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c0010 Permafrost Degradation

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ABSTRACT

Climatic changes over the last 50 years resulted in a decrease of permafrost extent, an increase of permafrost temperature, and deepening of the active layer in numerous locations across the Arctic and High Mountainous environments. Permafrost degradation poses serious impacts ranging from local changes in topographic and hydrologic conditions, impacts on infrastructure and sustainability of northern communities, changes to vegetation and wildlife dynamics, and to global impacts on climate system. Hazards associated with permafrost degradation are exacerbated in areas of human activities, especially in large settlements with developed infrastructure in the Arctic. Unlike smaller communities, which have higher mobility, large population centers have to build in situ adaptive capacity to face environmental changes. Permafrost degradation can have severe socioeconomic consequences as most of the existing infrastructure will require expensive engineering solutions to maintain economic activities on permafrost.

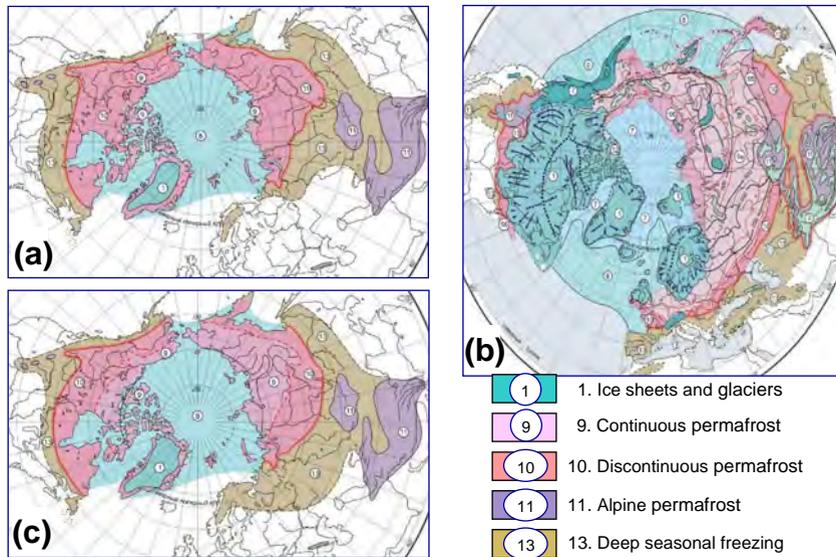
s0010 10.1 INTRODUCTION

p0010 Permafrost plays an important role in global climate change, in the balance of greenhouse gases, arctic environment ecosystems, and human activities in the Polar Regions (ACIA, 2005; AMAP, 2011; Hinzman et al., 2005; Romanovsky et al., 2010a; Shakhova et al., 2010). Changes in climatic parameters, particularly the air temperature, snow depth, and duration of the warm period over the last 50 years have resulted in an increase of permafrost temperature and deepening of the active layer in numerous locations across the Arctic. Several locations along the southern permafrost boundary have lost permafrost completely, whereas in others, upper portions of the permafrost have thawed to depths below that of seasonal freezing.

p0015 Permafrost degradation poses serious impacts ranging from local changes in topographic and hydrologic conditions (Hinzman et al., 2005; Shiklomanov and Nelson, 2013; Shur et al., 2005; Woo, 2012), impacts on infrastructure and

sustainability of northern communities (Anisimov and Reneva, 2006; Anisimov et al., 2010; Grebenets et al., 2012; Nelson et al., 2001), and changes to vegetation and wildlife dynamics (Jorgenson et al., 2013), and to global impacts on changes in greenhouse gas emissions (Tarnocai et al., 2009; Wisser et al., 2011; Zimov et al., 2006). Permafrost degradation is a spatially heterogeneous process, meaning that permafrost characteristics, such as temperature, thickness, or extent, may react differently in different climatic zones.

p0020 Multiple indications exist that modern climatic changes in the 20th to the early twenty-first century have caused permafrost degradation over the large areas in North America and Eurasia (Romanovsky et al., 2010a). From the geological perspective, this is not unique. Climatic transitions between glacial and interglacial periods have always been associated with changes in permafrost. The last glacial maximum of Late Pleistocene 20,000–18,000 years before present is very illustrative for understanding the relation between climate and alternative glaciation forms, that is, glaciers and permafrost. At this time, the Arctic was almost 20 °C colder, and the sea level was 120–130 m lower, leading to permafrost aggradation on exposed continental shelves of the Arctic seas (Figure 10.1). Much of the territory that received sufficient amounts of precipitation was covered by glaciers, including the zone from the Appalachians to the Rocky Mountains in North America, Greenland, Arctic islands, Ireland, the British Isles, Scandinavia, Polar Urals, and Taimyr. In contrast to this, territories with cold and dry climate, including parts of France, Germany, Poland, the Czech Republic, Hungary, Ukraine, the majority of the European part of Russia, southwestern Siberia, and northern Kazakhstan, were occupied by permafrost until around 12,000–18,000 years before present (French et al., 2009; Romanovskii and Hubberten, 2001; Romanovskii et al., 2005; Velichko and Faustova, 2009). During the early Holocene climatic optimum (8,000–6,000 years before present) permafrost retreated northward in North America (Zoltai, 1995), and disappeared in Europe and substantial areas of Northern Eurasia, including in large portions of West Siberia south of the Arctic Circle. Permafrost did not thaw completely in areas with high ice content and is still present at great depths (so-called “relict” permafrost). Subsequent cooling (5,000–3,000 years before present) resulted in permafrost aggradation that allowed the new Holocene permafrost to reach the top of the old (Pleistocene) permafrost located north of the Arctic Circle. In locations where Pleistocene permafrost thawed to a depth of 150–200 m, the newly formed Holocene permafrost was not able to reach the old permafrost. This created three-layered permafrost profiles, in which relatively young Holocene permafrost is separated from the Late Pleistocene permafrost by a zone of unfrozen ground. Smaller advances and retreats of the permafrost boundary occurred during the last 3,000 years. The last notable permafrost advance corresponded to the Little Ice Age (1550–1850 AD), when temperatures were about 1 °C colder than in the present, resulting in permafrost aggradation up to 25 m thick and the advance of permafrost to locations further south from the present terminus. Permafrost from the Little Ice Age occurs in



f0010 **FIGURE 10.1** Reconstructions of permafrost extent (Velichko and Faustova, 2009; Velichko and
[AU35] Nechaev, 2009): (a) Riss-Würm interglacial 125 ka BP, (b) Glacial maximum 20–18 ka BP, (c) Holocene optimum 6–8 ka BP.

locations where a thick peat layer has been able to preserve it despite warmer air temperatures.

p0025 The difference in present permafrost changes and the past events is threefold. First, the rate of contemporary climate change is unprecedented. Air temperatures in selected locations in the Arctic have increased up to 5 °C since the early twentieth century (Anisimov and Vaughan, 2007). Second, the impact of climate change on permafrost is exacerbated by technogenic factors and land use. Lastly, the current situation differs dramatically from the past due to the presence of substantial populations in regions currently occupied by permafrost. Economic activities and infrastructure development in cold regions are largely affected by the presence of permafrost. Whether constructing a cableway in the Swiss Alps (Haeberli, 1992), a railroad on the Tibetan Plateau (Ma et al., 2011), or a metallurgy plant in Siberia, changing permafrost conditions should be taken into account. Failure to do so may result in the deterioration of the natural environment resulting in hazardous conditions for human life and infrastructure.

p0030 To understand the hazards associated with permafrost degradation and their impacts on infrastructure, society, and environment, we first need to understand what makes the permafrost system unique, and what factors are responsible for its changes. Physical and mathematical representations of these factors allow for the construction of permafrost models capable of scaling local observations collected over limited observational areas to larger regions.

Combined with climate models, they are used to predict future changes to permafrost and to evaluate the impacts of these changes on other natural, human, and economic systems.

s0015 **10.2 PERMAFROST AND RECENT CLIMATE CHANGE**

p0035 Recent climatic changes are pronounced in permafrost regions. Since 1980 the Arctic has been warming at approximately twice the global rate, demonstrating the strongest temperature changes ($\sim 1^\circ\text{C}/\text{decade}$) in winter and spring, and the smallest changes in autumn (AMAP, 2011; IPCC, 2013). In the period 1976–2012, spring temperatures over large regions in Siberia and Chukotka have been rising by $0.8\text{--}1.2^\circ\text{C}$ per decade (Roshydromet, 2014). Sea ice declined at an unprecedented rate throughout all seasons reaching the absolute minimum of 3.41 million square kilometers in September 2012, which is 18 percent lower than in 2007, when the previous record of 4.17 million square kilometers was recorded (Jeffries et al., 2012). The Arctic Ocean is projected to become nearly ice-free in summer within this century, whereas some models suggest it may happen within the next thirty to forty years (IPCC, 2013). According to AMAP (2011), the duration of snow-cover extent and snow depth are decreasing in North America while increasing in Eurasia. These changes have important implications for permafrost. Since the late 1970s, permafrost temperatures have increased typically between 0.5 and 2°C , with warming rates being much smaller for warm, ice-rich permafrost at temperatures close to 0°C than for colder permafrost or bedrock (Romanovsky et al., 2010a).

p0040 Changes in permafrost are exacerbated in areas of human activities (Anisimov et al., 2010; Raynolds et al., 2014; Streletskiy et al., 2012a). Around 370 settlements exist in the Arctic tundra zone. Although these settlements are relatively small in most parts of the Arctic, several cities in the Russian Arctic have populations of $>100,000$ people. Thus, permafrost warming can have severe socioeconomic consequences as most of the existing infrastructure will require expensive engineering solutions to stabilize foundations on permafrost. Intensification of coastal erosion, mass wasting, and thermokarst processes in low-lying areas are likely to reshape tundra landscapes, with negative effects on northern communities.

s0020 **10.3 PERMAFROST OBSERVATIONS AND DATA**

p0045 A major milestone in permafrost investigations was the creation of the Global Terrestrial Network on Permafrost (GTN-P). GTN-P was created in 1999 within the framework of the Global Climate Observing System/Global Terrestrial Observing System in support of the United Nations Framework Convention on Climate Change as a network of permafrost observatories to obtain a set of standardized temperature measurements in all permafrost regions of the planet to provide a baseline for temperature change assessments

and data for validation of climatic models. Two components of GTN-P, the Circumpolar Active Layer Monitoring (CALM) program and the Thermal State of Permafrost currently serve as the major providers of permafrost and active-layer data (Figure 10.2) (Brown et al., 2000; Romanovsky et al., 2010a; Shiklomanov et al., 2012).

p0050 Despite the growing observational network and data rescue attempts, permafrost continues to be a data-limited science. Growing computational resources and available geospatial and remote sensing techniques allow permafrost scientists to scale limited local observations to large geographical areas. In order to do so, however, they first need to know what drives permafrost changes.

