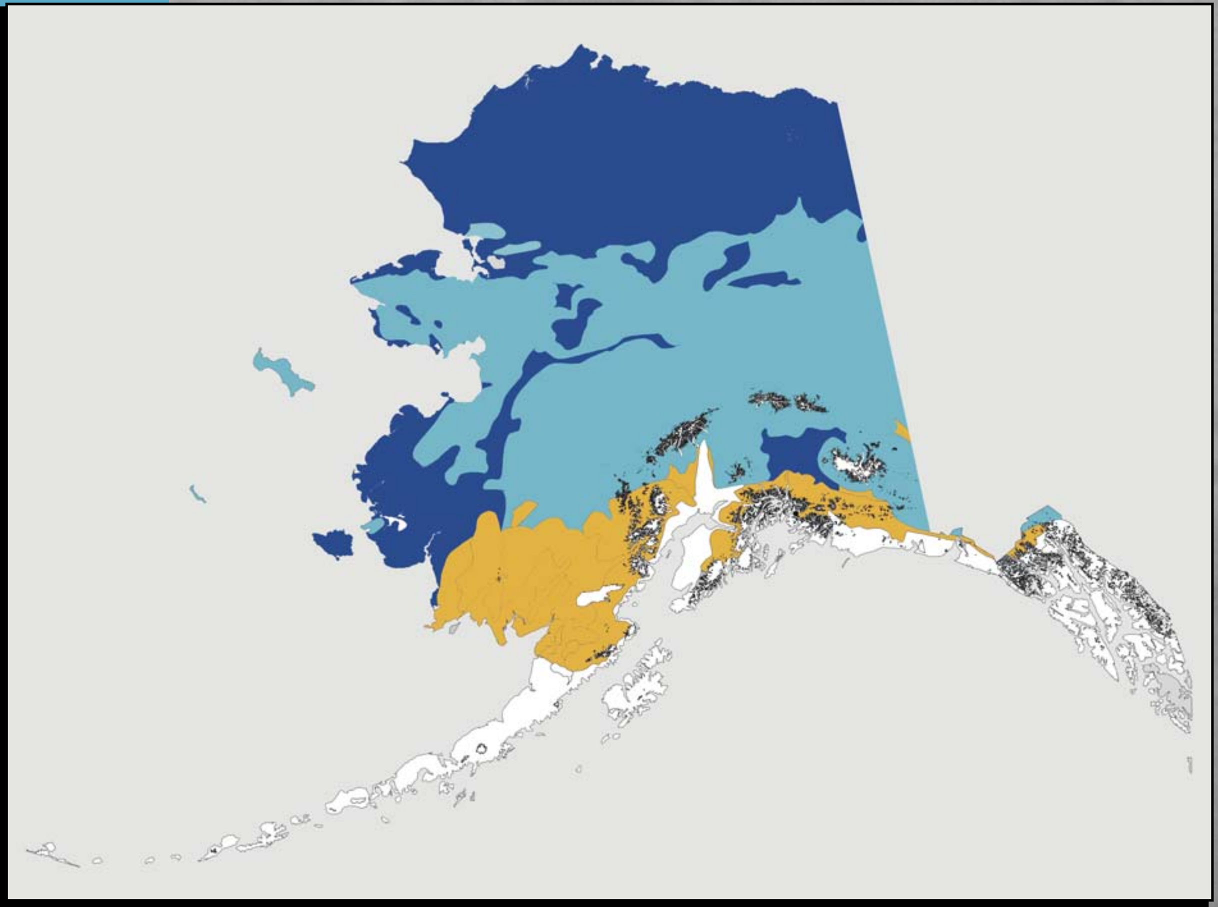
Climate Change, Permafrost, and Impacts on Civil Infrastructure



U.S. Arctic Research Commission

Permafrost Task Force Report

December 2003

Special Report 01-03

Executive Summary

Permafrost, or perenially frozen ground, is a critical component of the cryosphere and the Arctic system. Permafrost regions occupy approximately 24% of the terrestrial surface of the Northern Hemisphere; further, the distribution of subsea permafrost in the Arctic Ocean is not well known, but new occurrences continue to be found. The effects of climatic warming on permafrost and the seasonally thawed layer above it (the active layer) can severely disrupt ecosystems and human infrastructure such as roads, bridges, buildings, utilities, pipelines, and airstrips. The susceptibility of engineering works to thaw-induced damage is particularly relevant to communities and structures throughout northern Alaska, Russia, and Canada. It is clear from the long-term paleographic record in these areas that climatic warming can lead to increases in permafrost temperature, thickening of the active layer, and a reduction in the percentage of the terrestrial surface underlain by near-surface permafrost. Such changes can lead to extensive settlement of the ground surface, with attendant damage to infrastructure.

To advance U.S. and international permafrost research, the U.S. Arctic Research Commission in 2002 chartered a task force on climate change, permafrost, and infrastructure impacts. The task force was asked to identify key issues and research needs to foster a greater understanding of global change impacts on permafrost in the Arctic and their linkages to natural and human systems. Permafrost was found to play three key roles in the context of climatic changes: as a record keeper (temperature archive); as a translator of climatic change (subsidence and related impacts); and as a facilitator of climatic change (impact on the global carbon cycle). The potential for melting of ice-rich permafrost constitutes a significant environmental hazard in high-latitude regions. The task force found evidence of widespread warming of permafrost and observations of thawing —both conditions have serious, long-term implications for Alaska's transportation network, for the Trans-Alaska Pipeline, and for the nearly 100,000 Alaskan citizens living in areas of permafrost. Climate research and scenarios for the 21st century also indicate that major settlements (such as Nome, Barrow, Inuvik, and Yakutsk) are located in regions of moderate or high hazard potential for thawing permafrost. A renewed and robust research effort and a well-informed, coordinated response to impacts of changing permafrost are the responsibilities of a host of U.S. federal and state organizations. Well-planned, international polar research, such as the International Polar Year, is urgently needed to address the key scientific questions of changing permafrost and its impacts on the carbon cycle and overall global environment.

Key task force recommendations include: review by funding agencies of their interdisciplinary Arctic programs to ensure that permafrost research is integrated in program planning and execution; development of a long-term permafrost research program by the U.S. Geological Survey; enhanced funding for permafrost research at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory; adoption of the Global Hierarchical Observing Strategy in all permafrost monitoring programs; development of a high-resolution permafrost map of Alaska, including the offshore; development of new satellite sensors optimized for monitoring the state of the surface, temperature, moisture, and ground ice; full incorporation of permafrost hydrology, hydrogeology, and geomorphology in new Arctic research programs of the U.S. National Science Foundation; incorporation of permafrost research in all U.S. and international programs devoted to the global carbon cycle; enhanced and long-term funding for the U.S. Frozen Ground Data Center; and substantially increased federal funding for contaminants research in cold regions, including studies on the impacts of regional warming, predictive modeling, and mitigation techniques.

The task force report makes specific recommendations to eight U.S. federal agencies, the State of Alaska, and the U.S. National Research Council. Many of the recommendations will be incorporated in future Arctic research planning documents of the Commission, including its biennial *Report on Goals and Objectives*. The task force report will also be presented to the U.S. Interagency Arctic Research Policy Committee and to appropriate international bodies, including the International Arctic Science Committee and the Arctic Council.

Cover: Map of permafrost zonation in Alaska (modified from Brown et al., 1997, 1998). Dark blue: zone of continuous permafrost. Light blue: zone of discontinuous permafrost. Yellow: zone of sporadic permafrost. Background shows a network of active ice-wedge polygons on the North Slope of Alaska.

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REFERENCE CITATION

U.S. Arctic Research Commission Permafrost Task Force (2003) *Climate Change, Permafrost, and Impacts on Civil Infrastructure.* Special Report 01-03, U.S. Arctic Research Commission, Arlington, Virginia.

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MESSAGE FROM THE CHAIR

This report on *Climate Change, Permafrost, and Effects on Civil Infrastructure* is the result of the outstanding efforts of a team of experts serving as Special Advisors to the Arctic Research Commission. The Commissioners authorized this report in order to bring the Nation's attention to the connections between climate change research and the changes to civil infrastructure in northern regions that will come about as permafrost changes.

The Commission believes strongly that basic research has important connections to the way our citizens live and work. The study of climate change is an interesting discipline, but it is important to carry the results and predictions of these changes through to their effects on roads, bridges, buildings, ports, pipelines, and other infrastructure. This report suggests future research programs for the federal agencies, programs that the Commission will incorporate into our recommendations to the Interagency Arctic Research Policy Committee in our biennial *Report on Goals and Objectives for Arctic Research.*

The Commission is grateful for the effort and enthusiasm of the Task Force on Climate Change, Permafrost, and Civil Infrastructure and commends their efforts. Without this voluntary effort by the community of researchers, the Commission would be unable to help the residents of the North to cope with the changing and occasionally extreme environment in which they live.

George B. Newton, Jr.
Chair

Climate Change, Permafrost, and Impacts on Civil Infrastructure

Contents

Chapter 1

PERMAFROST AND ITS ROLE IN THE ARCTIC

1.1 Introduction

Climate-change scenarios indicate that human-caused, or *anthropogenic*, warming will be most pronounced in the high latitudes. Empirical evidence strongly indicates that impacts related to climate warming are well underway in the polar regions (Hansen et al., 1998; Morison et al., 2000; Serreze et al., 2000; Smith et al., 2002). These involve air temperature (Pavlov, 1997; Moritz et al., 2002), vegetation (Myneni et al., 1997; Sturm et al., 2001), sea ice (Bjorgo et al. 1997), the cumulative mass balance of small glaciers (Dyurgerov and Meier, 1997; Serreze et al., 2000; Arendt et al., 2002), ice sheets and shelves (Vaughan et al., 2001; British Antarctic Survey, 2002; Rignot and Thomas, 2002), and ground temperature (Lachenbruch and Marshall, 1986; Majorowicz and Skinner, 1997).

Many of the potential environmental and socioeconomic impacts of global warming in the high northern latitudes are associated with *permafrost*, or perennially frozen ground. The effects of climatic warming on permafrost and the seasonally thawed layer above it (the *active layer*) can severely disrupt ecosystems and human infrastructure and intensify global warming (Brown and Andrews, 1982; Nelson et al., 1993; Fitzharris et al., 1996; Jorgenson et al., 2001). Until recently, however, permafrost has received far less attention in scientific reviews and media publications than other cryospheric phenomena affected by global change (Nelson et al., 2002).

Throughout most of its history, permafrost science in western countries was idiosyncratic, performed by individuals or small groups of researchers, and not well integrated with other branches of cold regions research. Owing to the importance of permafrost for development over much of its territory, the situation in the former Soviet Union was distinctly different, with a large institute in Siberia and departments in the larger and more prestigious universities devoted exclusively to permafrost research.

Several factors converged in the late 1980s and early 1990s to integrate permafrost research into the larger spheres of international, systems, and global-change science:

- Easing of Cold-War tensions facilitated interactions between Soviet and western scientists. Conferences held in Leningrad (Kotlyakov and Sokolov, 1990), Yamburg, Siberia (Tsibulsky, 1990), and Fairbanks (Weller and Wilson, 1990) during the late 1980s and early 1990s were instrumental in achieving international agreements.
- Publicity about the impacts of climate warming in the polar regions followed several decades of unprecedented resource development in the Arctic and raised concerns about the stability of the associated infrastructure (Vinson and Hayley, 1990).
- The global nature of climate change made apparent the need for widespread cooperation, both within the permafrost research community and between permafrost researchers and those engaged in other branches of science (Tegart et al., 1990).
- Permafrost scientists became increasingly aware of the benefits accruing from the development of data archives and free exchange of information (Barry, 1988; Barry and Brennan, 1993). Moreover, the increasingly integrated nature of arctic science

The Ground Temperature Profile

Figure 1 shows a typical temperature profile through permafrost, from the ground surface to the base of the permafrost. Higher temperatures are to the right and lower to the left; 0°C is represented as a dashed vertical line. The heavier curves show current conditions. The summer profile curves to the right, indicating above-freezing temperatures near the ground surface. The winter profile curves to the left, indicating that the lowest temperatures are experienced at the surface, with higher temperatures deeper in the permafrost. The summer and winter profiles intersect at depth; below this point, temperatures are not affected by the seasonal fluctuations at the surface. The ground warms gradually with depth in response to the geothermal gradient. The base of the permafrost is situated where the temperature profile crosses 0°C. The *active layer* is a layer of earth material between the ground surface and the permafrost table that freezes and thaws on an annual basis.

