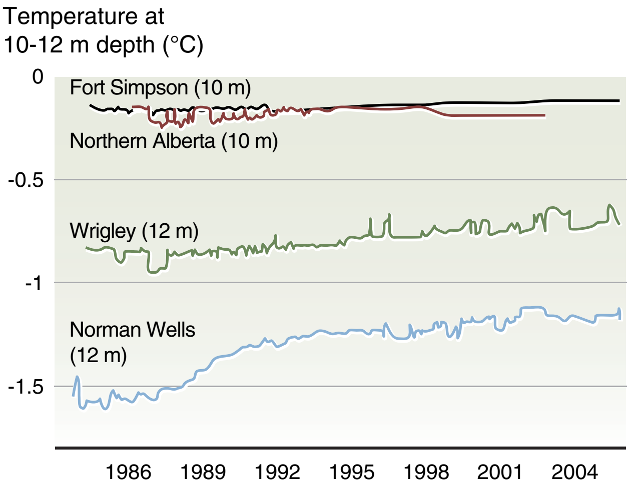


Figure 7.3: Ground temperatures at depths of 10 or 12 m between 1984 and 2006 in the central (Norman Wells and Wrigley) **and southern** (Fort Simpson and Northern Alberta) **Mackenzie Valley,** showing increases of up to 0.3°C per decade.

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].

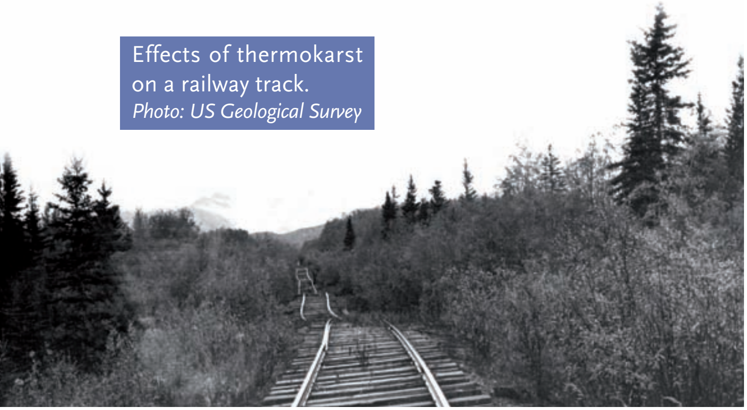
In environments containing permafrost, the top layer (active layer) of soil thaws during the summer and freezes again in the autumn and winter. Trends in the depth of this active layer are less conclusive than trends in permafrost temperature. In the North American Arctic, the depth of the active layer 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.



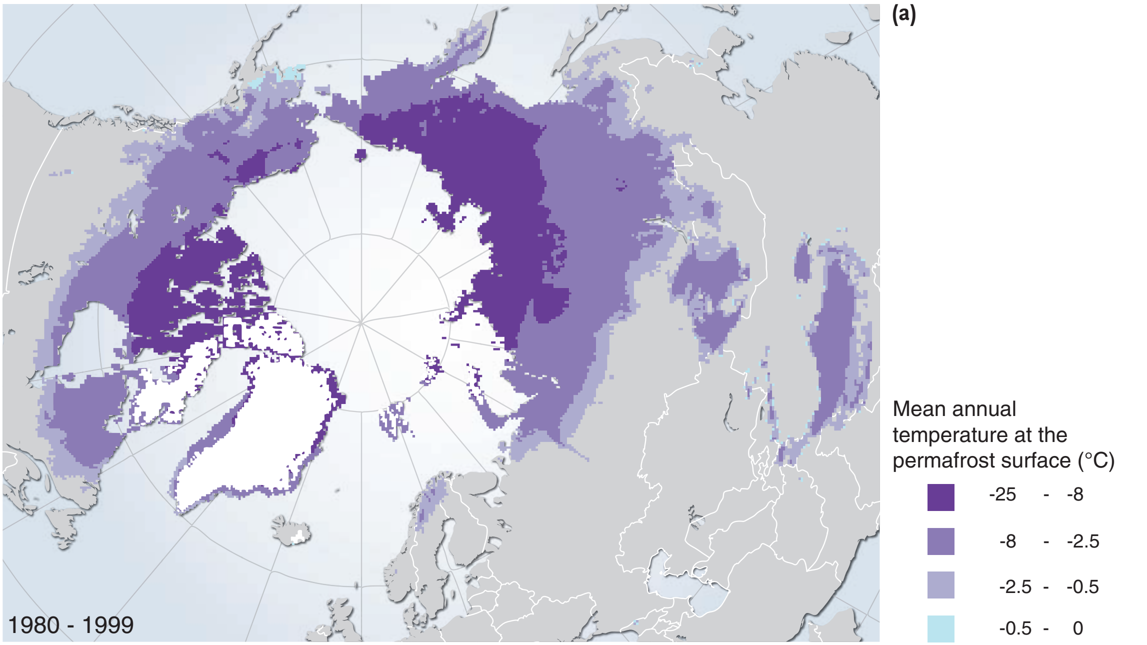
Effects of thermokarst on a railway track.
Photo: US Geological Survey