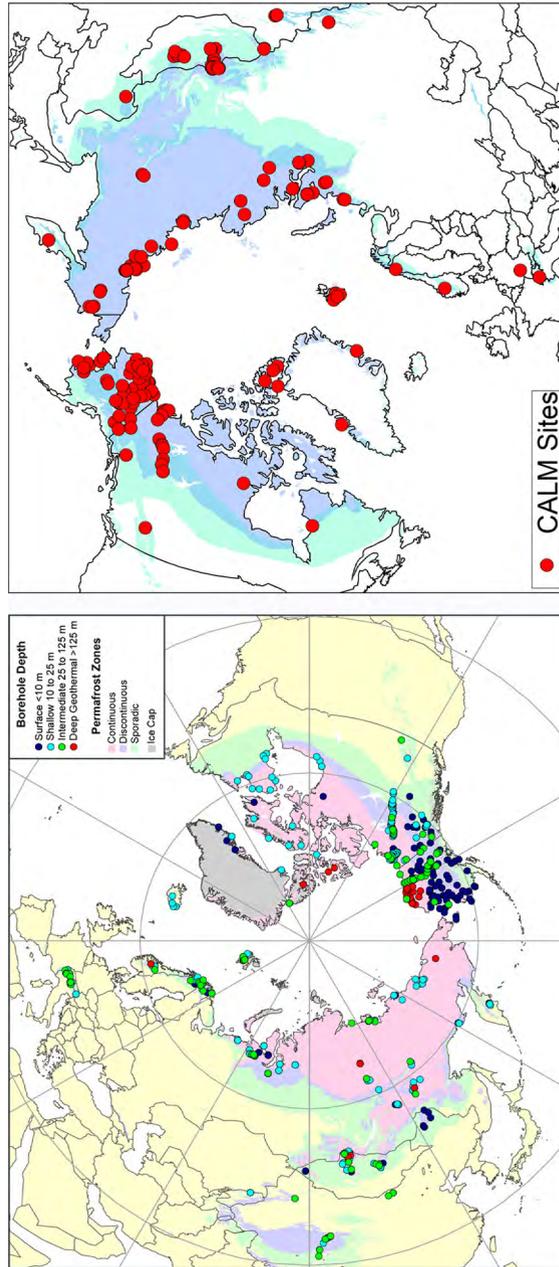
s0025 **10.4 DRIVERS OF PERMAFROST AND ACTIVE LAYER CHANGE ACROSS SPACE AND TIME**

p0055 Interactions between permafrost and the factors responsible for its dynamics are complex, and depend on many interrelated physical processes as well as on geographic scale. Climatic factors play a dominant role in explaining the spatial variability of the permafrost and active layer over large areas, whereas nonclimatic factors can be assumed to be represented by generalized vegetation and soil classes. Over small areas, the leading role in spatial variability is attributed to edaphic factors, such as soil–vegetation associations changing considerably over areas of similar climatic conditions. This explains why, at small geographical scales, the broad spatial pattern of permafrost parameters are closely related to climate: permafrost temperature and thickness, together with the active layer, vary systematically along the climatic gradient. In similar soil–vegetation units, active-layer thickness (ALT) increases from <15 cm in the High Arctic up to 1.5–2.0 m in the southern reaches of the permafrost zone. Permafrost thickness generally decreases from the north to the south, whereas its temperature increases following the same gradient.

p0060 These general geographic trends can be modified significantly by the influence of more localized factors such as topography, vegetation, soil type, moisture, and snow redistribution. For example, even at the southern fringes of permafrost distribution, taller vegetation with denser plant canopies and thicker organic horizons can counter the effects of warmer temperatures, explaining why there can be little correspondence between climatic factors and permafrost temperature and active layer even within small areas.

s0030 **10.4.1 Role of Climate: Air Temperature and Precipitation**

p0065 On an annual basis, the temperature at the top of permafrost and ALT will vary according to the particular climatic conditions of a given year. The majority of studies confirm that seasonal variations of ALT are controlled by the duration of the warm period, fluctuations in accumulated degree-days of thawing, and



f0015 **FIGURE 10.2** Location of GTN-P monitoring sites: Left—temperature boreholes, right—active-layer sites.

by landscape features (Brown et al., 2000). A strong relationship between thawing degree-days and ALT has been demonstrated by several studies showing that warm summers on average produce a deeper active layer and cold summers produce shallow depths of thaw (Hinkel and Nelson, 2003; Romanovsky and Osterkamp, 1997; Streletskiy et al., 2008). Heavy rain in midsummer is a warming factor that promotes thaw through the convective warming of permeable soils, whereas scattered showers in the fall are a cooling factor that suppresses active-layer thickening during the next summer by increasing the ice content at the base of the active-layer (Melnikov et al., 2004). However, the role of summer precipitation relative to temperature is less significant. Although summer temperatures can be quite variable from year to year explaining the large temporal variability of ALT, permafrost temperature is a function of mean annual temperature and its amplitude and hence a more conservative characteristic, since inter-annual variations are smaller than seasonal variations from year to year.

p0070 Over a period of several years, both ALT and permafrost temperature will approach the climatic mean. If climate change exceeds the established equilibrium, the permafrost will adjust accordingly to the new conditions, establishing a new equilibrium in the land–atmosphere system. Substantial evidence exists that the Arctic is experiencing an unprecedented degree of warming (IPCC, 2013; Serreze and Francis, 2006). Due to the attenuation of the climatic signal with depth and differences in ground conditions, particularly with the presence of ice and unfrozen water, the reaction of the permafrost to warming can be quite variable, which is reflected in the observed permafrost trends.

s0035 10.4.2 Role of Topography

p0075 Relief is an important factor that influences the temperature regime within the ground as it is a prime factor of heat-exchange differentiation in the atmosphere–ground system, especially in mountain environments. The amount of solar radiation reaching the Earth’s surface depends on elevation, slope, and exposure. Normal environmental lapse rates lead to decreases of air temperature by about 6.5 °C per 1 km of altitude, which leads to a decreased heat flux, lowered permafrost temperature, and shallower ALT. Therefore, a general decrease in permafrost temperature and ALT with elevation is expected if other factors are constant. However, local wind circulation (e.g., foehn winds and cold-air drainage) can substantially change the altitudinal distribution of temperature. Moreover, temperature inversions are a common phenomenon in Arctic regions during the cold season, so actual environmental lapse rates can significantly differ from the normal ones. The difference between ground temperatures on north- and south-facing slopes vary, depending on the slope gradient. Slope aspect also influences the variation of the ground temperature amplitude. Terrain geometry also exerts an important control over ALT

through its influence on the spatial variability of soil moisture and vegetation. [Repelewska-Pekalowa and Pekala \(2004\)](#) found that high values of ALT in Spitsbergen were associated with terrain units (primarily concave hillslope segments) in which the movement of surface or ground water produced convective heat transfers. The presence of microtopographic relief features at large geographical scales increases the variability of snow-cover distribution, leading to a delay of ground thawing in depressions as compared to thawing in blowouts ([Voitkovskiy, 1999](#)).

p0080 Leveling of topography prior to economic development leads to the alteration of heat and moisture exchange and can lead to the development of subsidence and thermokarst, particularly in areas with ice-rich permafrost. Thermal erosion and solifluction rates increase under warmer climatic conditions, which may further be exacerbated if measures are not taken to protect vegetation on slopes. Decreased slope stability resulting from the melting of ground ice, decreased soil cohesion, and deeper water infiltration under a warmer climate is a major concern in mountain environments and is discussed in detail in the corresponding chapter of this volume ([Deline et al.](#) this volume) and elsewhere ([Bommer et al., 2010](#); [Gruber and Haeberli, 2007](#); [Harris and Isaksen, 2008](#); [Kääb et al., 2007](#)).

[AU8]
[AU9]

p0085 Substantial alterations to topography in permafrost regions are found in areas of mining. Mining activities on permafrost commonly result in the dumping of crushed rocks near the extraction sites, which have the potential to form technogenic rock glaciers. The largest technogenic rock glacier is located in the Norilsk area as a byproduct of mining activities that lasted from 1960 to 1984. It is located on the northern slope of Rudnaya Mountain, up to 120 m thick, and has a volume of 60 million cubic meters or about 110 million tons ([Grebenets et al., 1998](#)). Rain and snowmelt water percolation through the dump site and its subsequent refreezing, the overall increase in permafrost temperature, the decreased cohesion of the dump and bedrock slope, all resulted in the displacement of the frontal side of the dump body with a speed that has reached 60–80 mm/day. About 60 percent of the rock glacier collapsed into the nearby Medvezhy Ruchi River destroying the road and water pipeline supplying the city in 1996. The permafrost creep ([Haeberli et al., 2006](#)) still poses a danger to the city of Norilsk and numerous examples of other such technogenic rock glaciers exist, particularly on the Kola Peninsula. Smaller features called either “frozen debris lobes” or rock glaciers in the Brooks Range of Northern Alaska were recently found to have accelerated movement, which creates a potentially hazardous situation for the *Trans-Alaskan Pipeline* and Dalton Highway operations ([Daanen et al., 2012](#)).

s0040 10.4.3 Role of Vegetation and Mosses

p0090 Vegetation cover acts as a thermal insulator between the atmosphere and the ground and can play a substantial role in the redistribution of snow cover. One

study involving 17 sites along a North Alaskan bioclimatic gradient has shown that increased plant biomass along the gradient acts as a negative feedback to increases in ALT, because of the insulative effect of vegetation and the highly organic soil horizons. This relationship underscores the importance of vegetation on the development of the active layer and near-surface permafrost (Walker et al., 2003).

p0095 A significant role in heat exchange at the surface in Arctic environments is attributed to moss cover. Generally, its presence leads to lower mean annual temperatures, as moss has a low thermal conductivity in summer and a high thermal conductivity of the frozen material in winter facilitating the effective cooling and storage of cold within the permafrost. The evaporative regime of the moss layer also promotes cooler summer temperatures (Riseborough and Burn, 1988). The addition of a 10-cm layer of moss resulted in almost a 3 °C decrease in the mean summer soil temperature and a 15 percent reduction in ALT in northern Alaska (Kade and Walker, 2008). Mosses dominate the surface cover in high northern latitudes and have the potential to play a key role in modifying the thermal and hydrologic regime of Arctic soils. These modifications in turn feed back into surface energy exchanges and hence may affect regional climate. Beringer et al. (2001) concluded that the addition of a surface layer of moss underlain by peat and loam had a substantial impact on modeled surface processes. They found that the thermal conductivity of the top layer consisting of moss, lichen, and peat in experiments was only one-quarter of that for sand and loam, because of the high air volume and lower water content. The addition of a surface moss layer resulted in higher simulated winter soil temperatures and lower summer temperatures. Decrease of organic layer due to forest fires may trigger long-term changes in permafrost stability as regrowth of the moss takes a considerable number of years (Burn, 1998; Jafarov et al., 2013). Removal of vegetation including the moss layer caused by economic development or forest fires leads to an increased heat flux in the ground during summer months, increased active layer and ground temperature, melting of ground ice and subsidence and may lead to the development of thermokarst terrain.