In its simplest approximation, climate warming can be envisioned as a shift of the temperature profile to the right, as shown by the gray curves. The surface temperatures in summer and winter are higher, the active layer is thicker, and the mean annual temperature at the thermal damping depth is higher. In time, the base of the permafrost thaws and moves toward the surface. Thus, the permafrost body warms and thins as thaw progresses both above and below.

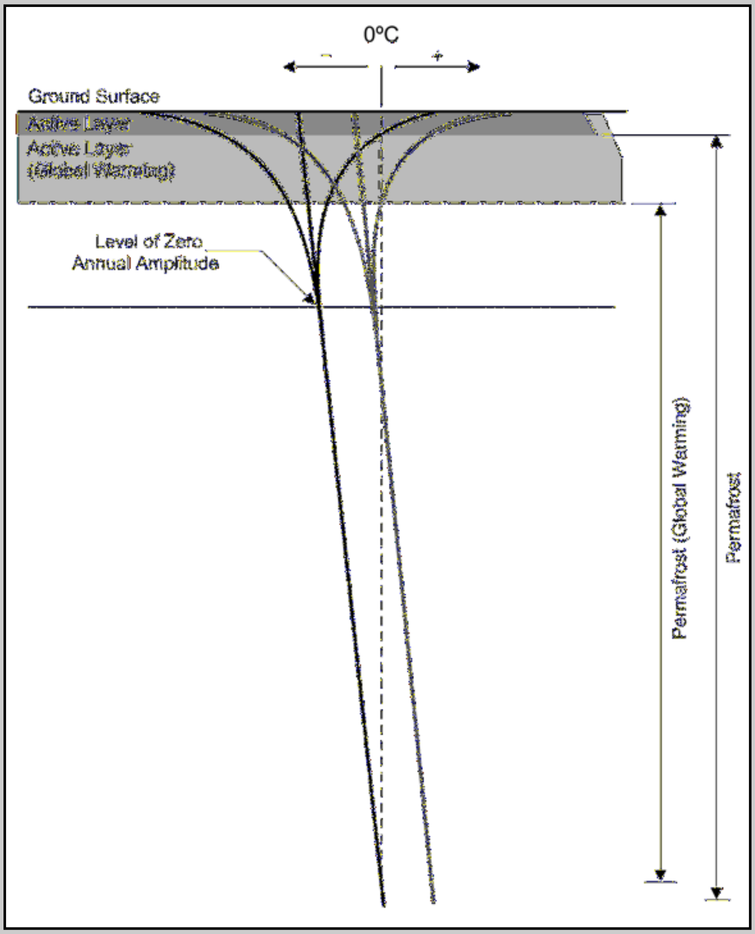


Figure 1. Ground temperature profile.

demands widespread cooperation and collaboration. Some funding agencies, such as the U.S. National Science Foundation, now require, as a condition of funding, that data be made accessible to all interested parties.

U.S. scientists have made major contributions to the study of frozen ground (*geocryology*), particularly since World War II. Useful English-language reviews, many with emphasis on Alaska, have been provided by Muller (1947), Black (1950), Terzaghi (1952), Stearns (1966), Ives (1974), Washburn (1980), Andersland and Ladanyi (1994), Davis (2001), and Hallet et al. (2004). Péwé (1983a) reviewed the distribution of permafrost in the cordillera of the western U.S.; Walegur and Nelson (2003) discussed its occurrence in the northern Appalachians. Péwé (1983c) outlined the distribution of permafrost and associated landforms in the U.S. during the last continental glaciation.

Permafrost science employs a complex and occasionally confusing lexicon derived from several languages and scientific disciplines. A brief Glossary and a List of Acronyms at the end of this document provide assistance for navigating unfamiliar terminology. A more comprehensive glossary, published under the auspices of the International Permafrost Association (IPA), is readily available (van Everdingen, 1998).

1.2 Background and Concepts

1.2.1 Thermal Regime

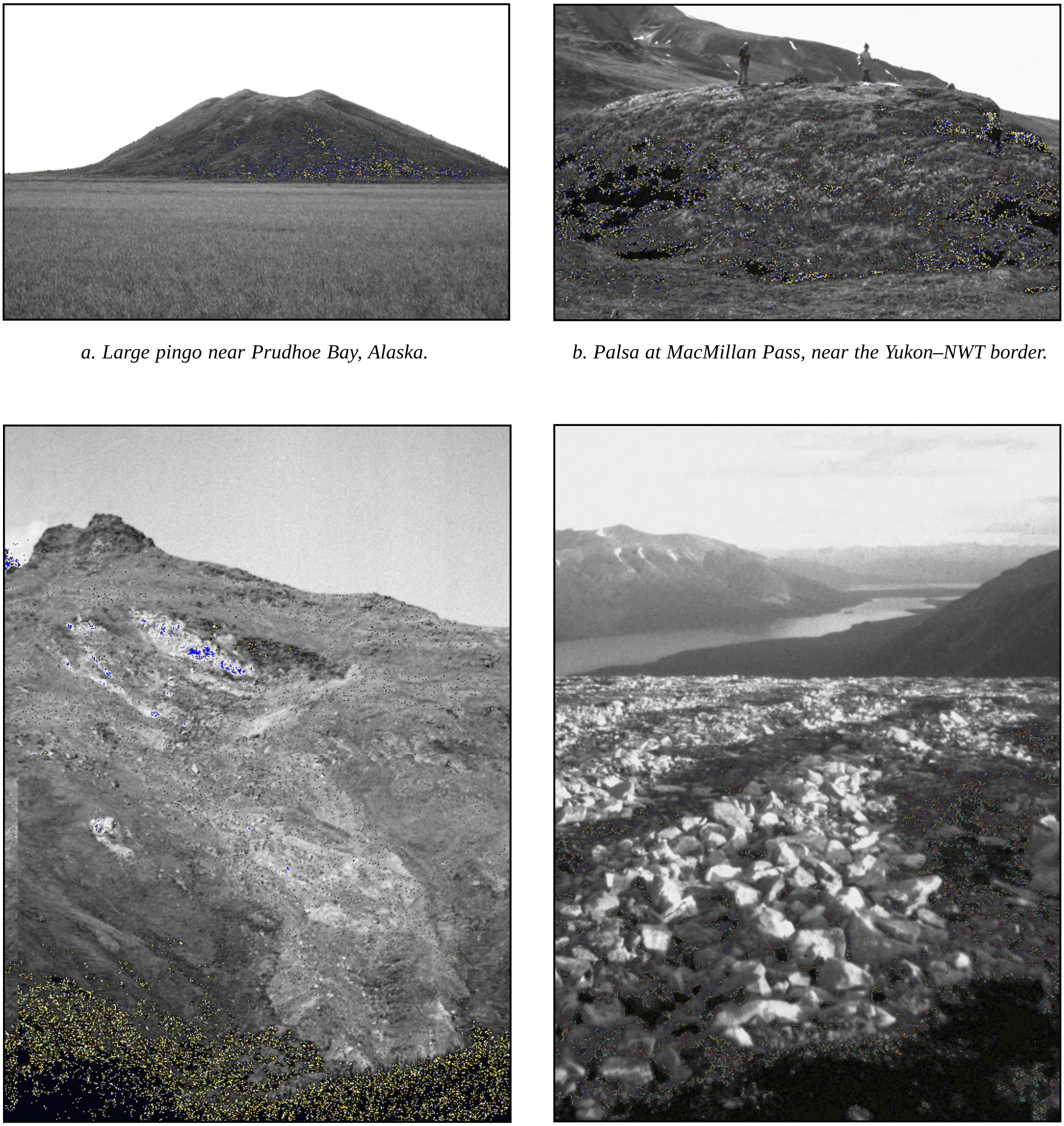
Two classes of frozen ground are generally distinguished: *seasonally frozen ground*, which freezes and thaws on an annual basis, and *perennially frozen ground* (permafrost), defined as any subsurface material that remains at or below 0ºC continuously for at least two consecutive years. The term *permafrost* is applied without regard to material composition, phase of water substance, or cementation. Permafrost can be extensive in areas where the mean annual temperature at the ground surface is below freezing. Because the temperature at the surface and the temperature in the air often differ substantially (Klene et al., 2001), and because of differences in the thermal conductivity of many soils in the frozen and unfrozen states (the *thermal offset*), permafrost can exist for extended periods at locations with mean annual air temperatures above 0ºC (Goodrich, 1982). Climate statistics do not, therefore, provide a reliable guide to the details of permafrost distribution. Although ultimately a climatically determined phenomenon, the presence or absence of permafrost is strongly influenced by local factors, including microclimatic variations, circulation of ground water, the type of vegetation cover, and the thermal properties of subsurface materials.

The range of temperatures experienced annually at the ground surface in typical permafrost terrain decreases with depth, down to a level at which only minute annual temperature variation occurs, termed the damping depth or *level of zero annual amplitude*. The active layer above permafrost often experiences complex heat-transfer processes (Hinkel et al., 1997; Kane et al., 2001). Below the *permafrost table*—the upper limit of material that experiences a maximum annual temperature of 0ºC—heat transfer occurs largely by conduction. In situations where, unlike Figure 1, the bottom of the active layer is not in direct contact with the top of the permafrost, the permafrost is a relic of a past colder interval and may be substantially out of equilibrium with the contemporary climate.

1.2.2 Landforms

Many distinctive landforms exist in permafrost regions, although only some unambiguously indicate the presence of permafrost. Surface features formed under cold, nonglacial conditions are known as *periglacial landforms* (Washburn, 1980; French, 1996) (Fig. 2). One periglacial feature that serves as a good indicator of the presence of permafrost is *ice wedges*—vertical ice inclusions created when water produced from melting snow seeps into cracks formed in fine-grained sediments during severe cold-weather events earlier in winter. Repeated many times over centuries or millennia, this process produces tapered wedges of foliated ice more than a meter wide near the surface and extending several meters or more into the ground. Viewed from the air, networks of ice wedges form striking polygonal patterns over extensive areas of the Arctic (Lachenbruch, 1962, 1966). Other landforms diagnostic of the presence of permafrost are *pingos*—ice-cored hills frequently over 10 m in height that can form when freezing fronts encroach from several directions on saturated sediments remaining after drainage of a deep lake (Mackay, 1998). *Palsas*—smaller, mound-shaped forms often found in subarctic peatlands—can form through a variety of mechanisms (Nelson et al., 1992).

Other periglacial landforms occur frequently in association with permafrost but are not necessarily diagnostic of its presence. When *ice-rich permafrost* or another impermeable layer prevents infiltration of water, the soil on a hillside may become vulnerable to a slow, flow-like process known as *solifluction*, giving rise to a network of lobes and terraces that impart a crenulated or festooned appearance to the slope. Other small landforms frequently encountered in subpolar and polar regions, collectively referred to as *patterned ground*, include small



a. Large pingo near Prudhoe Bay, Alaska.

b. Palsa at MacMillan Pass, near the Yukon–NWT border.

c. Detachment slide in the Brooks Range foothills.

d. Large-diameter sorted patterned ground, Cathedral Massif, northwestern British Columbia.