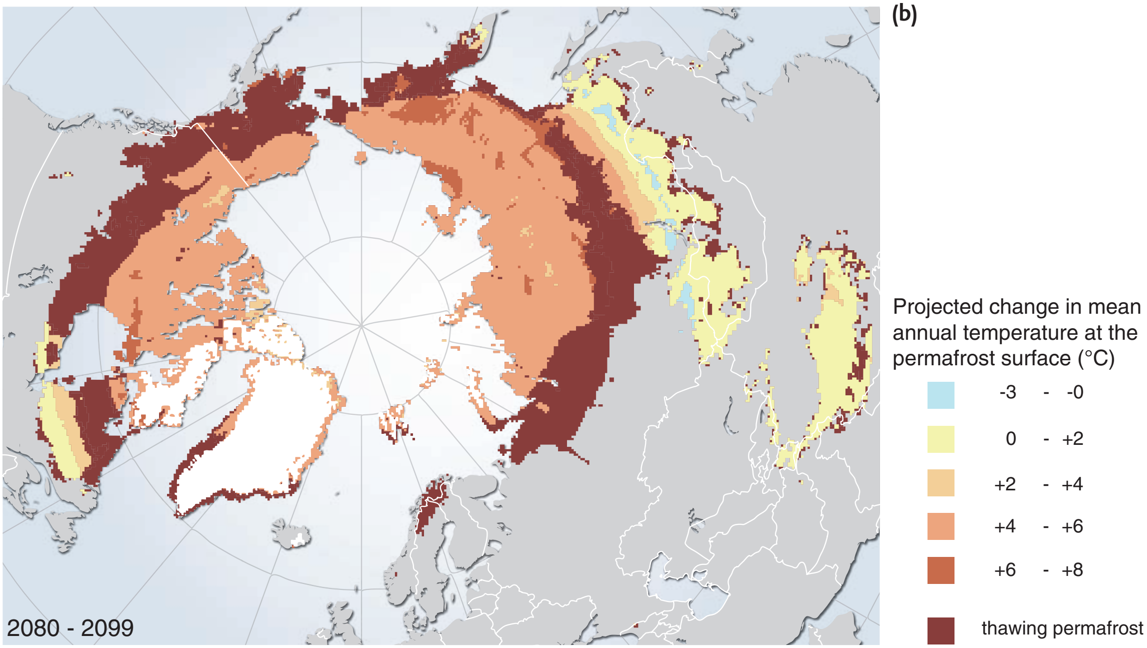
The form and rate of permafrost degradation will differ between regions, depending on geographical location and on specific environmental settings. On the Arctic tundra, the ground temperatures are generally cold and no widespread permafrost thawing is expected during the 21st century, with the possible 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)
1980 - 1999
Mean annual temperature at the permafrost surface (°C)
-25 - -8
-8 - -2.5
-2.5 - -0.5
-0.5 - 0


(b)
2080 - 2099
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].