s0045 10.4.4 Role of Snow

p0100 It is difficult to overstate the influence of snow cover on the heat balance at the ground surface in cold environments. Variations in the duration, thickness, accumulation and melting processes, structure, density, and thermal properties have significant impacts on the insulating effect of seasonal snow cover (Zhang et al., 1996). Variations in permafrost temperatures are largely attributed to changes in snow-cover thickness. A recent study found that in Siberia changes in the mean annual ground temperature (MAGT) are more dependent on snow-cover thickness than on changes in air temperature (Sherstyukov, 2008). Late-lying snow cover in the summer increases albedo

and therefore decreases the surface temperature. In spring, melting snow delays the warming of the soil surface while it is close to 0 °C, even if the air temperature is positive (Romanovsky and Osterkamp, 1997). Interception and sublimation of snow strongly control snow accumulation in forest environments (Pfister and Schneebeli, 1999). For example, increases of 30–45 percent in seasonal snow accumulation have been measured after the removal of evergreen forest cover by clear-cutting at sites across Canada. Snowmelt under forest canopies is very different from that in open environments because the overlying canopies intercept radiation and suppress turbulent transfer. As a result, melting rates are lower in forests than in equivalent open areas (Woo, 2012). Tirtikov (1978) found that beneath trees and tall shrubs in the forest tundra of West Siberia, where about 1 m of snow accumulates, ground temperatures were 3–5 °C higher than in the surrounding tundra. However, Smith (1975) found that in some locations in the Mackenzie Delta the MAGT was raised above 0 °C because of the higher amounts of snow accumulation in areas of low willow shrubs as compared to those with tall willow shrubs and sites without vegetation. These examples show a complexity of snow–vegetation interactions in modulating the ground thermal regime. Based on the results from long-term monitoring of the insulating effect of different landcover types in Central Yakutia, Varlamov (2003) concluded that the greatest insulating effect of snow occurs on wet and oversaturated surfaces, while it is minimized on dry sandy soils. This fact is attributed to the higher rates of heat exchange associated with saturated soils. Snow also plays a role in thaw depth development. Experimental data from Igarka and Yakutsk show that in areas where snow was removed after each snowfall event during the winter, ALT in the following summer was from 5 to 10 percent lower compared to areas with undisturbed snow cover, since variations in ALT depend on the MAGT, which in turn depends on snow-cover conditions.

p0105 Redistribution of snow is a common practice in areas of human activities in cold environments. Roads, entrances to residential houses, industrial facilities, parking lots, and airports all require snow removal in order to be operational. At the same time, certain areas are used to store the removed snow. Areas of snow removal and storage occupy the same locations from year to year, resulting in significant alterations to the ground thermal regime relative to natural conditions. Piling snow in the same locations is likely to result in warmer permafrost temperatures over a several-year period, but snow compaction may offset the thermoinsulating effect of thicker snow. Moreover, late-lying snow cover increases albedo and can decrease surface temperature, further offsetting the warming impact of thicker snow. The areas of snow removal lack this natural seasonal thermoinsulating layer and have winter temperatures similar to those of the air. Not only does the removal of snow decrease the temperature of permafrost resulting in permafrost aggradation under the roads but it also increases the amplitude of temperature variations leading to the intensification of frost cracking and cryogenic weathering. This

leads to a much faster destruction of construction materials and to the deterioration of road networks in permafrost-dominated areas.

p0110 A major part of the soil's moisture comes from melted snow (Sokratov and Barry, 2002). Areas of artificial snow accumulation, especially along roads, are subjected to water logging. Roads act as frozen dams with little or no infiltration capacity even by the end of the warm period of the year. Standing water along the roads in permafrost environments is one of the biggest problems requiring constant attention, as the standing water accumulating and heat retained during warm periods leads to the development of thermokarst topography.

s0050 10.4.5 Role of Soil Properties

p0115 The ability of permafrost to transfer and hold heat depends on thermal conductivity and heat capacity, which change depending on soil texture and water content (Romanovsky and Osterkamp, 1997). Under dry conditions, thermal conductivity increases along the textural sequence clay-loam-silt-sand-indurated rock, leading to much thicker permafrost in bedrock relative to fine-grained sediments under similar climatic conditions. Higher soil-moisture content requires more latent heat for water phase transitions than does low moisture content leading to a thinner active layer. On the other hand, increases in moisture content during the summer or winter (without phase transition) increases soil-thermal conductivity, because air with low thermal conductivity ($0.023 \text{ W/m}^\circ\text{C}$) replaced by water with a higher conductivity ($0.57 \text{ W/m}^\circ\text{C}$), or ice ($2.29 \text{ W/m}^\circ\text{C}$) leads to the deeper propagation of freeze/thaw (Yershov and Williams, 1998). The latter case was supported by a hydrological manipulation experiment in the drained lake basin near Barrow, Alaska. ALT in the experimentally drained area was found to be 25 percent less than in the experimentally flooded area (Shiklomanov et al., 2010), which shows the importance of the moisture regime and surface hydrology in the variability of ALT.

p0120 Development of construction sites on permafrost begins with the construction of pads. Artificial pads commonly have soil characteristics that are different from natural landscape settings. Large logistic costs associated with the transportation of raw materials commonly result in the dragging of local streams in order to obtain the necessary sand and gravel. Corresponding changes in ground properties may result in changing permafrost thermal conditions and hydraulic conductivity resulting in increased water infiltration and warming permafrost during summer months.

p0125 Technogenic salinization and water logging is another problem facing some of the cities located on permafrost, particularly those with developed mining and metallurgy industries, such as Norilsk and Vorkuta. For example, the salinization of soils in Norilsk is reaching up to 21 mg/l near the nickel plant (Grebenets et al., 2012). Technogenic salinization is not only leading to

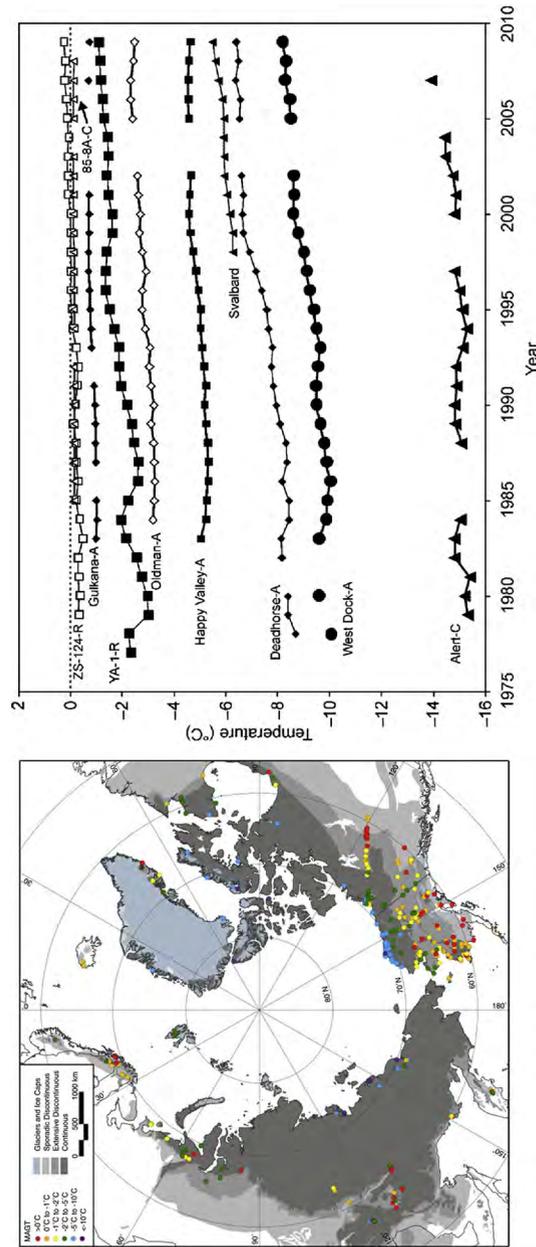
decreases in the stability of infrastructure through increases in ALT and the decreased freezing temperature of the soil but it also directly affects foundations through the corrosion of metal and concrete within the active layer.

s0055 10.5 OBSERVED PERMAFROST AND ACTIVE-LAYER CHANGES

p0130 Changes in the air temperature and snow depth over the second half of the twentieth century have resulted in permafrost degradation, which is evident from the limited observations of permafrost temperatures summarized in [Romanovsky et al. \(2010a\)](#). It was concluded that following air temperature trends, permafrost has been experiencing warming in the majority of sites in the Arctic since the 1970s, but that this warming is not uniform ([Figure 10.3](#)). Large areas occupied by permafrost are still not monitored, so the conclusions are still based on relatively few and for most places rather short time series.

p0135 [Romanovsky et al. \(2010b\)](#), based on analysis of a large observational data set, estimated that permafrost has warmed from 0.5 to 2 °C over the last 20 to 30 years in the Russian Arctic. The European Russian North was characterized by warming trends of about 0.01–0.04 °C/year in the western portion ([Malkova, 2010](#)) and up to 0.08 °C/year in the eastern portion ([Oberman, 2008](#)). The northward retreat of permafrost by 30–40 km in the Pechora lowland and up to 70–100 km in the Foothills of the Ural Mountains occurred during 1970–2005 ([Oberman and Shesler, 2009](#)). The highest rates of permafrost warming occurred in peatlands, and the lowest rates were in sediments composed of loams. A similar situation has been characterized for the forest tundra of Western Siberia, where the highest observed warming trends were attributed to frost mounds covered by peat (0.04 °C/year). In locations where permafrost temperature is close to 0 °C, no changes were registered for the entire period of measurements (1975–2009), as important exchange of latent heat melting was already taking place in the ground. Permafrost thawing was also observed over the last 30 years in the southern forest tundra of the Urengoy gas-condensate field ([Vasiliev et al., 2008](#)). Both in West Siberia and in the European Russian North, temperature changes were observed to be more significant in colder permafrost sites. Northern Yakutia experienced permafrost warming up to 1.5 °C since 1980 in the eastern part; however, sites located in the west did not show a significant warming trend until recently. Smaller warming trends were observed near Chara (Baykal region), ranging from 0.025 to 0.04 °C/year.

p0140 Even higher permafrost changes are observed in some locations of North America ([Smith et al., 2010](#)). Since the 1980s, permafrost was recorded as having warmed 0.3–1.0 °C in Interior Alaska, 1–2 °C in the Arctic Foothills, and up to 3–4 °C in the Arctic Coastal Plain ([Clow, 2008](#)). [Burn and Zhang \(2009\)](#) estimated that the permafrost on Herschel Island warmed only 2 °C in the last 100 years, showing that permafrost warming has accelerated in recent



f0020 **FIGURE 10.3** Left: Mean annual ground temperature (MAGT) snapshot. Right: time series of MAGTs at depths between 10 and 20 m for boreholes throughout the circumpolar northern permafrost regions. From *Romanovsky et al. (2010a)*.