Figure 2. Periglacial landforms often associated with permafrost.

hummocks and networks of striking geometric forms arranged into circles, polygons, or stripes of alternating coarse- and fine-grained sediment.

1.2.3 Permafrost Distribution

The permafrost regions occupy approximately 24% of the terrestrial surface of the Northern Hemisphere (Brown et al., 1997; Zhang et al., 1999, 2003). Substantial areas of subsea permafrost also occur around the land margins of the Arctic Ocean, much of it ice rich (Brown et al., 1997; Danilov et al., 1998). The distribution of offshore permafrost is not well known, and new occurrences are found frequently. As shown in Figure 3, the distribution of permafrost is often classified on the basis of its lateral continuity. In the Northern Hemisphere the various classes form a series of

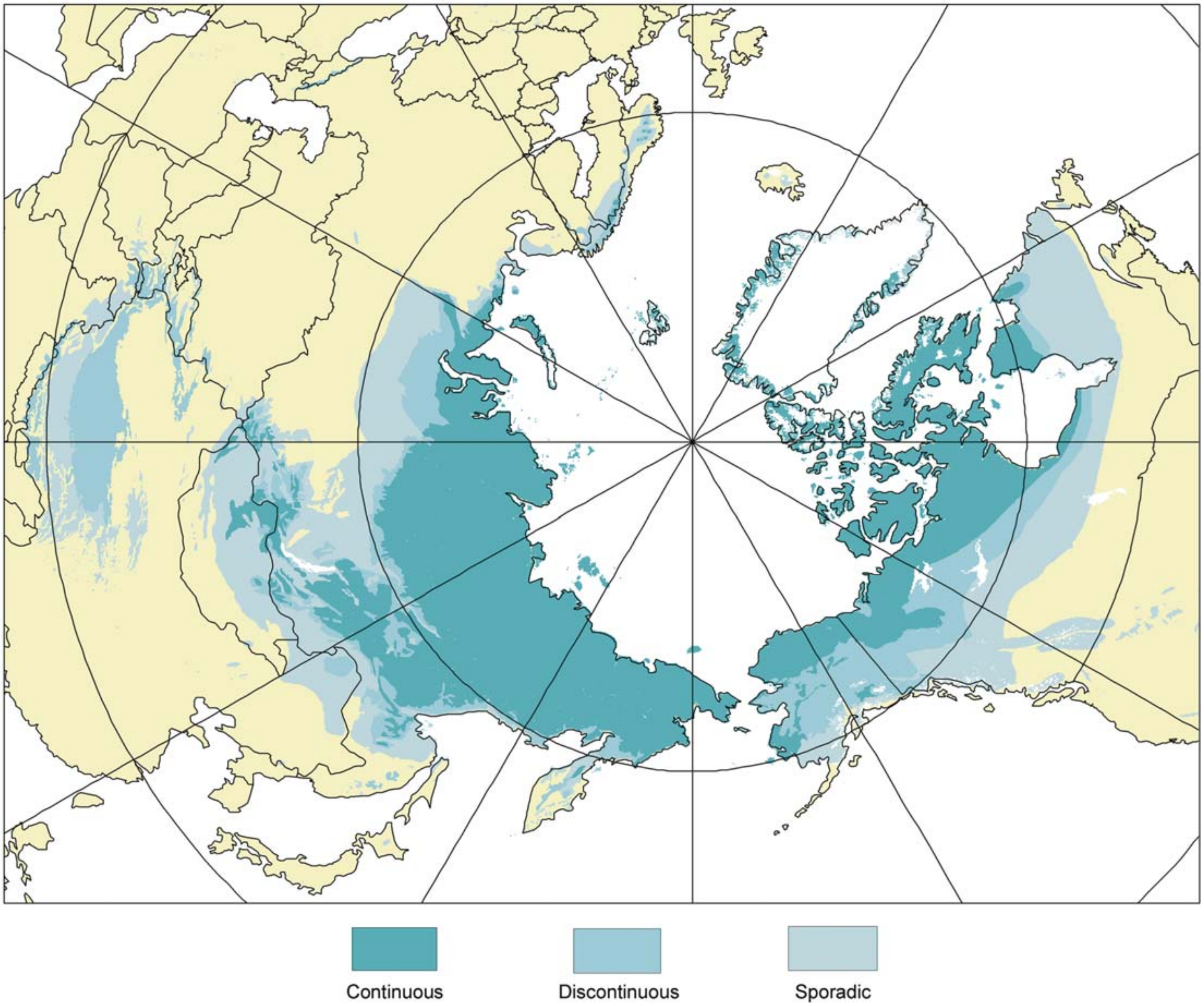


Figure 3. Permafrost zonation in the Northern Hemisphere. Zones are defined on the basis of percentage of land surface underlain by permafrost: continuous zone, 90–100%; discontinuous zone, 50–90%; sporadic zone, 10–50%; isolated patches, 0–10%. The 1997 map on which this figure is based is the first detailed document to show permafrost distribution in the Northern Hemisphere based on standardized mapping criteria. [After Nelson et al. (2002) adapted from Brown et al. (1997, 1998).]

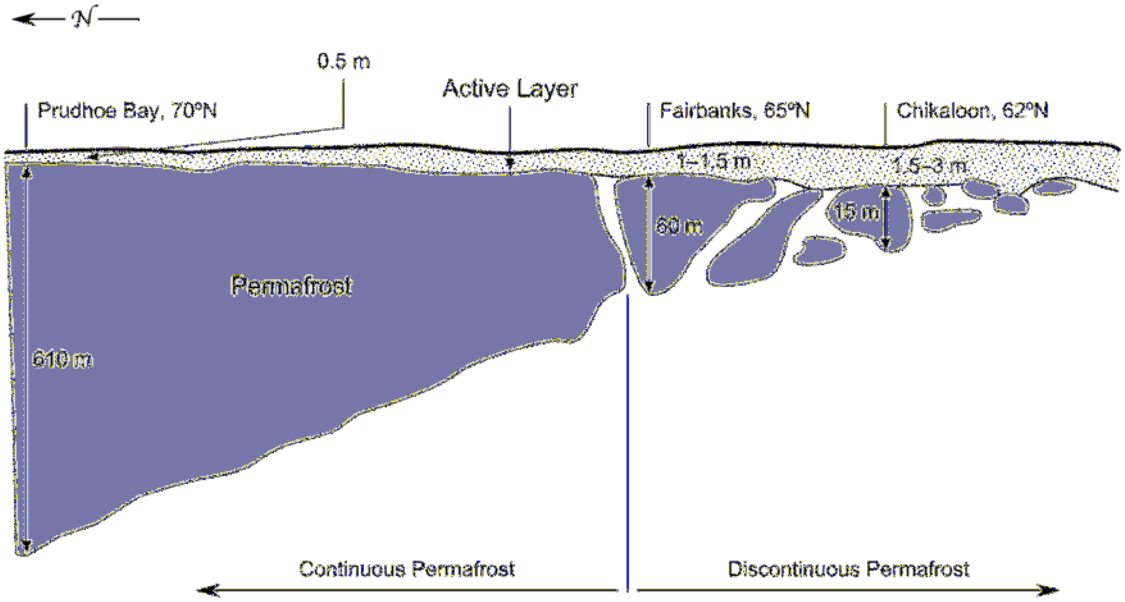


Figure 4. Latitudinal profile through the permafrost zones in Alaska, extending from the vicinity of Chikaloon in the Interior to Prudhoe Bay near the Arctic Ocean. Near the southern boundary, where the average annual temperature is around 0°C, isolated permafrost bodies may exist sporadically at depth. As the mean annual temperature decreases with increasing latitude, discontinuous permafrost bodies become larger and thicker, existing where local conditions are favorable, for example, on north-facing slopes. At average annual temperatures around –5°C, permafrost in Alaska is essentially continuous, and in northern Alaska it extends to depths of over 400 m, although local unfrozen zones (taliks) may exist beneath large rivers and lakes. The active layer can be quite thick in the sporadic permafrost zone, and it decreases in thickness with latitude, although local factors can make it highly variable (Nelson et al., 1999). Near the coast of the Arctic Ocean the active layer reaches a maximum mean thickness of only about 60 cm in mid- to late August.

concentric zones that conform crudely to the parallels of latitude (Fig. 4). Southward deviations in the extent of permafrost in Siberia and central Canada are a response to lower mean annual temperatures in the continental interiors.

In the *zone of continuous permafrost*, perennially frozen ground underlies most locations, the primary exception being under large bodies of water that do not freeze to the bottom annually. In the *discontinuous zone*, permafrost may be widespread, but a substantial proportion of the land surface can be underlain by seasonally frozen ground, owing to variations in such local factors as vegetation cover, snow depth, and the physical properties of subsurface materials. Some authors also refer to a zone in which permafrost is *sporadic*, occurring as isolated patches that reflect combinations of local factors favorable to its formation and maintenance. Because the thermal properties of peat are conducive to the existence of frozen ground, subarctic bogs are the primary locations of permafrost in southerly parts of the subarctic lowlands (Zoltai, 1971; Beilman and Robinson, 2003). In the Southern Hemisphere, permafrost occurs in ice-free areas of the Antarctic continent and in some of the subantarctic islands (Bockheim, 1995). Permafrost is also extensive in such midlatitude mountain ranges as the Rockies, Andes, Alps, and Himalayas, a response to progressively lower mean annual temperatures at higher elevations. Given sufficient altitude and favorable local conditions, patches of permafrost can exist even in the subtropics, such as in the crater of Mauna Kea (4140 m above sea level) on the island of Hawaii (Woodcock, 1974).

The thickness of permafrost is determined by the mean annual temperature at the ground surface, the thermal properties of the substrate, and the amount of heat flowing from the earth's interior. Permafrost thicknesses range from very thin layers only a few centimeters thick to about 1500 m in unglaciated areas of Siberia (Washburn, 1980). In general, the thickness of lowland permafrost increases steadily with increasing latitude.

1.2.4 Ground Ice and Thermokarst

Although the presence of ice is not a criterion in the definition of permafrost, ground ice is responsible for many of the distinctive features and problems in permafrost regions. Ice can occur within permafrost as small individual crystals within soil pores, as lenses of nearly pure ice parallel to the ground surface, and as variously shaped intrusive masses formed when water is injected into soil or rock and subsequently frozen. The origin and morphology of ground ice are varied (Mackay, 1972), ranging from thick layers of buried glacier ice, through horizontally oriented ice lenses formed by the migration of moisture to freezing fronts (*segregation ice*), to the distinctive polygonal networks of vertical veins known as *ice wedges*. If their thermal stability is preserved, perennially frozen ice-bonded sediments can have considerable bearing capacity and are often an integral part of engineering design in cold regions (Andersland and Ladanyi, 1994; Yershov, 1998). Figure 5 shows the generalized distribution of ground ice in the Northern Hemisphere. A digital database on ground ice is under development at Moscow State University (Streletskaya et al., 2003).