[AU36]

- [ED3] decades. Canadian High Arctic permafrost has warmed at a rate of 0.03–0.05 °C/year (Taylor et al., 2006) and up to 0.1 °C/year on Ellesmere Island. Warming in the western part of the North American Arctic has been underway since the 1970s, but it has slowed down in the last decade. Meanwhile, the eastern part is still undergoing warming trends that started in the early 1990s (Smith et al., 2010). A 130-km northward retreat of the southern permafrost boundary over the last 50 years was reported in the Quebec province of Canada (Thibault and Payette, 2009).
- p0145 Permafrost temperature is significantly increasing in Scandinavia (Christiansen et al., 2010). Harris and Isaksen (2008) analyzed permafrost temperatures in the European Arctic and observed that permafrost temperature increase is characteristic for three deep boreholes located along a latitudinal transect through southern Norway, northern Sweden, and in Svalbard. At a 30-m depth warming rates were about 0.025–0.035 °C/year. Higher rates are characteristic for the top of the permafrost (0.04–0.07 °C/year) with the greatest changes attributed to permafrost on Svalbard. Monitoring sites located in Southern Norway experienced permafrost warming about 0.015–0.095 °C/year (Isaksen et al., 2011); permafrost temperature is also increasing in Sweden (Johansson et al., 2011).
- p0150 Central Asia is also characterized by increased permafrost temperatures and ALT (Zhao et al., 2010). The highest rate of permafrost temperature increase in the region is characteristic for sites located on the Qinghai–Tibet Plateau and is 0.06 °C/year. Reported ground temperature increases in the Tian Shan Mountains were considerably less over the last 25 years (0.012–0.025 °C/year). Sharkhuu et al. (2008) reported that the increase of permafrost temperature in Mongolia was higher over the last 15–20 years compared to that in previous years, averaging at a rate of about 0.015 °C/year.
- p0155 Examples from various regions show that near-surface permafrost is quite sensitive to observed climate change. In general, colder permafrost undergoes faster warming rates compared to warmer permafrost; however, large heterogeneity persists both spatially and temporarily, even within relatively small regions (Figure 10.3). Colder temperature permafrost has less unfrozen water, which allows for more effective heat conduction. As climate shifts to warmer temperatures, permafrost temperature increases accordingly, until a new climate–permafrost equilibrium is reached. Increasing the amount of unfrozen water decreases the ability of permafrost to transfer heat. When permafrost is close to the melting point of ice, a significant amount of latent heat is required to convert the water from frozen to liquid state, requiring substantial time to thaw permafrost rather than warm it. This explains why colder permafrost warms at a faster rate than permafrost that is close to the melting point. Other environmental and technogenic factors can add to the current permafrost warming trend, such as an increase in snow-cover depth or the removal of vegetation.
- p0160 Permafrost degradation occurs differently in the continuous (cold) permafrost zone and the discontinuous permafrost zones (warm). Degradation

of the continuous permafrost zone is expressed as an increase in permafrost temperature and a corresponding decrease in permafrost thickness in order to establish a new equilibrium. Although the adjustment of the permafrost temperature as measured at the depth of zero mean annual amplitude (10–20 m) is a relatively fast process (e.g., lags only several years behind air temperature changes), permafrost that thaws from the bottom takes much longer (hundreds of years).

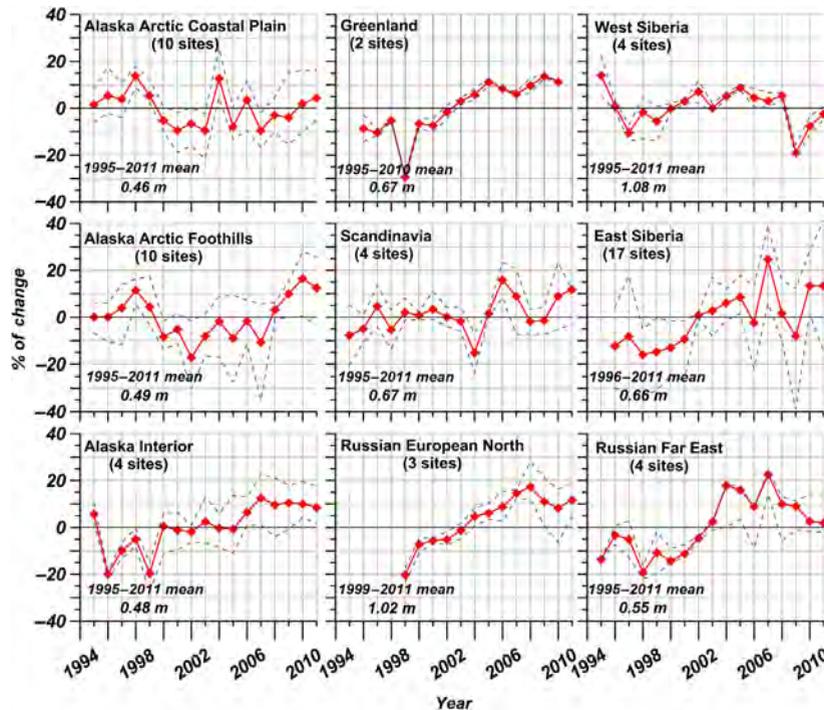
p0165 Degradation of the discontinuous permafrost zone is expressed as a slow increase in temperature until the melting point, after which it may take decades to hundreds of years to thaw the permafrost depending on ground composition and ice content. Sporadic and island permafrost zones in the Arctic are largely controlled by nonclimatic factors, such as the presence of peat.

p0170 Increases in the ground temperature in the majority of permafrost regions were accompanied by increases in ALT (Shiklomanov et al., 2012); however, the magnitude was variable even within small regions (Figure 10.4). Significant increases in ALT were reported in Greenland and Svalbard, but are not spatially uniform (Christiansen et al., 2010). A progressive increase in ALT since 1970 resulted in the disappearance of permafrost in several mire landscapes in the Abisko area (Sweden) (Åkerman and Johansson, 2008). A similar situation occurred in the Russian European North, where a progressive increase of ALT was observed during 1996–2013 (Kaverin et al., 2012; Malkova, 2010), and in the Alaskan Interior. Central and Eastern Canada (Smith et al., 2010) and Central Asia (Zhao et al., 2010) also underwent increases in ALT. Sites located in West Siberia, on the North Slope of Alaska, and in Western Canada did not show long-term increasing trends but over the last several years have experienced slightly deeper depths of annual thaw (Smith et al., 2009; Streletskiy et al., 2008; Vasiliev et al., 2008). Spatially distributed long-term monitoring of thaw subsidence showed that an apparent lack of active-layer thickening may be attributed to melting of segregation ice at the bottom of the active layer due to consolidation of ice-rich permafrost (Shiklomanov et al., 2013).

s0060 10.6 PERMAFROST MODELING AND FORECAST

p0175 Geocryology remains a data-limited science with relatively small amounts of ground-truth data. Development of computational and modeling techniques have resulted in a dramatic increase in the number of permafrost models and in the variety of their applications (Anisimov and Reneva, 2006, 2011; Arzhanov et al., 2013; Goodrich, 1978; Koven et al., 2013; Malevsky-Malevich et al., 2001; Nelson and Outcalt, 1987; Shiklomanov and Nelson, 2002; Stendel and Christensen, 2002; Streletskiy et al., 2012b).

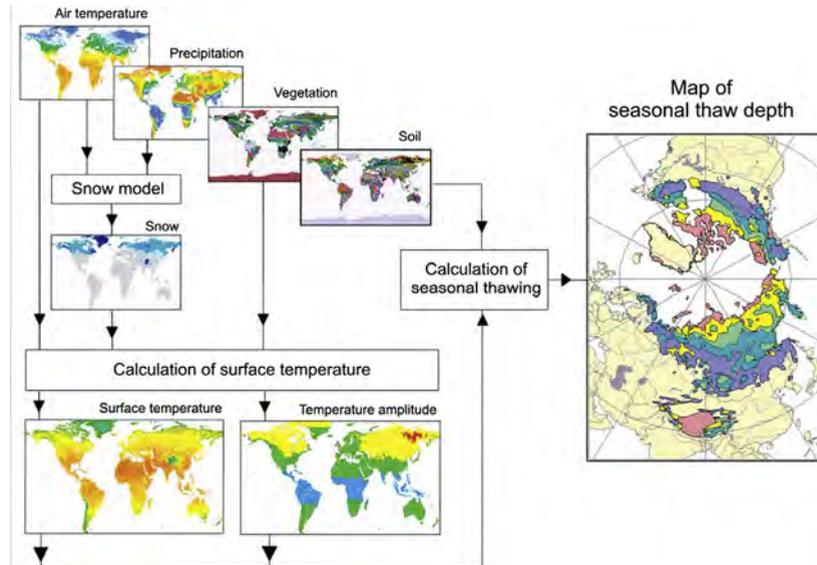
p0180 The simplest approaches are based on several variations of the analytical Stefan solution to the heat-conduction problem with phase change. Several variations of a more comprehensive model, based on the adaptation of the



f0025 **FIGURE 10.4** Active-layer change in nine different Arctic regions according to the Circumpolar Active Layer Monitoring program. The data are presented as annual percentage deviations from the mean value for the period of observations (indicated in each graph). *Figure from Shiklomanov et al. (2012).*

analytical solution by Kudryavtsev et al. (1974) to the geographic context, have been developed and used with the aid of a Geographic Information System (GIS) technology to calculate both ALT and MAGTs at regional and circumpolar scales (Anisimov and Reneva, 2006; Anisimov et al., 1997; Sazonova and Romanovsky, 2003; Shiklomanov and Nelson, 1999; Slater and Lawrence, 2013). The input data for these models include mean annual air temperature, and its annual amplitude, the thickness and thermal properties of ground cover (snow and vegetation), soil-thermal properties, and soil-moisture content (Figure 10.5). More complex models include dynamic interactions between permafrost and other components of the environment, but require more rigorous parameterization, which is largely unavailable.

p0185 Although the complexity of parameterization ranges from very simple, heat-conduction solutions to fully coupled transient Global Climate Models (GCMs), all models represent permafrost distribution depending on the nature of the climatic forcing. Climate inputs required to run these models come in the form of gridded data sets, which are created through the interpolation of point observations. Differences in data sources, interpolation, and validation



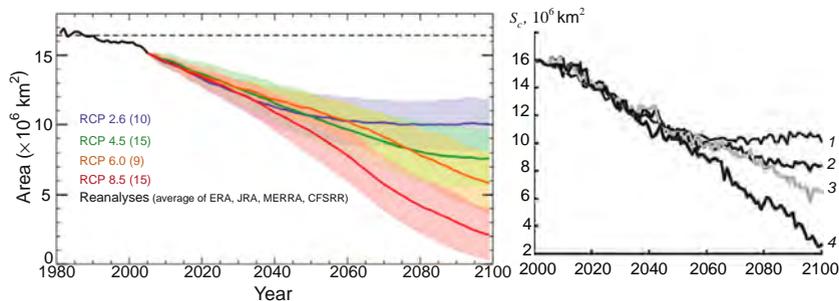
[AU37]

f0030 **FIGURE 10.5** Computational design of the hemispheric-scale permafrost model. From *Anisimov and Reneva (2006)*.

techniques used to construct the data sets result in differences in the resulting climatic fields. For example, the differences between commonly used observational data sets and reanalysis may reach about 1 °C over the Arctic and 10 times that within a relatively small area within a given grid (*Streletskiy et al., 2012b*). Projected climate changes have much higher uncertainty ranges, as some models produce warmer or colder temperatures relative to the others.

p0190 *Slater and Lawrence (2013)* compared the ability of numerous state-of-the-art climate models (CMIP5) used by IPCC to portray present permafrost characteristics and tested their ability to predict future permafrost changes. The authors found that significant biases of temperature and snow depth representations lead to large deviations from the present permafrost extent (ranging from 4 to 25 million square kilometers, *Figure 10.6*). That is why scientists commonly apply the so-called ensemble approach that uses a combination of several climate models.

p0195 Despite large differences in the extent and rate of changes of permafrost, all models agree that projected warming and increases in snow thickness will result in near-surface permafrost degradation over large geographic areas (*Koven et al., 2013*). The sensitivity of permafrost to climate change is between 0.8 and 2.3 million square kilometers per degree centigrade meaning that an increase of global temperature by 1° corresponds to a decrease in near-surface permafrost area equal to the size of Mongolia or even Greenland. The combination of local factors such as snow redistribution, vegetation, and hydrological and soil properties may offset or increase the rate, but are unlikely



f0035 **FIGURE 10.6** Total area of near-surface permafrost on the Northern Hemisphere land computed by Slater and Lawrence (2013) (left) and Arzhanov et al. (2013) (right) under the scenarios: (1) RCP 2.6, (2) RCP 4.5, (3) RCP 6.0, and (4) RCP 8.5.

to reverse the overall trend. Slater and Lawrence (2013) estimated that the reduction of the near-surface permafrost extent by the end of the century will be about 10 million square kilometers under RCP 2.6 and to 2.1 million square kilometers under RCP 8.5. Arzhanov et al. (2013) arrived at slightly larger estimates of 10.5 million square kilometers and 3 million square kilometers, respectively (Figure 10.6). Thawing of near-surface permafrost may result in differential subsidence of several decimeters or more in areas with ice-rich permafrost leading to the deterioration of overlying infrastructure, especially linear structures on permafrost.

s0065 10.7 PERMAFROST AND INFRASTRUCTURE

p0200 Arctic settlements range in size from small native villages in Alaska and Scandinavia to large industrial towns in Siberia. Depending on location, climatic and environmental conditions, proximity to the coastline, density, structure, and economic orientation of the settlements, the impact of climate change is expected to be diverse. Changing climatic conditions may benefit some aspects of arctic economies as heating costs are likely to decrease, and diminishing sea-ice extent has the potential to foster economic development along the coasts. However, these benefits may be outnumbered by the new challenges facing northern communities as coastal erosion is expected to intensify due to increasing wave activity, shorter winter road operational seasons lower the accessibility of remote settlements, and thawing permafrost may not be able to support existing infrastructure. A recent study of the economic effects of climate change on infrastructure in Alaska concluded that an additional 3.6–6.1 billion USD will be required to maintain infrastructure between 2010 and 2030 and up to 7.6 billion USD between 2010 and 2080 (Larsen et al., 2008). Despite no such comparison being conducted for other regions on permafrost, the direct cost of permafrost degradation is at least several billion dollars per year. For example, pipeline maintenance in

permafrost regions of Russia requires more than 1.5 billion USD annually (Streletskiy et al., 2012a). The impacts of permafrost degradation are expected to be most pronounced in large population and mining centers, as substantial populations and infrastructure will be affected. Impacts of permafrost degradation in mountain regions are omitted as they are discussed in Deline et al., (this volume).

s0070 10.7.1 Buildings on Permafrost

p0205 A large number of structural deformations have been reported in settlements built on permafrost (Grebenets et al., 2012; Hinkel et al., 2003; Khurstalev et al., 2011; Kronik, 2001). Observed increases in near-surface permafrost temperatures are decreasing the ability of foundations to support structures at rates that may not have been anticipated at the time of construction (Khurstalev and Davidova, 2007; Streletskiy et al., 2012c). An increased ALT decreases the effective area of a foundation freezing within permafrost, intensifying the processes of frost heave and thaw subsidence, and increasing the corrosion of the foundation materials. The projected climate change in the Arctic has the potential to cause a further deterioration and deformation of structures on permafrost, which can have severe socioeconomic consequences, as most of the existing infrastructure will require expensive mitigation strategies to support them.

p0210 Russian permafrost regions account for half of the population in the Arctic, and at the same time, this is the most problematic region with respect to infrastructure on permafrost. The majority of Russian urban infrastructure consists of mass-produced standard design structures built in the 1960s–1970s, which were rarely designed to withstand the changes in climatic conditions beyond natural variability at the time of construction (Khurstalev et al., 2011). A survey of structures in a series of settlements across the Russian Arctic indicated that buildings with deformations account for 10 percent of their total numbers in Norilsk, 22 percent in Tiksi, 55 percent in Dudinka, 35 percent in Dikson, 50 percent in Pevek and Amderma, 60 percent in Chita, and 80 percent in Vorkuta (Kronik, 2001). During 1990–2000, the rate of building failures has increased by 42 percent in the city of Norilsk, 61 percent in Yakutsk, and 90 percent in Amderma. The number of observed deformations in structures in Norilsk during 2003–2013 was higher than the corresponding number of deformations during 1963–2013 (Grebenets et al., 2012).

p0215 Construction of houses on permafrost can be a tricky business, as heat and permafrost contradict each other. Through trial and error, Russia accumulated a tremendous amount of experience with construction on permafrost, which was later adopted by western engineers. Despite the fact that by 1906 Nezdánov had proposed the use of ventilated basements to protect permafrost from thawing and by 1912 Bogdanov had summarized much of the engineering problems in his book “Permafrost and construction upon it”, houses

without proper thermoinsulation of the ground floor were a common reality until the midtwentieth century. To avoid warming permafrost from buildings and structures and to redistribute the pressure associated with high structural loads, engineer Mikhail Kim promoted the idea of piling foundations, which were originally designed in 1956 in Norilsk. The piles were installed and frozen into the permafrost prior to the construction of the structure itself. The piles embedded in permafrost allowed for much greater structural weights relative to the shallow foundations since much of the structural load was carried by the side contact of piles with permafrost. It also decreased the disturbance of permafrost during construction as pile diameters were relatively small compared to other foundation types and allowed for the redistribution of pressure from pile to pile through the system of horizontal beams on which the buildings were erected. The piles, commonly 4–12 m in length and 0.2–0.5 m in diameter, were installed in predrilled boreholes, with the upper portion of the pile sticking 0.5–2 m above the ground. The system of horizontal beams was put on top of the piles redistributing the structural load. The elevated first floor with a crawl space basement was clearly advantageous, as the basement was ventilated during the winter and provided shading during the summer preventing the permafrost from thawing.

p0220 Presently, urban architecture in the Russian Arctic is predominantly represented by a mixture of prefabricated panel or standard design, brick, five- to nine-floor buildings. The majority of such structures on permafrost were built using piling foundations according to the ideas of Kim, which have become known as the passive principle of construction on permafrost (Shur and Goering, 2009). According to the passive principle of construction (also known as Principle I in the Russian literature), the permafrost is used as the base for foundation and is protected from thaw during construction and throughout the entire life span of the structure, which is expected to be between 30 and 50 years.

p0225 The ability of a pile foundation to carry a building structural load depends on many factors such as ground temperature, texture, density, salinity, the amount of ice in the ground, and the presence of unfrozen water. In coarse soils (gravels and denser), soil strength is primarily a function of internal friction. In frozen fine-grained materials, however, it is primarily a function of ice bonding. The strength and deformation characteristics of frozen soils are temperature dependent. Two parameters, namely, the thickness of the active layer (maximum thaw depth) and the maximum ground temperature, along the embedded pile length are incorporated into the site-specific design for a foundation in a permafrost region (Instanes and Anisimov, 2008). As previously mentioned, piles embedded in permafrost allow for much heavier loads compared to those in nonpermafrost regions, as the majority of the bearing capacity is gained by adfreezing of the sides of piles to the surrounding permafrost. The shear stress per side unit of a pile is much lower compared to the normal stress at the bottom of a pile, but this

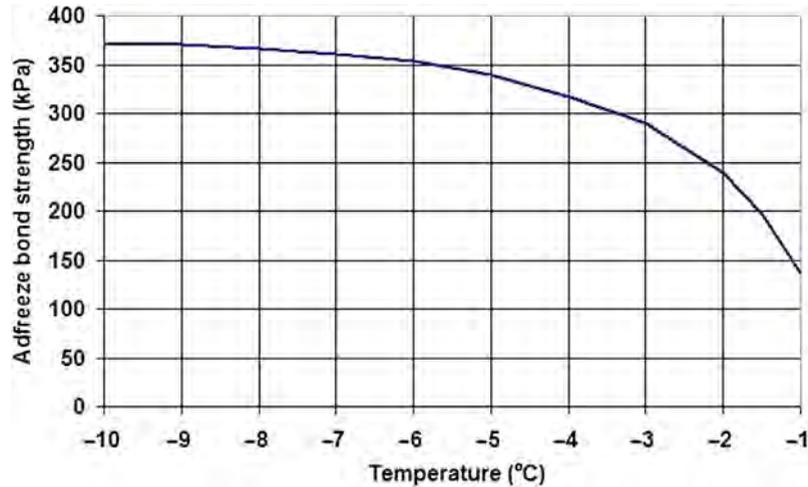
also means a much larger adfreezing area of the pile side relative to the bottom, allowing for the redistribution of up to 80 percent of the pile-bearing capacity to its sides.