Changes in the thickness and geographical extent of permafrost have considerable potential for disrupting human activities if substantial

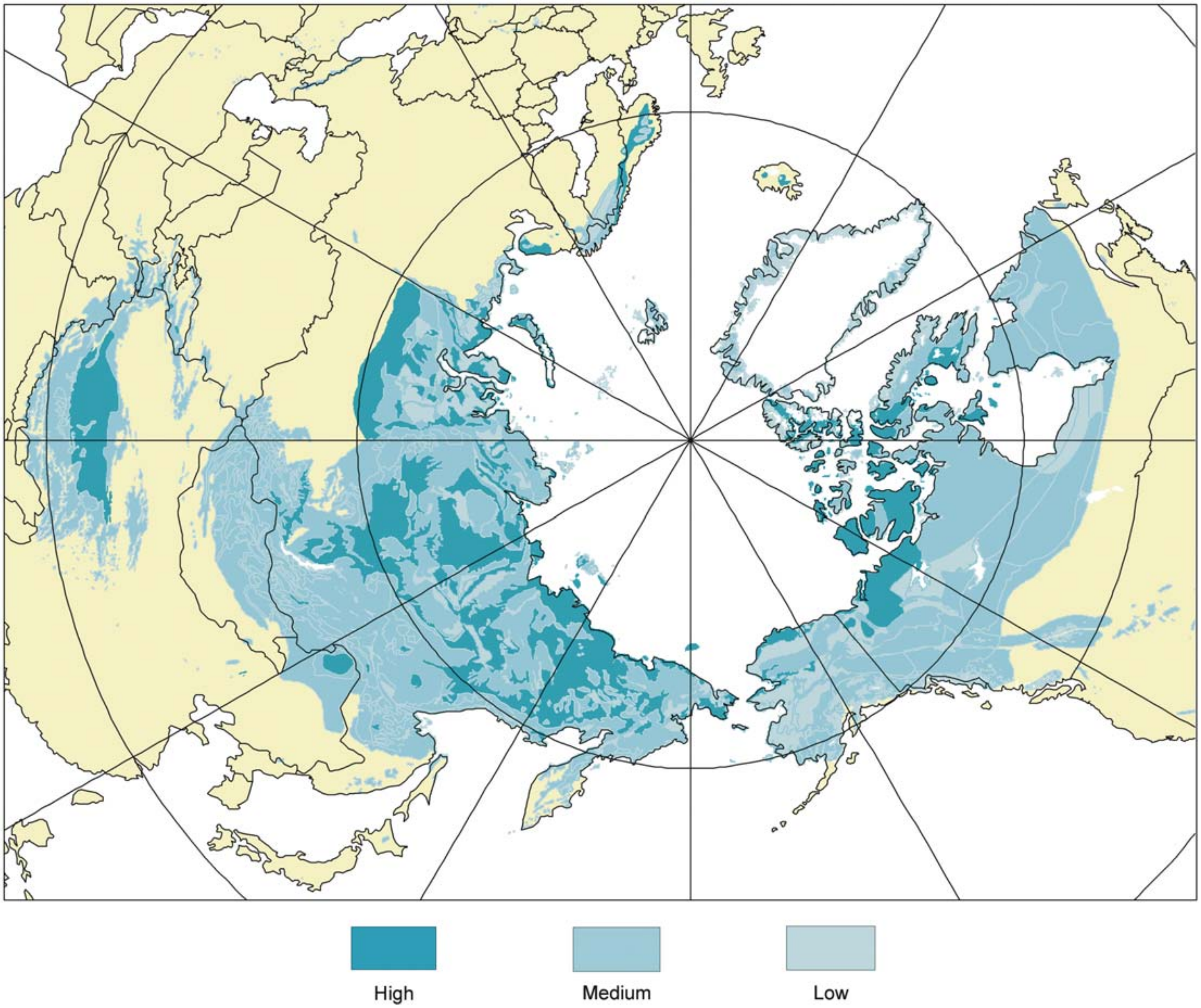


Figure 5. Generalized distribution of ground ice in the Northern Hemisphere. Ground-ice content is expressed on a relative volumetric basis: low: 0–10%; medium: 10–20%; high: >20%. Ice-cored landforms of limited extent (e.g., pingos) are not shown. [From Nelson et al. (2002) and adapted from Brown et al. (1997, 1998).]

Thermokarst and Ground Subsidence

Thickening of the active layer has two immediate effects. First, decomposed plant material frozen in the upper permafrost thaws, exposing the carbon to microbial decomposition, which can release carbon dioxide and methane to the atmosphere. Second, the ice in the upper permafrost is converted to water. In coarse materials such as sand and gravel, this is not necessarily a problem. However, fine-grained sediments often contain excess ice in the form of lenses, veins, and wedges. When ice-rich permafrost thaws, the ground surface subsides; this downward displacement of the ground surface is termed *thaw settlement* (Fig. 6). Typically, thaw settlement does not occur uniformly over space, yielding a chaotic surface with small hills and wet depressions known as *thermokarst terrain*; this is particularly common in areas underlain by ice wedges (Fig. 7). When thermokarst occurs beneath a road, house, pipeline, or airfield, the structural integrity is threatened. If thermokarst occurs in response to regional warming, large areas can subside and, if near the coast, can be inundated by encroaching seas.

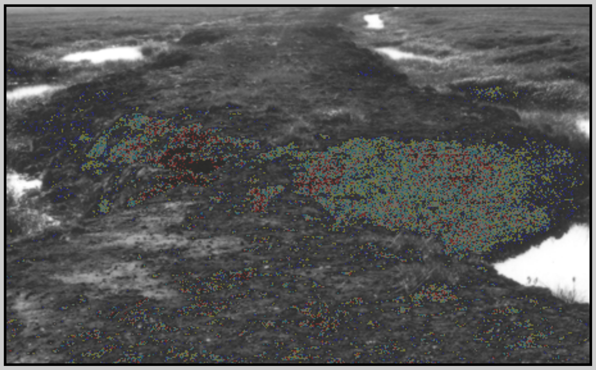


Figure 6. Thaw settlement, which develops when ice-rich permafrost thaws and the ground surface subsides.

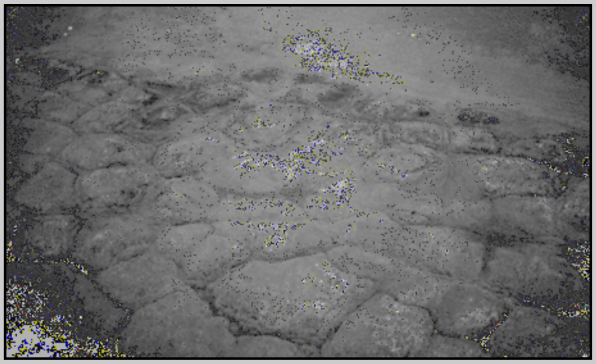


Figure 7. High-centered polygons near Prudhoe Bay, Alaska. This form of thermokarst terrain develops through ablation of underlying ice wedges.

amounts of ground ice are present. Because the volume is reduced when ice melts and because pore water is squeezed out during consolidation, thawing of ice-rich sediments leads to subsidence of the overlying ground surface, often resulting in deformation of an initially level surface into irregular terrain with substantial local relief. By analogy with terrain developed by chemical dissolution of bedrock in areas underlain extensively by limestone, the irregular surface created by thawing of ice-rich permafrost is known as *thermokarst terrain*. Thermokarst subsidence occurs when the energy balance at the earth's surface is modified such that heat flux to subsurface layers increases. The process occurs over a wide spectrum of geographical scale, ranging from highly localized disturbances associated with the influence of individual structures to depressions tens of meters deep and occupying many square kilometers (Washburn, 1980, p. 274).

On slopes, particularly in mountainous regions, thawing of ice-rich, near-surface permafrost layers can create mechanical discontinuities in the substrate, leading to *active-layer detachment* slides (Figure 8b) and *retrogressive thaw slumps* (Lewkowicz, 1992; French, 1996), which have a capacity for damage to structures similar to other types of rapid mass movements. Thermokarst subsidence is amplified where flowing water, often occurring in linear depressions, produces *thermal erosion* (Figure 8e; Mackay, 1970). Similarly, wave action in areas containing ice-rich permafrost can produce extremely high rates of coastal and shoreline erosion (Walker, 1991; Wolfe et al., 1998).

Anthropogenic disturbances in permafrost terrain have been responsible for striking changes over relatively short time scales. Removal or disturbance of the vegetation cover for agricultural purposes (Péwé, 1954), construction of roads and winter vehicle trails (Claridge and Mirza, 1981; Nelson and Outcalt, 1982; Slaughter et al., 1990), and airfields (French, 1975) have resulted in subsidence severe enough to disrupt or prevent the uses for which land was developed. A controlled experiment at the Permafrost National Test Site near Fairbanks, Alaska, caused the permafrost table to

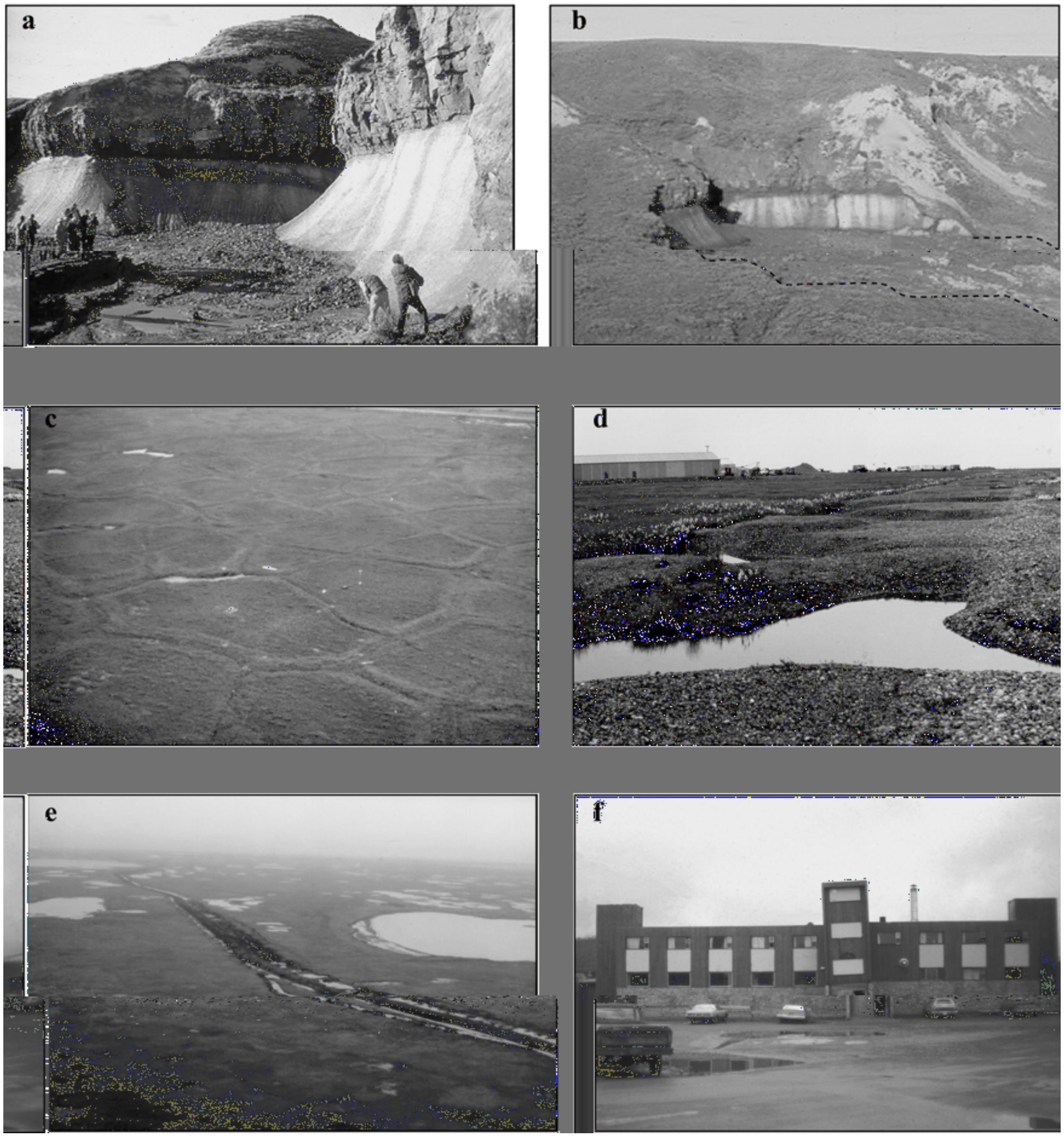


Figure 8. Effects of thermokarst processes on natural landscapes and engineered works. (a) Massive ground ice in the Yamal Peninsula, western Siberia; (b) Active-layer detachment slide, delineated below the headwall with dashed lines. The slide is associated with the presence of massive ground ice and developed in response to a particularly warm summer in the late 1980s; (c) Network of ice-wedge polygons near Prudhoe Bay; (d) Thermokarst that developed in terrain underlain by ice wedges near Prudhoe Bay, resulting from an inadequate amount of gravel fill in road construction; (e) Severe thermokarst developed over one decade in a winter road near Prudhoe Bay; the road was constructed by stripping the organics and stacking the mats in the intervening area; (f) Building in Faro, Yukon, undergoing differential settlement because of thawing of ice-rich permafrost. [From Nelson et al., 2002.]

move downward as much as 6.7 m over a 26-year period, simply by removing the insulating layer of vegetation (Linell, 1973). Even trampling can trigger thermokarst (Mackay, 1970), so agencies regulating tourism in the Arctic (Johnston, 1997) will have to thoroughly assess the relative merits of developing concentrated traffic through systems of foot trails or encouraging more diffuse patterns of use. Developmental encroachment on lands traditionally used to support herbivores may increase herd densities to such an extent that overgrazing could induce widespread thaw settlement (Forbes, 1999). Brown (1997) provided a comprehensive review of a wide range of anthropogenic disturbances affecting permafrost terrain.