p0230 The dependence of freezing strength on permafrost temperature along the sides of piles makes a foundation's bearing capacity highly dependent on permafrost temperature, which in turn depends on air temperature variations and characteristics of heat exchange at the ground surface, such as the presence and properties of snow and vegetation. Air temperature and snow-cover oscillations create conditions in which strength and bearing capacity vary with climatic conditions (Khrustalev and Davidova, 2007).

p0235 The previously described conventional permafrost engineering design is based on the analysis of historical variations of climatic and permafrost data and accounts for the frequency of extreme events, such as abnormally high temperatures resulting in deeper seasonal thawing of permafrost. Each foundation is designed with a construction-specific safety factor that depends on the probability of such extremes. The adfreeze bond strength between the pile surface and surrounding frozen soil is both temperature and time dependent. For a specific pile foundation design, this parameter should be determined from geotechnical field and laboratory investigations (Figure 10.7).

p0240 Engineers, however, were commonly using historical climatic averages available at the time of construction, in which case climate change was not accounted for. This fact raises questions about the stability of structures whose design is based on the purported climatic normal of past decades when climatic conditions were changing rapidly.

p0245 Assessing the stability of infrastructure located in permafrost regions Streletskiy et al. (2012a) found that the present deterioration of infrastructure can, to some degree, be attributed to climatic changes observed in permafrost regions over the last 50 years. Using a combination of permafrost-geotechnical modeling and climate data, these authors mapped changes in foundation bearing capacity for five Russian regions located on permafrost (Figure 10.8). These five regions, with a total population of almost two million people, experienced an overall increase of mean annual air temperature of 1 °C since the 1970s. Associated increases in near-surface permafrost temperatures and thickening of the active layer resulted in the decreased ability of foundations within the studied regions of Russia to support their structures. Combined with the low safety coefficients this raises a question about the safety of thousands of people living in houses built on permafrost in the Russian North. Projected climate change is likely to further decrease the stability of existing infrastructure as large areas of ice-rich permafrost are expected to experience differential subsidence (Anisimov and Reneva, 2006; Arzhanov et al., 2010; Nelson et al., 2001) and decreased foundation bearing capacity (Khrustalev et al., 2011; Streletskiy et al., 2012c). A comprehensive study of cumulative geocological effects of infrastructure development and climate change in Prudhoe Bay Oil field (Northern Alaska) showed that significant

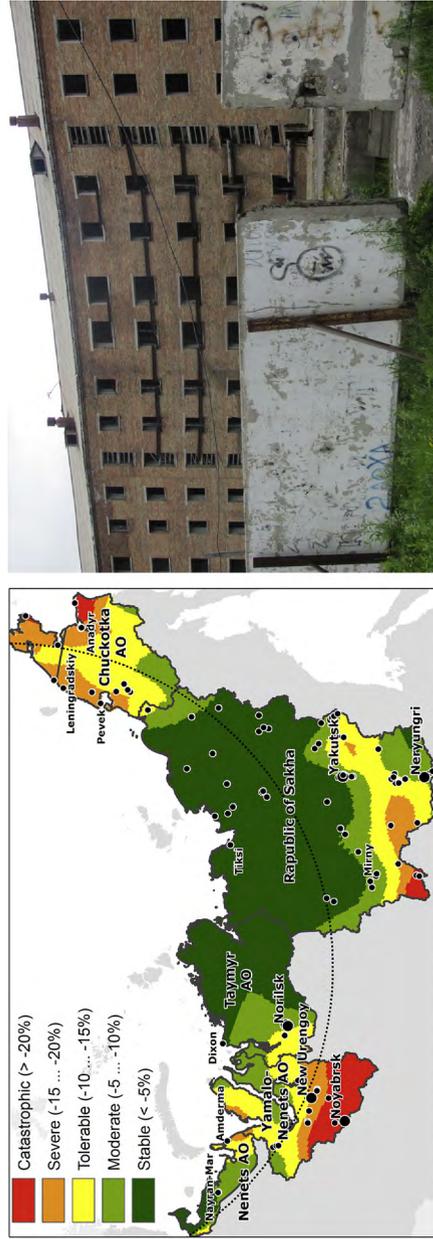


f0040 **FIGURE 10.7** Typical diagram of adfreeze bond strength as a function of the ground temperature. From *Instanes and Anisimov (2008)*.

intensification of thermokarst development occurred over the life span of the oil field (Raynolds et al., 2014). Although some of the thermokarst resulted directly from the infrastructure development (construction of roads, pipelines, gavel pads, and others) or indirect impacts associated with infrastructure (infrastructure-related flooding, roadside dust, and offroad vehicle traffic), numerous changes were attributed to warmer climatic conditions during 1994–2014, particularly during summer months. The increase of thermokarst extent may have serious negative implications on future economic development of the oil field, wildlife habitat, and sustainability of the native community of Nuiqsut located west of the development area.

s0075 10.7.2 Pipelines on Permafrost

p0250 Pipelines are a common means of transporting liquid and semiliquid products and are widely used in cold regions to transport heat, water, and by-products of oil and mineral resources. The latter ones are of greatest interest since they extend over large areas with drastically different environmental and climatic conditions. For example, the *Trans-Alaskan* pipeline extends more than 1,200 km through taiga and tundra and crosses through all permafrost zones. Extensive networks of oil and gas pipelines in Russia extend more than 71,000 km, with a considerable portion built on permafrost. Several gas pipelines are currently under consideration for construction in Alaska, Canada, and Russia. Deformation of pipelines and associated spills of petroleum products are particularly hazardous in regions on permafrost as the low biologic activity in tundra environments means that it would require years to restore these fragile



f0045 **FIGURE 10.8** Left: Map of changes in the ability of foundations to support the structures in permafrost areas (from Streletskiy et al. (2012a)). Deformation of building constructed on permafrost using passive construction principle in Igarka. Photograph by D. Streletskiy, July 2013.

Arctic ecosystems. Despite the fact that microbiological transformation of hydrocarbon products in the Arctic occurs at a slow rate, it should not be ignored in restoration efforts (Kachinskii et al., 2014).

p0255 Deformations of pipelines in regions on permafrost are commonly associated with frost heave and subsidence processes, ground ice melting, water logging and thermokarst development, and thermoerosion and solifluction on slopes. Above-ground pipelines may experience deformation associated with intensified frost heave as the active-layer increases following the removal of vegetation and the organic layer during the construction. Increases in the ALT also lead to a decrease in the effective area of side freezing for supporting piles in permafrost, which eventually leads to pile jacking and the decreased ability to support structural weight. Redistribution of weight among neighboring piles creates additional mechanical stresses, which may result in the fracturing of the overhead pipe(s). For example, due to frost heave processes, about 8,000 pipeline supports had to be readjusted during 2007–2009 in the Yamburg region (West Siberia) alone. Subsurface pipelines suffer from intensive corrosion, heat loss associated with transportation of petroleum products, ground subsidence, and water logging. Subsidence can continue for more than a decade after the construction of trenches for underground cables and pipelines (Streever, 2012). Although it is rare in the North America, it is not uncommon to see floating pipelines in permafrost regions (Figure 10.9).

p0260 A study conducted in Yakutia analyzed 2,174 km of pipelines to classify deformations during 2000–2010. The authors found that permafrost conditions were responsible for only 3 percent of all deformations (Chuhareva and Tikhonova, 2012). However, if deformations due to operational maintenance are taken into account, this number reaches 17 percent, illustrating the indirect effects of permafrost changes. Other studies of pipeline deformations in West Siberia give a comparable value of 21 percent due to mechanical deformations, including those attributed to the decreased ability of piles to support structural weight. In West Siberia, there are 35,000 pipeline accidents occurring annually. The pipeline deformations commonly occur in locations where linear structures cross ice wedges and massive ice deposits (Stanilovskaya and Merzlyakov, 2013) (Figure 10.10). In Russia, 55 billion RUB are spent annually to maintain the operational stability of pipelines on permafrost (Streletskiy et al., 2012c). Considering that oil and gas development in the Arctic is likely to continue, aging infrastructure and projected climate change will increase the number of deformations and leaks from pipelines leading to the deterioration of ecosystems.

s0080 10.7.3 Railroads, Roads, and Utility on Permafrost

p0265 Permanent road networks on permafrost are likely to suffer from projected subsidence associated with melting ground ice. The projected increase in snow accumulation, and consequently larger volumes of redistributed snow off roads, will further enhance permafrost warming, resulting in the development



f0050 **FIGURE 10.9** Thermokarst development around the subsurface pipeline, Kharp (Yamal-Nenents Autonomous Okrug, Russia). Photograph by D. Streletskiy, July 2012.



f0055 **FIGURE 10.10** Above-ground pipeline in Northern Yakutia crossing the area with ice-rich permafrost. Photograph by A.N. Fedorov.

of thermokarst and waterlogged surfaces. Railroads can also suffer significant deformation due to differential frost heave and thaw settlement. Out of 3,539 km of Far East road in Siberia, 18 percent is deformed due to differential permafrost settlement. A similar situation is happening to the Baikal-Amur railroad where about 20 percent of the rail is deformed. The problem of railroad deformation in areas of ice-rich permafrost has been relevant not only in Russia but also in Alaska, Canada, and recently in China with the construction of the Qinghai-Tibetan railroad on warm permafrost (Kondratiev,

2013). About 550 out of 2,000 km of the Qinghai-Tibetan railroad was constructed on permafrost. A high operational speed of 100 km/h over the permafrost sections required innovative designs and construction methods. Some areas on warm permafrost required construction of rail track on elevated piping foundation using an extensive network of thermosiphons, as in the case of the *Trans-Alaska* pipeline. The presence of permafrost significantly increased the cost of the project, which was estimated on the order of 30 billion Yuan. Thermosiphons are used quite extensively to decrease permafrost temperature and to mitigate negative consequences of climate change or technogenic disturbances. However, the high price of thermosiphons and relatively small effective area (a few meters) can significantly increase the cost of construction and maintenance of linear infrastructure, including that of railroads and pipelines.

p0270 Large arctic countries heavily rely on winter roads and drivable ice pavements to supply communities in remote areas. As a result, many areas of the Canadian North and the Russian Arctic are land accessible only during winter. Several studies indicate that changes to the operational length of winter roads have already occurred. These changes, however, are not uniform across space. For example, some regions of East Siberia show an increase in the operational length of winter roads, whereas regions of intensive oil and gas exploration and development in West Siberia have experienced a significant decrease. Other economically vital regions with decreased overland accessibility include areas along the Yenesei River north of Igarka up to Dickson, around Cherskiy in North-Eastern Yakutia, and Pevek and Anadyr in Chukotka (Streletskiy et al., 2012a). A comprehensive study of the effects of climate change on transportation in Northern Canada concluded that a shorter winter road operational season will be compensated by longer navigation seasons on lakes and rivers during summer months (Lonergan et al., 1993). A decrease in winter road operation could also be offset by improved maritime transportation conditions in the Arctic (Stephenson et al., 2011).