1.3 Effects on Civil Infrastructure

Thermokarst can have severe effects on engineered structures, in many cases rendering them unusable. Because of its potential for settlement, thawing of ice-rich permafrost constitutes a significant environmental hazard in high-latitude regions, particularly in the context of climatic change. Although hazards related to permafrost have been discussed in specialist literature and textbooks (e.g., Brown and Grave, 1979; Péwé, 1983b; Williams, 1986; Woo et al., 1992; Andersland and Ladanyi, 1994; Koster and Judge, 1994; Yershov, 1998; Dyke and Brooks, 2000; Davis, 2001), they are given scant attention in most English-language texts focused on natural hazards (e.g., Bryant, 1991; Coch, 1995). Much of the literature treating social science and policy issues in the polar regions (e.g., Peterson and Johnson, 1995; Brun et al., 1997) also fails to adequately consider issues related to permafrost.

Although the permafrost regions are not densely populated, their economic importance has increased substantially in recent decades because of the abundant natural resources in the north circumpolar region and improved methods of extraction and transportation to population centers. Economic development has brought expansion of the human infrastructure: hydrocarbon extraction facilities, transportation networks, communication lines, industrial projects, civil facilities, and engineering maintenance systems have all increased substantially in recent decades. Rapid and extensive development has had large costs, however, in both environmental and human terms (e.g., Williams, 1986; Smith and McCarter, 1997), and these could be aggravated severely by the effects of global warming on permafrost.

Construction in permafrost regions requires special techniques at locations where the terrain contains ice in excess of that within soil pores. Prior to about 1970, many projects in northern Alaska and elsewhere disturbed the surface significantly, triggering thermokarst processes and resulting in severe subsidence of the ground surface, disruption of local drainage patterns, and in some cases destruction of the engineered works themselves. The linear scar in Figure 8e marks the route of a winter road constructed in 1968-69 by bulldozing the tundra vegetation and a thin layer of soil (Anonymous, 1970). This disturbance altered the energy regime at the ground surface, leading to thaw of the underlying ice-rich permafrost and subsidence of up to 2 m along the road (Nelson and Outcalt, 1982), which became unusable several years after construction.

Environmental restrictions in North America, based on scientific knowledge about permafrost, now regulate construction activities to minimize their impacts on terrain containing excess ice. The Trans-Alaska Pipeline, which traverses 1300 km from Prudhoe Bay on the Arctic coastal plain to Valdez on Prince William Sound near the Gulf of Alaska, carries oil at temperatures above 60°C. To prevent the development of thermokarst and severe damage to the pipe, the line is elevated where surveys indicated the presence of excess ice. To counteract conduction of heat into the ground, many of the pipeline's vertical supports are equipped with heat pipes that cool the permafrost in winter, lowering the mean annual ground temperature and preventing thawing during summer. In several short sections of ice-rich terrain where local above-ground conditions required burial of the line, the pipe is enclosed in thick insulation and refrigerated.

Other unusual engineering techniques devised for ice-rich permafrost include constructing heated buildings on piles, which allows air to circulate beneath the structures and prevents conduction of heat to the subsurface. Roads, airfields, and building complexes are frequently situated atop thick gravel pads or other insulating materials. In relatively large settlements such as Barrow, water and sewage are transported in insulated, elevated pipes known as "utilidors" (Fig. 9).

Figure 9. Utilidor in Barrow, Alaska.

Chapter 2

FUTURE CLIMATE CHANGE AND CURRENT RESEARCH INITIATIVES

2.1 General Considerations

Climate change is one of the most pressing issues facing science, governmental bodies, and, indeed, human occupation of the earth. Because of the extreme temperature sensitivity of cryospheric phenomena (snow, ice, frozen ground), the world's cold regions are and will continue to be heavily impacted by climate warming. Moreover, climate models indicate that warming will be particularly acute in the polar regions, exacerbating these impacts and broadening their geographic distribution. Changes involving permafrost are likely to be as profound. Owing to its multivariate role in climate change, its potential impact on human activities, and its widespread distribution, permafrost is among the most important of cryospheric phenomena.

Recognition of the importance of permafrost in global-change research, although slow in developing, has become widespread in recent years (e.g., McCarthy et al., 2001; Goldman, 2002; Hardy, 2003). Because permafrost is highly susceptible to long-term warming, it has been designated a "geoindicator," to be used as a primary tool for monitoring and assessing environmental change (Berger and Iams, 1996). This chapter outlines the role of permafrost in global-change studies and describes several national and international programs designed to monitor geocryological changes and ameliorate their impacts on human communities.

2.2 Permafrost and Global Change

Despite implications contained in the term "permafrost," perennially frozen ground is not permanent. Permafrost was more widespread during past episodes of continental glaciation. Evidence for the former existence of permafrost, including ice-wedge casts and pingo scars, has been found in areas of North America and Eurasia now far removed from current permafrost regions. Detailed environmental reconstructions in which permafrost is a critical paleogeographical indicator have been produced for Eurasia (e.g., Ballantyne and Harris, 1994; Velichko 1984). Although the former extent of permafrost in North America is not as well known, evidence that it existed during colder intervals is scattered along the glacial border from New Jersey to Washington state (Péwé, 1983c).

Abundant geological evidence also exists that widespread thermokarst terrain developed in response to past intervals of climatic warming. In parts of the unglaciated lowlands of the central Sakha Republic (Yakutia) in Siberia, nearly half of the Pleistocene-age surface has been affected by development of *alases*, steep-sided thermokarst depressions as much as 20–40 m deep and occupying areas of 25 km^2 or more (Soloviev, 1973; Koutaniemi, 1985; French, 1996). Kachurin (1962), Czudek and Demek (1970), and Romanovskii et al. (2000) attributed the development of these Siberian alases to warm intervals during the Holocene. In arctic parts of North America, thaw unconformities (Burn, 1997), sedimentary evidence (Murton, 2001), and extensive degradation of ice-cored terrain (Harry et al., 1988) attest to periods in which widespread, climatically induced thermokarst developed. Global warming is likely to trigger a new episode of widespread thermokarst development, with serious consequences for a large proportion of the engineered works constructed in the permafrost regions during the twentieth century.

Permafrost plays three important roles in the context of climatic change (Nelson et al., 1993; Anisimov et al., 2001): as a *record keeper* by functioning as a temperature archive; as a *translator* of climate change through subsidence and related impacts; and as a *facilitator* of further change through its impact on the global carbon cycle. These roles are discussed briefly in subsequent sections of this chapter and are treated in more detail in Nelson et al. (1993), Anisimov et al. (2001), and Serreze et al. (2000).

2.2.1 Record Keeper: Permafrost as a Temperature Archive

Permafrost is a product of cold climates and is common in high-latitude and high-elevation environments. Air temperature, the most influential parameter, determines the existence of permafrost, as well as its stability. Although the mean annual air temperature can be used as a very general indicator of the presence of permafrost, other factors are involved in determining its thickness, including substrate composition, thermal evolution, and groundwater distribution.

The thickness, thermal properties, and duration of the snow cover exert a profound influence on permafrost (Brown and Péwé, 1973; Smith, 1975; Hinzman et al., 1991; Romanovsky and Osterkamp, 1995; Zhang et al., 1997; Burn, 1998; Hinkel et al., 2003a). At sites underlain by permafrost in Alaska, the mean annual ground surface temperature is commonly 3–6ºC higher than the mean annual air temperature. At sites without permafrost, this difference can be even larger, reaching 7–8ºC in some years.

Despite subzero mean annual air temperatures, boreal areas of central Alaska may experience mean annual ground surface temperatures above 0ºC, owing to the insulating effect of low-density snow cover. Nonetheless, permafrost may exist at such locations because of a *thermal offset* attributable to differences in the thermal properties of the substrate in the frozen and unfrozen states (Kudryavtsev et al., 1974; Goodrich, 1978, 1982; Burn and Smith, 1988; Romanovsky and Osterkamp, 1995, 1997, 2000). This situation is common in peatlands, which often form the southernmost occurrences of subarctic permafrost (Zoltai, 1971). In a dry, unfrozen state, peat is an extremely efficient thermal insulator. When saturated and frozen, however, its thermal conductivity approaches that of pure ice. In such a situation, frost penetration in winter exceeds the depth of summer thaw, and permafrost can form or persist, despite mean annual air temperatures that would otherwise preclude its existence.

Permafrost records temperature changes and other proxy information about environmental changes (Lachenbruch and Marshall, 1986; Burn, 1997; Murton 2001). Because the transfer of heat in thick permafrost occurs primarily by conduction, it acts as a low-pass filter and has a “memory” of past temperatures. Through the use of precision sensors, temperature trends spanning a century or more can be recorded in thick permafrost (Lachenbruch and Marshall, 1986; Clow et al., 1998; Osterkamp et al., 1998a, b; Taylor and Burgess, 1998; Romanovsky et al., 2003).

The U.S. Geological Survey (USGS) has measured permafrost temperatures from deep boreholes in northern Alaska since the 1940s. Typically, this entails lowering a precision resistance thermistor down the access hole and obtaining a highly accurate and precise temperature measurement at known, closely spaced depths down the borehole. Analysis of these data through the mid-1980s indicates that permafrost on Alaska’s North Slope has generally warmed by 2–4ºC in the past century (Lachenbruch et al., 1982; Lachenbruch and Marshall, 1986), although some locales show little change or a slight cooling. Additional warming has occurred since that time (Clow and Urban, 2002), although increased snow cover may be responsible for a significant proportion of the temperature increase near the surface (Stieglitz et al., 2003).

Permafrost at many Arctic locations has experienced temperature increases in recent decades, including central and northern Alaska (Lachenbruch and Marshall, 1986; Osterkamp and Romanovsky, 1999), northwestern Canada (Majorowicz and Skinner, 1997), and Siberia (Pavlov, 1996). Temperature increases are not uniform; cooling has occurred recently in permafrost in northern Quebec (Allard and Baolai, 1995). More recent observations indicate, however, that permafrost is warming rapidly in this region (Allard et al., 2002). Serreze et al. (2000) summarized the extent and geographic distribution of recent changes in permafrost temperature in the Arctic.

In Alaska, temperature measurements made over the last two decades show that permafrost has warmed at all sites along a north–south transect spanning the continuous and most of the discontinuous permafrost zones, from Prudhoe Bay to Glennallen (Osterkamp and Romanovsky, 1999). Modeling indicates that in the continuous permafrost zone, mean annual permafrost surface temperatures vary interannually within a range of more than 5ºC. In discontinuous permafrost, the observed warming is part of a trend that began in the late 1960s. The total magnitude of the warming at the permafrost surface since then is about 2ºC. Observational data indicate that the last “wave” of recent warming began on the Arctic Coastal Plain, in the Foothills, and at Gulkana in the mid-1980s and in areas of discontinuous permafrost about 1990 (typically 1989–1991). The magnitude of the observed warming at the permafrost surface is about 3–4ºC at West Dock and Deadhorse near the Arctic Ocean, about 2ºC over the rest of the Arctic Coastal Plain and south into the Brooks Range, and typically 0.5–1.5ºC in discontinuous permafrost. At some sites in discontinuous permafrost south of the Yukon River, permafrost is now thawing from both the top and the bottom. Thawing of ice-rich permafrost is presently creating thermokarst terrain in the Alaskan interior and is having significant effects on subarctic ecosystems and infrastructure (Jorgenson et al., 2001).

Permafrost also contains abundant proxy information about climatic change. Cryostratigraphic techniques (Burn, 1997; French, 1998; Murton 2001), combined with isotopic analysis, can provide information about the increases in active-layer thickness that occurred millenia ago (Lauriol et al., 2002). Flora and fauna incorporated in permafrost can be dated radiometrically to determine cooling episodes.

2.2.2 Translator: Permafrost and Global-Change Impacts

Permafrost can translate climatic change to other environmental components (Jorgenson et al., 2001; Nelson et al., 2002). Thawing of ice-rich permafrost may induce settlement of the ground surface, which often has severe consequences for human infrastructure and natural ecosystems. Stratigraphic and paleogeographic evidence indicates that permafrost will degrade if recent climate warming continues into the future (e.g., Kondratjeva et al., 1993). The Arctic’s geological record contains extensive evidence about regional, climate-induced deterioration of permafrost. Melting of glaciers in Alaska and elsewhere will increase the rates of coastal erosion in areas of ice-rich permafrost, already among the highest in the world. Sediment input to the Arctic shelf derived from coastal erosion may exceed that from river discharge (ACD, 2003).

Degradation of ice-rich permafrost has also been documented under contemporary conditions in central Alaska and elsewhere (e.g., Francou et al., 1999; Osterkamp and Romanovsky, 1999; Osterkamp et al., 2000; Jorgenson et al., 2001; Tutubalina and Ree, 2001; Nelson et al., 2002; Beilman and Robinson, 2003). Little is known, however, about specific processes associated with thawing of permafrost, either as a function of time or as a three-dimensional process affecting the geometry of permafrost distribution over a wide spectrum of geographic scale. There is urgent need to conduct theoretical, numerical, and field investigations to address such issues.

It is clear from the paleogeographic record that climatic warming in the polar regions can lead to increases in permafrost temperature, thickening of the active layer, and a reduction in the percentage of the terrestrial surface underlain by near-surface permafrost. Such changes could lead to extensive settlement of the ground surface, with attendant damage to infrastructure.

Changes in Permafrost Distribution. Anisimov and Nelson (1996, 1997) investigated the impact of projected climate changes on permafrost distribution in the Northern Hemisphere using output from general circulation models (GCMs). Predictive maps of the areal extent of near-surface permafrost were created using the "frost index" (ratio of freezing- to thawing-degree-day sums) to estimate the likelihood of permafrost [see Nelson and Outcalt (1987) for a derivation of the frost index]. The primary conclusion of these experiments is that a significant reduction in the area of near-surface permafrost could occur during the next century (Fig. 10). Smith and Riseborough (2002) recently presented an alternative, very promising computational method for addressing permafrost distribution under conditions of climate change.

Until recently, however, GCMs did not incorporate permafrost and permafrost-related processes. During the last few years the GCM community has developed a general understanding that, unless permafrost and permafrost-related properties and processes are taken into account, there is little reason to expect that GCMs will produce physically reasonable results (Slater et al., 1998 a,b). Including permafrost in GCMs is a major challenge to both the GCM and permafrost scientific communities. Without a solution to this problem, however, GCMs cannot adequately represent arctic and subarctic regions. Modeling is a powerful tool for both climate and permafrost research. Although there has been significant progress during the last three decades, much remains to be done.

Changes in Active-Layer Thickness. The active layer plays an important role in cold

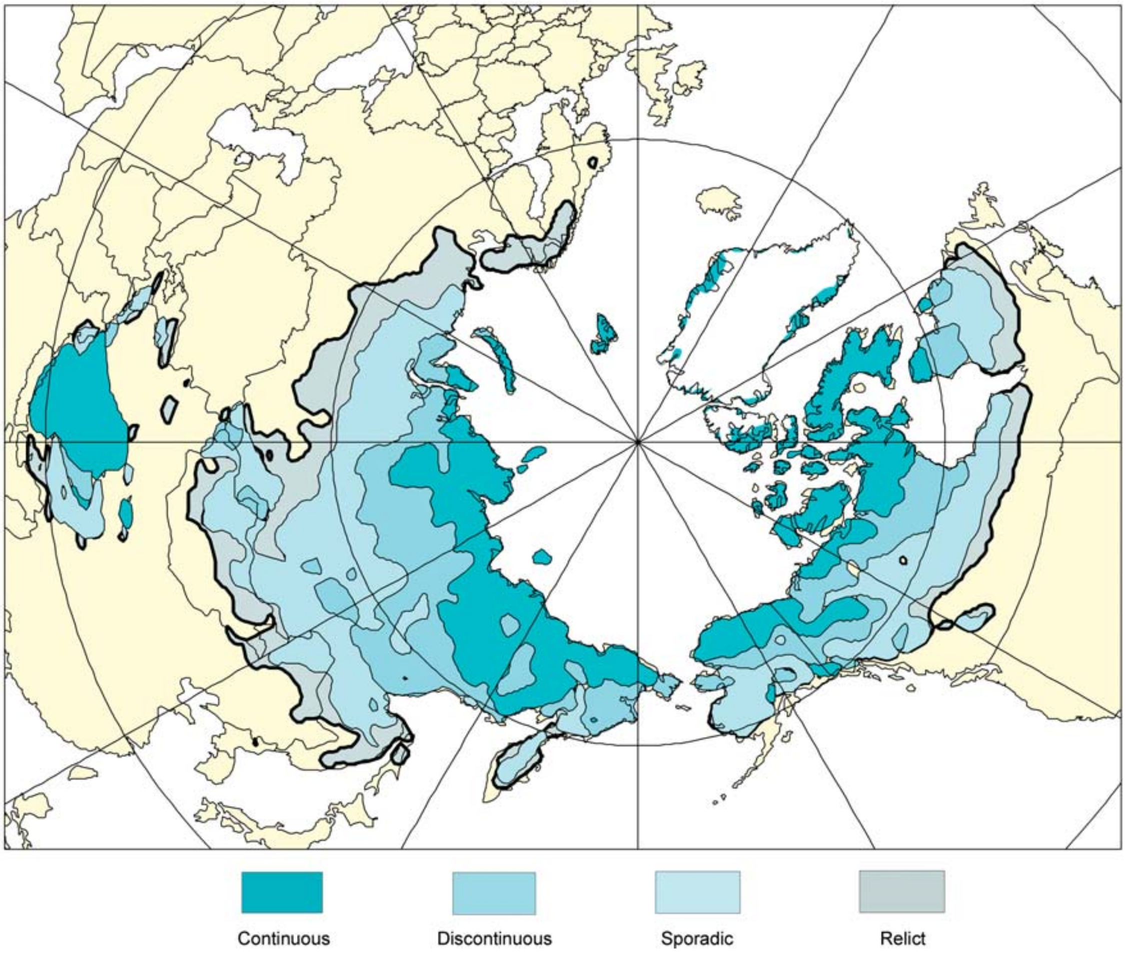


Figure 10. Distribution of permafrost in 2050 according to the UKTR general circulation model, based on calculations by Ansimov and Nelson (1997, Figure 2). Zonal boundaries were computed using criteria for the "surface frost number," a dimensionless index based on the ratio of freezing and thawing degree-days (Nelson and Outcalt, 1987). The solid line shows the approximate southern limit of contemporary permafrost as presented in Figure 3. Areas occupied by permafrost have been adjusted slightly from those in the original publication to account for marginal effects.

regions because most ecological, hydrological, biogeochemical, and pedogenic activities take place within it (Hinzman et al., 1991; Kane et al., 1991). The thickness of the active layer is influenced by many factors, including surface temperature, thermal properties of the surface cover and substrate, soil moisture, and the duration and thickness of the snow cover (Hinkel et al., 1997; Paetzold et al., 2000). Consequently, there is widespread variation in active-layer thickness across a broad spectrum of spatial and temporal scales (e.g., Pavlov, 1998; Nelson et al., 1999; Hinkel and Nelson, 2003). The active layer can be thought of as a filter that attenuates the temperature signal as it travels from the ground surface into the underlying permafrost. The properties of this filter change with time, behaving in a radically different manner in summer and winter because of the changes in the phase of the water–ice system (Hinkel and Outcalt, 1994). Over longer time periods, the accumulation of peat at the surface, cryoturbation, and ice enrichment at depth can alter the filter properties. Thus, to understand and interpret the signal recorded in permafrost, monitoring programs must incorporate intensive active-layer observations. The hypothesis and existing evidence that warming will increase the thickness of the active layer, resulting in thawing of ice-rich permafrost, ground instability, and surface subsidence, require further investigation under a variety of contemporary environmental settings.

Several monitoring methods are used to measure seasonal and long-term changes in the thickness of the active layer: physical probing with a graduated steel rod at the end of the thaw season (mid-August to mid-September), temperature measurements, and stratigraphic observations of ground ice occurrences (e.g., Burn, 1997; French, 1998; Murton, 2001). Other recommended measurements include soil moisture and vertical displacement of the active layer by thaw subsidence and frost heave. An extended description of monitoring methods is presented in the monograph by Brown et al. (2000).

Measurements of thaw depth are often collected on plots or grids that vary between 10, 100, and 1000 m on a side, with nodes evenly distributed 1, 10, or 100 m apart, respectively. The gridded sampling design allows for analysis of intra- and inter-site spatial variability (Nelson et al., 1998, 1999; Gomersall and Hinkel, 2001; Shiklomanov and Nelson, 2003). Summary statistics are generated for each sample period, and thaw depth on the grid is mapped using a suitable interpolation algorithm.

Soil and near-surface permafrost temperatures are commonly determined with thermistor sensors inserted in the ground, and subdiurnal readings are made manually or recorded at regular time intervals by battery-operated dataloggers. Closely spaced thermistors in the upper sections of shallow to intermediate-depth boreholes (25–125 m) provide continuous data to interpolate active-layer thickness and to observe interannual to decadal changes in permafrost temperatures.

Changes in Soil Moisture and Ground Ice Content. Soil moisture content has an important effect on soil thermal properties, soil heat flow, and vegetation and is, therefore, a crucial parameter. Although arctic hydrology has received serious attention in science planning documents, little attention has been devoted to subsurface hydrologic and hydrogeologic processes in permafrost regions. The omission of ground and soil water as a central focus is unfortunate, because subsurface flow and subsurface storage are extremely important components in the arctic hydrological system and in the arctic water cycle as a whole. Studies of permafrost hydrogeology are rare in the U.S. arctic sciences plans and programs. This is a serious gap in the research agenda and monitoring programs, in both the high Arctic and the Subarctic.

Several methods are employed to measure soil moisture, including gravimetric sampling, time-domain reflectometry (TDR), and portable soil dielectric measurements. Soil moisture can vary over short distances, and near-surface soil moisture fluctuates seasonally and in response to transient rainfall events (e.g., Miller et al., 1998; Hinkel and Nelson, 2003). Kane et al. (1996) had some success using satellite-based synthetic aperture radar to estimate soil moisture in the Kuparuk basin. Ground-based radar systems (e.g., Doolittle et al., 1990; Hinkel et al., 2001) show considerable promise for directly determining the long-term position of the active layer over limited areas.