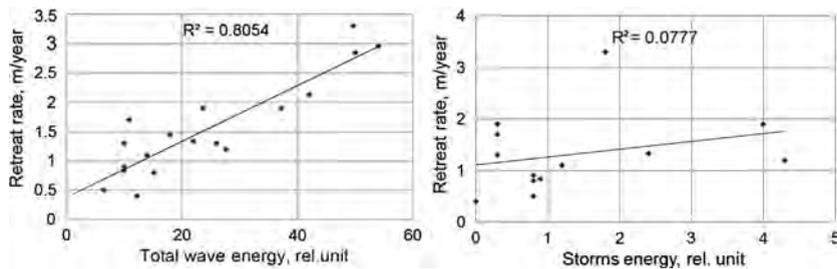
s0085 10.8 COASTAL EROSION AND PERMAFROST

p0275 The majority of Arctic settlements are located in the coastal zone. Increasing air and permafrost temperature, sea-ice retreat, and accelerating rates of coastal erosion can have highly detrimental impacts on arctic coastal communities. Arctic permafrost coasts are sensitive to climate changes due to the presence of sediments with high ice content. Degradation of Arctic coasts is one of the leading processes reflecting complex interactions between terrestrial and marine systems. Primarily, the destruction of coasts occurs due to the kinetic energy of waves and permafrost thawing. The entire suite of processes leading to the destruction of Arctic coasts is known as coastal erosion. Coastal erosion occurs only during the sea ice-free season. The formation of sea ice in the beginning of a cold season temporarily stops coastal erosion processes for

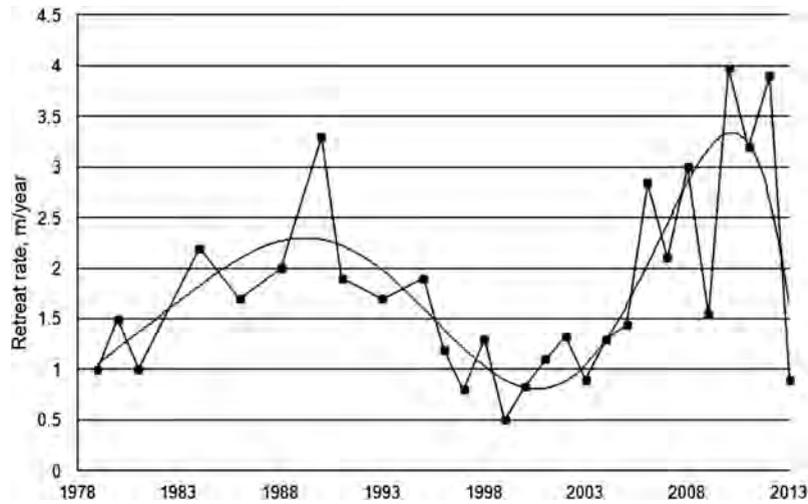
the duration of the land-fast ice until it opens enough again along the coastal zone allowing for wave action.

p0280 The main factors determining rates of coastal erosion in the Arctic include wave energy applied to the base of the coastal cliffs (wave erosion), and the thawing and mass wasting of sediments to the beach zone (thermal denudation). Strong storms are considered to play a leading role in coastal erosion. However, this is not always the case, such as in western part of the Russian Arctic where regular wave action at the base of the cliffs is considered to be the primary erosional agent. Persistent wave activity was found to be more effective at eroding the coasts compared to strong, but short wave activity associated with storm surges. Storm surges account for less than a quarter of annual wave energy. The role of storm activity in coastal erosion is shown in Figure 10.11, which demonstrates a strong dependence of coastal retreat rate on the total wave energy compared to the weak dependence of the rate of retreat and storm energy. Coastal retreat rates have high internal variability. Long-term monitoring of coastal erosion in the Barents and Kara Sea coasts (Vasiliev et al., 2005) showed that periods of high retreat rates alternate with periods of low retreat rates (Figure 10.12).

p0285 Retreat rates are quite variable throughout the Arctic, depending on climatic and geologic conditions that range from just a few centimeters per year to 30 m per year, but usually fall within 0.5–2 m/year (Forbes, 2011). The highest retreat rates are found in ice-complex (“edoma”) coasts composed of silty sediments with high ice content, up to 90 percent by volume. Minimal rates are characteristic for bedrock coasts with a low ice content. Spatial and temporal variabilities of coastal erosion rates in the Arctic are monitored under the umbrella of the Arctic Coastal Dynamics (ACD) project, initiated by the International Permafrost Association in 1999. Recently, the ACD group released the geomorphologic classification database for arctic coasts covering 101,500 km of coastline (Figure 10.13). Roughly 65 percent of arctic coasts are characterized by the presence of ground ice, such as the Beaufort, Laptev, and East Siberian coasts (Jones et al., 2009; Lantuit et al., 2012). The presence of various types of ground ice creates unique features of thermal–mechanical



f0060 **FIGURE 10.11** Dependence of coastal retreat rate at Western Yamal on total wave energy and storm energy.



f0065 **FIGURE 10.12** Temporal changes of retreat rates of Kara sea coasts (Western Yamal Peninsula example).



f0070 **FIGURE 10.13** Circum-Arctic map of coastal erosion rates. From Lantuit et al. (2012).

erosion, making the coasts especially vulnerable to changes in land–ocean and land–atmosphere fluxes.

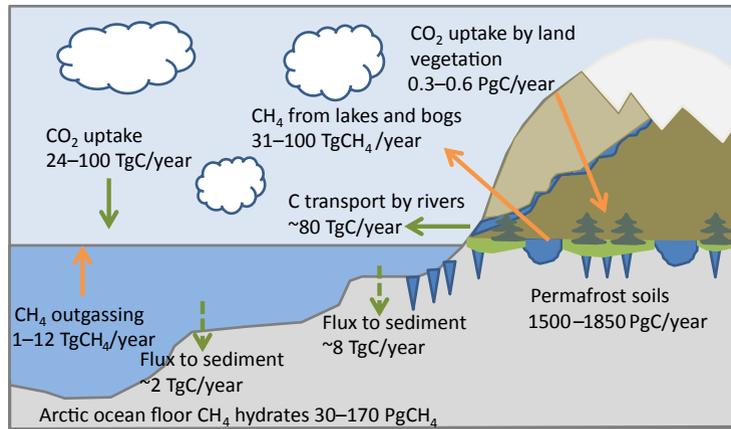
p0290 Climate change in the Arctic has resulted in increased air temperatures, decreased sea-ice extent, and a lengthened ice-free period. Although no direct effects between increasing air temperatures and coastal erosion rates have been found, the combined effect of climate change is likely to have caused the increased coastal erosion rates in the Arctic through the increased length of the ice-free period. The rough estimate of land loss along Arctic sea coasts can be computed using the total length of 101,500 km and the average retreat rate of 0.5 m/year (Lantuit et al., 2012). The resulting 51 km² gives an idea of the land lost annually, which is roughly equal to the size of a town such as the Swiss capital of Bern, or, over a two-year period, roughly equal to the size of Paris, the capital of France. Increased rates of coastal erosion have already resulted in a series of negative consequences for native settlements in Alaska and elsewhere. For example, Kivalina, a native settlement located in Northwest Alaska, is planning to be relocated due to coastal erosion. The estimated price for this relocation was 176 million USD (Wilson, 2007). Coastal erosion is also threatening oil terminals located in Varandei (Yamal, Russia). Industrial activity around Varandei Oil Field (Pechora Sea coast) has already led to intensified aeolian, mass wasting, and erosional processes along the coast, resulting in twice the rate of coastal retreat compared to a natural environment (Ogorodov, 2005). One of the major factors that played a role in increasing the rate of erosion was the excavation and removal of shoreline sediment for construction, which combined with vegetation degradation, led to increased ALT. Deeper thaw made sand dunes more susceptible to wind deflation and erosion.

p0295 Coastal erosion in permafrost regions supplies sediments and organic carbon to the sea in amounts comparable to organic carbon supplied by large rivers. Organic carbon is an important source of nutrients for sea biota in coastal zones (Lisitzin, 1999). One study estimated that the amount of material generated from coastal erosion dumped into the Kara Sea is about 35 million tons, including 0.4 million tons of organic carbon (Streletskaia et al., 2009).

p0300 Projected increases in air temperature and a subsequent decline in sea-ice extent will further promote coastal erosion as the duration and intensity of wave activity is likely to increase and the cohesion of permafrost coasts is likely to decrease. Intensified rates of coastal erosion will require additional costs to maintain existing and planned coastal infrastructure, and will lead to increased sedimentary and organic carbon input to the Arctic seas.

s0090 10.9 PERMAFROST AND THE CARBON CYCLE IN THE CONTEXT OF CLIMATE CHANGE

p0305 One of the relatively poorly studied natural hazards associated with changes in permafrost is the potential amplification of global warming through emission of greenhouse gases with implications for the climate-dependent systems and



f0075 **FIGURE 10.14** Major carbon pools and flows in the Arctic domain, including permafrost on land, continental shelves and ocean. Adapted from McGuire et al. (2009) and Tarnocai et al. (2009).

processes. The permafrost–climate feedback is described by the following conceptual model (Ciais and Sabine, 2013). Permafrost contains large amounts of carbon, of which the bulk was sequestered during the Holocene (Figure 10.14). Part of it is localized in the active layer and is involved in the annual carbon cycle, whereas the other part is trapped in frozen sediments on land and in the shelf of the Arctic seas. Climate change and rising temperature may have the twofold effect on terrestrial permafrost-carbon cycle by (1) thickening the active layer and increasing the portion of soil carbon stock involved in the seasonal cycle and (2) shifting the balance between the annual carbon sink and source. Thawing subaquatic permafrost may further enhance the climate feedback. It may lead to the increased gas permeability of the bottom sediments on the Arctic shelf, creating pathways for methane venting to the water column and to the atmosphere from deep layers, where it is currently stored in the form of gas hydrate. The strength of climate–permafrost feedback depends on the soil carbon pool; net fluxes, which are the balance between the sources and sinks of CO₂ and methane; and the sensitivity of climate to these two gases. Results from recent field studies and comprehensive carbon–permafrost models significantly reduced the uncertainty in quantifying the elements of this chain.