Frozen ground supersaturated with ice (i.e., containing excess ice) is particularly susceptible to thaw subsidence. Probing may not detect this. Careful surveying is necessary to determine if thaw subsidence or frost heave has occurred, but surveying is often not feasible. Experiments involving high-precision (<1 cm) differential GPS (global positioning systems) to map and determine the scale of variability of heave and subsidence are underway in northern Alaska (Little et al., 2003).

Changes in active-layer thickness, accompanied by melt of ground ice and thaw settlement, can have profound impacts on local environments (Burgess et al., 2000; Dyke and Brooks, 2000). Where the distribution of ground ice is not uniform, thawing can lead to differential subsidence, resulting in thermokarst terrain. In the Sakha Republic (Yakutia) of Siberia, thaw depressions coalesced during warm intervals of the Holocene to form thaw basins (alases) tens of meters deep and occupying areas of 25 km^2 or more. Where human infrastructure has been built on ice-rich terrain, damage to infrastructure can accompany thaw settlement (Fig. 8d and f); recent geographic overviews indicate that the hazard potential associated with ice-rich permafrost is high in many parts of the Arctic (Nelson et al., 2001, 2002).

Modeling Strategies. Changes in the active layer may be substantial in coming decades. To predict such changes, modeling experiments are required. Many formulations have been used to calculate active-layer thicknesses and mean annual permafrost surface temperatures using simplified analytical solutions (Kudryavtsev et al., 1974; Pavlov, 1980; Zarling, 1987; Balobaev, 1992; Aziz and Lunardini, 1992, 1993; Romanovsky and Osterkamp, 1995, 1997; Smith and Riseborough, 1996; Nelson et al., 1997). For contemporary work involving locations for which subsurface data are available, analytical solutions are less important than in previous decades. Numerical models are widely available for permafrost problems, and they can be used with some confidence when adequate information about climatic, boundary layer, and subsurface parameters is available.

Analytical equations can also be helpful in providing insights into the physics of the coupling between permafrost and the atmosphere. However, these simple equations have limited usefulness because they do not include the effects of inhomogeneous active layers with multiple layers, variable thermal properties, unfrozen water dynamics, and non-conductive heat flow.

Serious problems arise when complex models are employed in a spatial context, particularly when little is known about the spatial variability of parameters important to geocryological investigation. In such cases, stochastic modeling (Anisimov et al., 2002) or the use of analytic procedures in a GIS environment (Nelson et al., 1997; Shiklomanov and Nelson, 1999; Klene et al., 2002) may yield results superior to complex, physically based models.

Anisimov et al. (1997) used a series of GCM-based scenarios to examine changes in active-layer thickness in the Northern Hemisphere. The results from these preliminary experiments indicate that increases of 20–30% could occur in many regions, with the largest relative increases occurring in the northernmost areas (Fig. 11).

Both empirical evidence (Moritz et al., 2002) and climate models (e.g., Greco et al., 1994) indicate that climate warming is not geographically homogeneous. With respect to degrading permafrost and its influence on human settlement, a critical concern is the spatial correspondence between areas of climate warming (accompanied by active-layer thickening) (Fig. 11) and those of ice-rich permafrost (Fig. 3 and 5). These relations were modeled by Nelson et al. (2001, 2002); the results from those experiments are given in Chapter 3. Harris et al. (2001b) have implemented a comprehensive, observation-based approach to mapping geotechnical hazards related to permafrost in the European mountains.

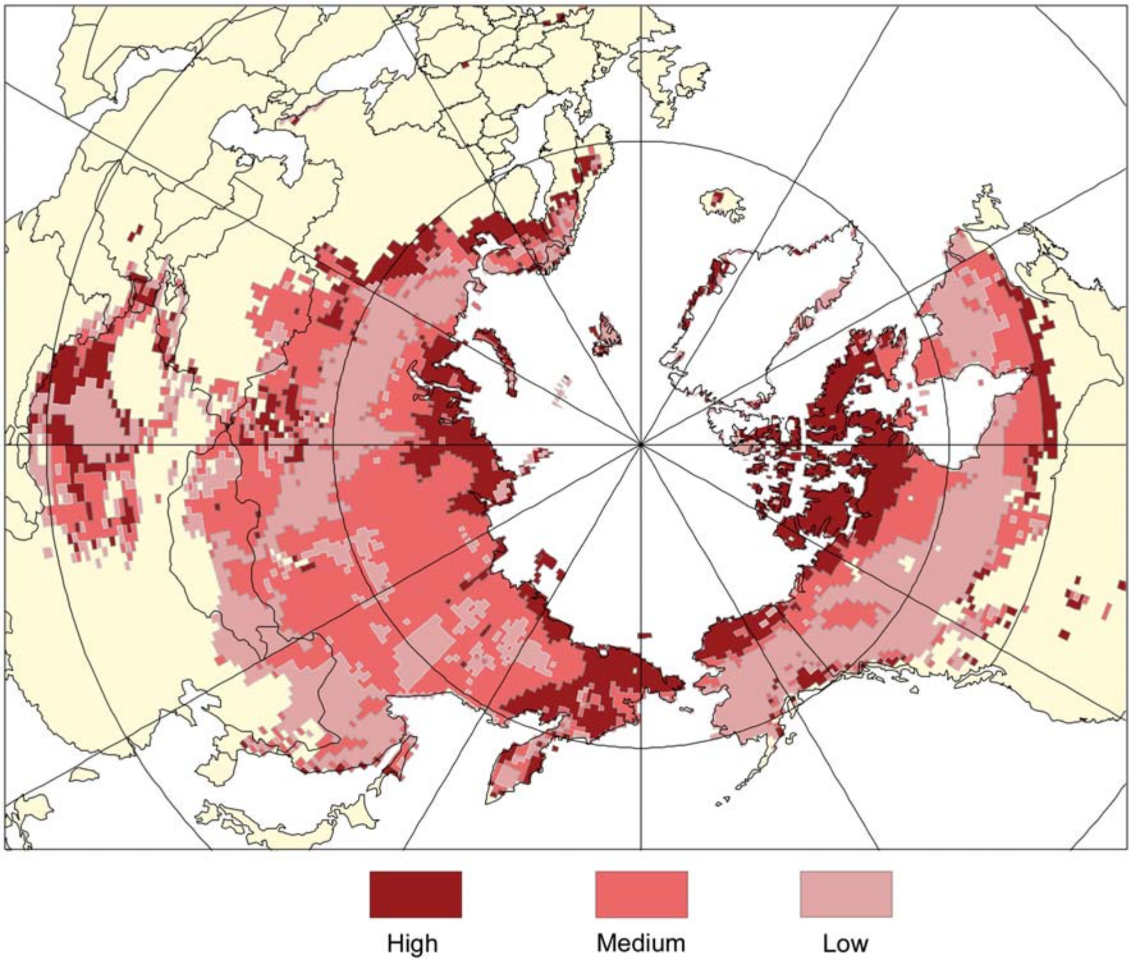


Figure 11. Relative changes in active-layer thickness in 2050 according to the UKTR general circulation model, reclassed from Ansimov et al. (1997, Figure 6): low: 0–25%; medium: 25–50%; high: >50%.

2.2.3 Facilitator: Permafrost and Global Carbon Impacts

Permafrost can facilitate further climate change through the release of greenhouse gases (Rivkin, 1998; Robinson and Moore, 1999; Robinson et al., 2003). Because considerable quantities of carbon are sequestered in the upper layers of permafrost, a widespread increase in the thickness of the thawed layer could lead to the release of large quantities of CO_2 and CH_4 to the atmosphere (Michaelson et al., 1996; Anisimov et al., 1997; Goulden et al., 1998; Bockheim et al., 1999). This in turn would create a positive feedback mechanism that can amplify regional and global warming.

Concerns have been raised about the impact of high-latitude warming on the global carbon cycle. According to Semiletov (1999) the greatest concentration and largest seasonal variations of carbon dioxide and methane concentrations occur between 60° and 70°N. Greenhouse gases released from thawing permafrost into the atmosphere could create a strong positive feedback in the climate system; this topic is currently under intensive investigation. Key questions include:

- What are the major mechanisms regulating the distribution and associated rates of carbon transfer, transformation, and burial in the arctic land–shelf system?
- How do biogeochemical processes on the margins of the Arctic Ocean influence the chemistry and biology of surface waters and associated fluxes of CO_2 at the air–water (ice) interface?

Answers to such questions require much more work on the state of offshore and onshore permafrost in the atmosphere–land–shelf system in the Arctic.

Plants remove carbon dioxide from the atmosphere during photosynthesis. Carbon dioxide is returned through plant respiration and decomposition of plant detritus. Studies on Alaska's North Slope indicate a delicate balance between these two competing processes. In some years, more CO_2 is released into the atmosphere, while in others more CO_2 is fixed by plants (Marion and Oechel, 1993; Oechel et al., 1993). In years when biomass production exceeds respiration, the atmosphere is a net source of carbon, which resides in plant biomass. Regional changes in climate can alter the vegetation communities and thus alter this balance in a direction not fully understood. Studies from Canada and Eurasia have demonstrated that many arctic sites are currently losing CO_2 to the atmosphere (Zimov et al., 1993, 1996). Higher temperatures and a reduction in soil moisture appear to be likely causes (Oechel et al., 1995, 1998).

Plants lose biomass as part of their natural growth cycle. They shed leaves and twigs, and they disperse seeds. In wet tundra, much of this surface detritus decays only partially, yielding a surface soil layer rich in organics. The organics can be transported deeper into the soil via several processes. In summer, water percolating through the active layer can transport organics to depth. In winter, soils are susceptible to a mechanical churning process known as cryoturbation. Over long time periods, surface materials are transported down into the soil and can become incorporated into the upper permafrost. This storage (sequestration) of carbon in the upper permafrost has been documented in several studies (Michaelson et al., 1996; Bockheim et al., 1999). Terrestrial arctic ecosystems may have been a net carbon sink during the Holocene, and perhaps 300 gigatons are sequestered (Miller et al., 1983).

Thickening of the seasonally thawed layer effectively means downward movement of the permafrost table. If organic material is present in the newly thawed layer, it again becomes subject to decomposition by soil microbes, ultimately releasing CO_2 and CH_4 to the atmosphere. This can act as a positive feedback mechanism by increasing the concentration of radiatively active gases in the high-latitude regions. By one estimate, carbon fluxes have the potential for a positive feedback on global changes amounting to about 0.7 Gt per year of carbon to the atmosphere, about 12% of the total emission from fossil fuel use (Oechel and Vourlitis, 1994).

High-latitude wetlands currently account for about 5–10% of the global methane flux (Reeburgh and Whalen, 1992), and, because methane flux is related closely to the thermal regime in the active layer (Goulden et al., 1998; Nakano et al., 2000), this component is likely to increase if the development of widespread thermokarst terrain is triggered by permafrost degradation. Thermokarst lakes emit methane during winter; methane is generated from carbon-rich terrestrial sediments sequestered during the Pleistocene epoch (Zimov et al., 1997).

Embedded within sediments on the ocean margins is a crystalline form of methane known as gas hydrates (e.g., Yakushev and Chuvilin, 2000). Although currently in quasi-equilibrium with temperature and pressure conditions, large volumes of gas hydrates are susceptible to disruption by warming ocean water. This could result in the release of these hydrocarbons, allowing them to escape to the surface and enter the atmosphere. Since methane has a radiative activity index of about 27 (molecule for molecule, it is 27 times more effective at absorbing thermal radiation than CO_2), this could provide a strong positive feedback.