s0095 10.9.1 Permafrost Soil Carbon Pool

p0310 In the early 1990s, the carbon content in arctic soils was estimated to be 455 Pg, whereas the global content in the upper one meter of all terrestrial ecosystems totaled 1,400–1,600 Pg C (Oechel et al., 1993). More recent investigations showed that the upper 3 m of arctic soils hold about 750 Pg C

(Schuur et al., 2008). This estimate excluded arctic bogs, which according to Gorham (1991) store an additional 200–450 Pg C depending on the assumed thickness of average accumulated peat of 1 or 2.3 m McGuire et al. (2009), gave a slightly lower estimate of 270–370 Pg C in arctic bogs. Later work by Tarnocai et al. (2009) gave an estimate of 150 Pg C for Canadian Arctic bogs, which confirmed the estimates by Gorham (1991), as roughly one-third of arctic bogs are located in Canada.

p0315 Several studies of ice complex (“edoma”) occupying large areas in East Siberia showed that significant amounts of carbon can be stored much deeper than 3 m as sediments of edoma were syngenetically frozen allowing for the accumulation of carbon during sedimentation (Walter et al., 2007; Zimov et al., 2006). These findings increase the estimated carbon pool by 400 Pg C in the upper 25 m of edoma. An additional 250 Pg C are potentially stored in seven deltas of major Arctic rivers (Schuur et al., 2008). Summarizing these findings gives about 1,400 to 1,850 Pg C, including 1,000 Pg C in arctic soils to a depth of 25 m, 200–450 in bogs and 200–400 Pg C in the edoma of Siberia. These numbers are consistent with the 1,672 Pg estimate by Tarnocai et al. (2009), and constitute about half of the global carbon stored in soils worldwide. The majority of the terrestrial permafrost soil carbon occurs within the upper 3-m layer, which is most susceptible to thawing under projected climate change.

s0100 10.9.2 Carbon Fluxes in Terrestrial Permafrost Regions

p0320 The net carbon flux between the atmosphere and permafrost depends on the interplay of sink (photosynthetic uptake of CO₂ by Arctic vegetation) and source (release of CO₂ due to soil respiration and/or emission of methane due to biogenic production and release from hydrates). Earlier observational studies suggested the near-zero average carbon balance in the circumpolar Arctic with large spatial and interannual variations (Corradi et al., 2005). In contrast, models showed a small sink of about $20 \pm 40 \text{ g/cm}^2/\text{year}$, and a consensus was reached between models and observations that the Arctic acts as a net source of methane (Anisimov and Vaughan, 2007). Observational data summarized by Callaghan et al. (2011) confirmed these findings and provided more details suggesting that tundra regions currently act as sources of carbon in warm and dry years or in well-drained settings, and as sinks in cold and wet years. The most recent IPCC AR5 assessment concluded that permafrost regions are currently a net sink of CO₂ sequestering about $0.4 \pm 0.4 \text{ PgC/year}$, and a modest source of methane estimated to be 15–50 Tg(CH₄)/year, which is emitted mostly from seasonally thawing wetlands (Ciais and Sabine, 2013). Methane (CH₄) has an approximately 20 times stronger greenhouse effect than CO₂ has. Deeper seasonal thawing of permafrost will lead to the involvement of the previously frozen organic material in the annual carbon cycle, and in combination with the higher soil temperatures and longer warm season will

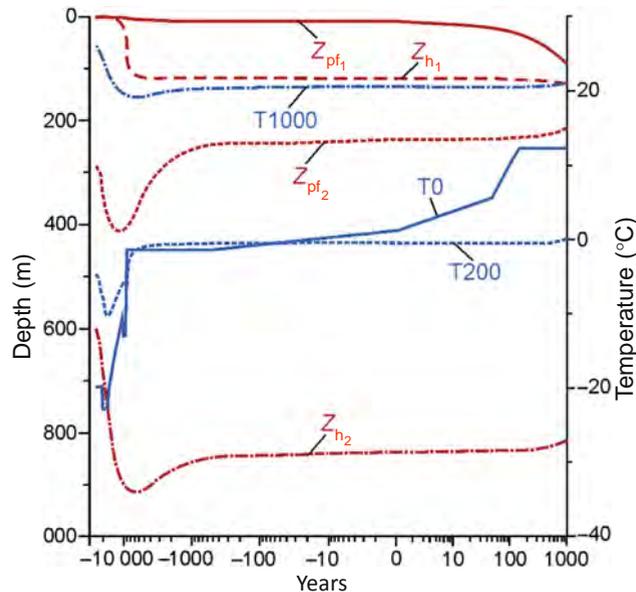
enhance the biogenic methane production, particularly in the organic-rich Arctic wetlands.

p0325 Although emissions from terrestrial permafrost are supposed to be gradual under conditions of climate change, the release of methane from hydrates underneath the subsea permafrost may potentially be abrupt. Higher-than average atmospheric methane concentrations occur around the continental shelves of East Siberian Seas (ESS), which could have been attributed to local methane sources, including those associated with decomposition of methane hydrates underneath the sea bottom (Shakhova et al., 2010). Because the ESS average depth is only 45 m, a significant portion of methane is able to reach the atmosphere without oxidation, which would be the case for a deeper water column. Total methane emission at ESS under current conditions is estimated at 7.9 Tg(CH₄)/year, which is relatively small compared to other sources (Shakhova et al., 2010).

s0105 10.9.3 The Effect on Global Climate

p0330 The impact of enhanced methane emissions from thawing permafrost on global temperature may be evaluated either by running the full-scale hydrodynamic climate model, or by calculations using climate sensitivity to greenhouse gases, that are relatively well known. The latter approach was used in several studies to assess the effects in terrestrial and subaquatic permafrost regions. All studies involved a comprehensive dynamic permafrost–carbon model (Anisimov et al., 2012b; Lavrov and Anisimov, 2011). A modeling study of carbon fluxes from Russian Arctic bogs found that increased methane emissions of the order of 0.008–0.01 Pg C per year could occur by mid-twenty-first century under the most extreme climatic scenario (Anisimov and Reneva, 2011). It would result in an average increase of atmospheric methane concentrations by 0.04 ppm, with a corresponding increase in the average global annual temperature by 0.012 °C, at most (Anisimov et al., 2012a; Dmitrenko et al., 2011). Modeling also indicated that in the following few centuries it is very unlikely that thawing of submarine permafrost in the East Siberian shelf will increase perforation and gas permeability of the frozen bottom sediments (Anisimov et al., 2012a; Dmitrenko et al., 2011). Except for selected permafrost-free locations near fault zones, gas hydrates in deep layers will remain trapped beneath the layer of the frozen sediments (Figure 10.15).

p0335 It would be appropriate to add that due to the absence of robust data some highly speculative sensational hypotheses have been suggested, as exemplified by the paper of Whiteman et al. (2013). These authors assessed the combined economic effect of an enhanced methane flux to the atmosphere. According to their estimate, the release of methane from thawing permafrost in the East Siberian Sea alone will cost 60 trillion USD to the global economy, which is comparable to the entire world economy (70 trillion USD in 2012). These authors concluded that 80 percent of economic consequences will occur in the

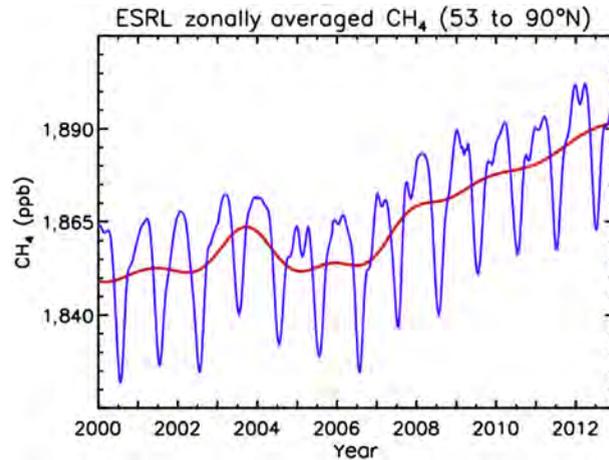


f0080 **FIGURE 10.15** Modeled depths to upper (index 1) and lower (index 2) boundaries of permafrost (Z_{pf}) and methane hydrate stability zone (Z_h), and temperatures at 0, 200, and 1000 m depths on the time interval from the last glacial maximum 18,000 years ago to the year 3000. X-axis designates time in logarithmic scale from before and after the contemporary period, 0 corresponds to the year 2000. From *Anisimov et al. (2012a)*.

developing countries of Africa, Asia, and South America. According to their model, a release of 50 Pg of methane from the shelf may increase the mean global temperature by 2 °C by 2035–2040. However, these dramatic projections are not supported by real data, and the model used in this study proves to be highly unrealistic. The recent IPCC assessment report analyzed the full set of available observational and model data and estimated the total amount of methane trapped in the hemispheric-scale Arctic shelves at 2–65 PgCH₄ (*Ciais and Sabine, 2013*); observations in the Arctic show that so far methane concentrations in the atmosphere are rising gradually and not abruptly (*Figure 10.16*); and comprehensive permafrost-carbon modeling results referenced above leave no space for such speculative judgments.

s0110 10.10 SUMMARY

p0340 Permafrost plays an important role in global climate, environmental systems, and human activities in the Arctic. Permafrost degradation has occurred many times throughout geological history, but the rate of climate change, presence of substantial population, and diverse economic and landuse activities in the Arctic, make contemporary permafrost degradation a unique process. The impacts of permafrost degradation are diverse and range from local to global,



f0085 **FIGURE 10.16** Methane mole fraction averaged over polar northern latitudes (blue). The red line is the deseasonalized trend. From Bruhwiler and Dlugokencky (2012).

such as the potential enhancement of climatic change through emission of greenhouse gases. Observational data on permafrost characteristics are limited, but show permafrost temperature is increasing, whereas the active layer is progressively thickening in the majority of regions. Although climate change is the main driver of permafrost changes, other environmental characteristics may significantly alter these general trends.

p0345 Natural landscapes, but more importantly areas of human activities, including large population and industrial centers, are facing numerous hazards associated with permafrost degradation, such as melting of ground ice, thaw subsidence, and thermokarst development; decrease of foundation stability and increase of corrosion of foundation materials; intensification of slope processes and coastal erosion. Although permafrost changes are already taking their toll on various types of infrastructure, numerous studies have showed that permafrost degradation will continue in the future. A series of planning activities and engineering solutions (e.g., thermosiphons) are capable of mitigating permafrost degradation to a certain extent and preventing immediate hazards to existing infrastructure. Climate change should be taken into account more seriously, when constructing on permafrost. More research is needed to develop informed and adequate adaptation and mitigation strategies with regard to land use and infrastructure. The limited permafrost observational network should be expanded to serve these needs.

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Non-Print Items



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