2.3 Monitoring: Organized International Collection, Reporting, and Archiving Efforts

Worldwide permafrost monitoring can provide evidence of climate-induced changes. Standardized in-situ measurements are also essential to calibrate and verify regional and GCM models. The Global Terrestrial Network for Permafrost (GTN-P) is the primary international program concerned with monitoring permafrost parameters. GTN-P was developed in the 1990s with the long-term goal of obtaining a comprehensive view of the spatial structure, trends, and variability of changes in permafrost temperature (Brown et al., 2000; Burgess et al., 2000). The program's two components are: (a) long-term monitoring of the thermal state of permafrost in an extensive borehole network; and (b) monitoring of active-layer thickness and processes at representative locations. The active-layer program, titled *Circumpolar Active Layer Monitoring (CALM)*, is described in a monograph by Brown et al. (2000).

The ideal distribution of sites for a global or hemispheric monitoring network should include locations representative of major ecological, climatic, and physiographic regions. Recently, efforts have been made to re-establish a deep borehole temperature monitoring program under the auspices of GTN-P to monitor, detect, and assess long-term changes in the active layer and the thermal state of permafrost, particularly on a regional basis (Burgess et al., 2000; Romanovsky et al., 2002). The borehole network has 287 candidate sites, half of which obtain data on a periodic basis. Borehole metadata are available on the Geological Survey of Canada's permafrost web site.

The International Permafrost Association (IPA), with 24 member nations, serves as the international facilitator for the CALM network, which is now part of GTN-P. Prior to the 1990s, many data sets related to the thickness of the active layer were collected as part of larger geomorphological, ecological, or engineering investigations, using different sampling designs and collection methodologies. Moreover, the typical study was short term and did not deposit data records in archives accessible for general use (Barry, 1988; Clark and Barry, 1998). The combined effect of these circumstances made it difficult to investigate long-term changes in seasonal thaw depth or possible interregional synchronicity.

The CALM program was formally established in the mid-1990s as a long-term observational program designed to assess changes in the active layer and provide ground truth for regional and global models. It represents the first attempt to collect and analyze a large-scale, standardized geocryological data set obtained using methods established under an international protocol. Funded by the Arctic System Science (ARCSS) program of the U.S. National Science Foundation, the network currently incorporates approximately 125 active sites involving participants from twelve countries in the Northern Hemisphere and three countries involved in Antarctic research. The majority of the network sites are in arctic tundra regions, with the remainder in warmer forested subarctic and alpine tundra of the mid-latitudes. Metadata and ancillary information are available for each site, including climate, site photographs, and descriptions of terrain, soil type, and vegetation. CALM data are transferred periodically to a permanent archive at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado.

Web Sites

GTN-P	http://www.gtnp.org
CALM	http://www.geography.uc.edu/~kenhinke/CALM/
CEON	http://ceoninfo.org/
FGDC	http://nsidc.org/fgdc/
PACE	http://www.earth.cardiff.ac.uk/research/geoenvironment/pace/31.EU_PACE_Project.htm
IPA	http://www.soton.ac.uk/ipa

GTN-P and the CALM program contribute to the Global Terrestrial Observing System (GTOS), the Global Climate Observing System (GCOS), and the associated Terrestrial Ecosystem Monitoring Sites (TEMS) network. The networks are co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC of UNESCO), the United Nations Environment Programme (UNEP), the International Council of Scientific Unions (ICSU), and the Food and Agriculture Organization (FAO). A detailed joint plan for GCOS and GTOS was developed by the Terrestrial Observational Panel for Climate (TOPC) for climate-related observations (GCOS, 1997). Program goals include early detection of changes related to climate, documentation of natural climate variability and extreme events, modeling and prediction of these changes, and assessment of impacts.

The affiliation of GTN-P and the CALM program within the GCOS/GTOS networks

The GHOST Hierarchical Sampling Strategy

The GTN-P network seeks to implement an integrated, multi-level strategy for global observations of permafrost thermal state, active layer thickness, and seasonally frozen ground, including snow cover, soil moisture, and temperature by integrating (a) traditional approaches and new technologies, (b) in-situ and remote observations, and (c) process understanding and global coverage. The provisional tiered system corresponds to the Global Hierarchical Observing Strategy (GHOST) developed for key variables of GTOS and includes:

Tier 1: Major assemblages of experimental sites [Kuparuk River basin, Alaska; Mackenzie River basin, Canada; Lower Kolyma River, Russia; Permafrost and Climate in Europe (PACE) transect from southern Europe to Svalbard].

Tier 2: Process-oriented research sites [Long-term Ecological Research (LTER) sites and Barrow (Alaska); Zackenberg (Greenland); Abisko (Sweden); and Murtel/Corvatsch (Switzerland)].

Tier 3: Range of environmental variations including ground temperatures and plots [CALM hectare to 1-km^2 grids; boreholes across landscapes gradients (southern Norway, Swiss Alps, Lake Hovsgol GEF in Mongolia)].

Tier 4: Spatially representative grids associated with gas flux, active layer, and borehole measurements [northern Alaska and Lower Kolyma, Russia, including MODIS and Fluxnet sites (such as Barrow, Alaska)].

Tier 5: Application of remotely sensed data covering entire regions [low state of development in geocryology due to difficulties in remotely sensing subsurface temperatures, ground ice, and frost penetration].

Tiers 1–4 mainly represent traditional methodologies, which remain fundamentally important for a deeper understanding of processes and long-term trends. Tier 5 constitutes challenges for scaling experiments and regional model validation, although progress has been made in active-layer mapping (Peddle and Franklin, 1993; Leverington and Duguay, 1996; McMichael et al., 1997). Activation of additional existing boreholes and establishment of new boreholes and active layer sites are required for representative coverage in the Europe/Nordic region, Russia and Central Asia (Russia, Mongolia, Kazakhstan, China), in the southern hemisphere (South America, Antarctica), and in the North American mountain ranges and lowlands. Additional cooperative activities through the NSIDC Frozen Ground Data Center are required to obtain data from continental regions where existing seasonal soil frost observations are collected.

Figure 12, modified from Brown et al. (2000), represents an established application of a hierarchical, GHOST-like strategy in permafrost science. The active-layer thickness in the 26,278-km^2 area (Tier 1), centered on the Kuparuk River basin of north-central Alaska, is mapped using data from the array of experimental and observation sites located within it. A wide range of intensive monitoring programs and manipulative experiments are conducted at the Toolik LTER site, which represents Tier 2. Soil and vegetation characteristics are collected at 1-km^2 Tier 3 sampling grids (squares) and are used for field experiments (e.g., frost heave and thaw settlement) and model verification. Small (1-ha) Tier 4 sites, represented by triangles, are distributed throughout the region and are used to collect air temperature, surface temper-

necessitates conformity with global observational protocols whenever and wherever possible. The Global Hierarchical Observing Strategy (GHOST) represents a strategic effort to obtain samples of environmental variables that can be integrated systematically over time and space to provide comprehensive estimates of the rates and magnitude of global-change impacts (WMO, 1997). The basic objective of GHOST site selection is to obtain valid regional and global coverage while taking maximum advantage of existing facilities and sites. The GHOST system incorporates a five-tier hierarchical system for surface observations; a more

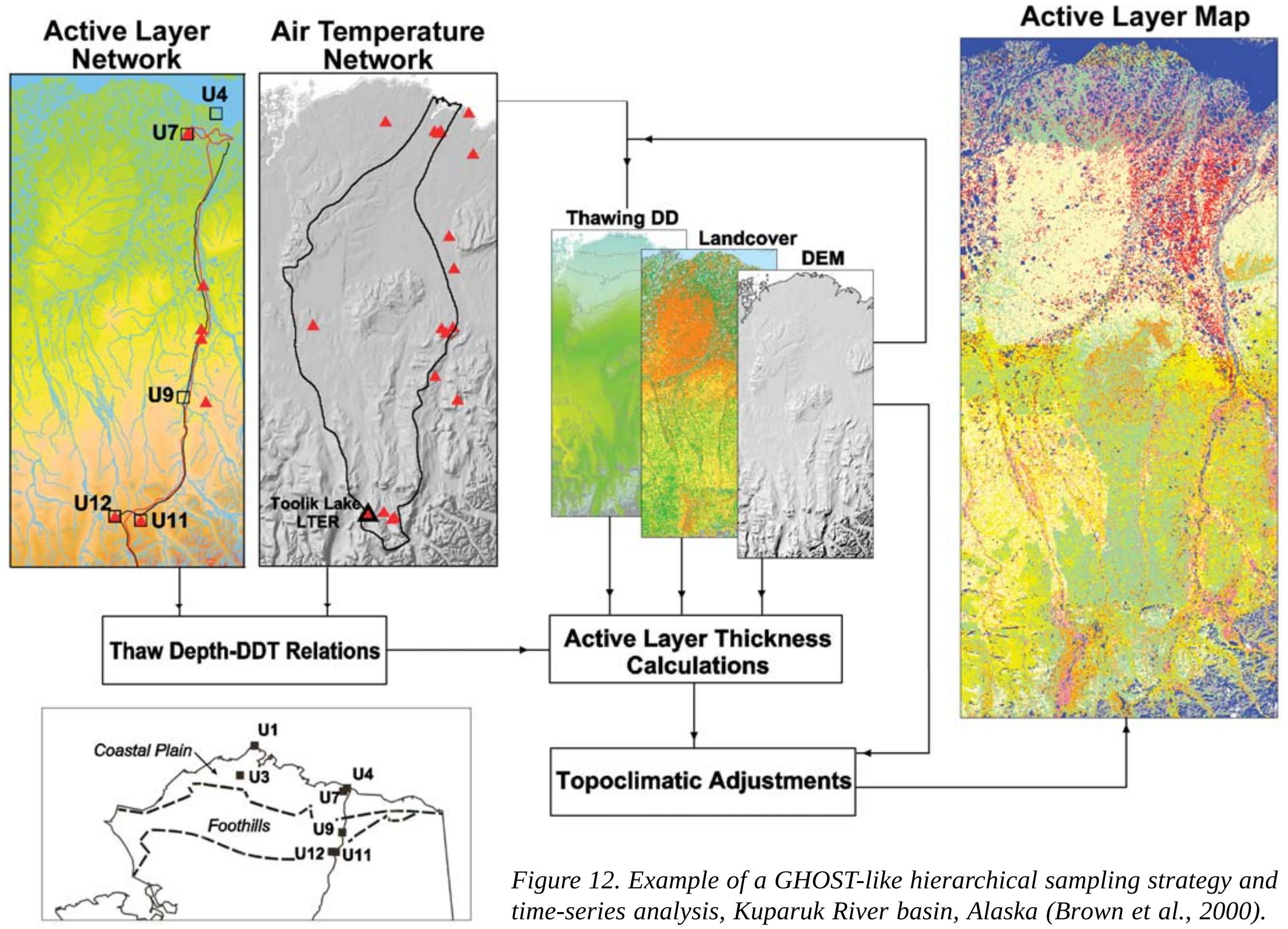


Figure 12. Example of a GHOST-like hierarchical sampling strategy and time-series analysis, Kuparuk River basin, Alaska (Brown et al., 2000).

ature, and thaw-depth data. Vegetation and digital elevation model (DEM) maps of the area, derived from satellite data, represent Tier 5 and are used to interpolate data over the entire map area. Details are given in Nelson et al. (1997) and Shiklomanov and Nelson (2002). The GHOST approach lends itself to a wide variety of analytical and modeling approaches. Alternative methodologies for producing active layer maps of this region have been explored by Hinzman et al. (1998), Shiklomanov and Nelson (1999), Anisimov et al. (2002), and Klene et al. (2001). Information about the Tier 3 (ARCSS/CALM) grids is contained in Nelson et al. (1998) and Hinkel and Nelson (2003). The Tier 4 (Flux Study) sites are discussed by Klene et al. (2001).

complete generic description can be found in Version 2.0 of the GCOS/GTOS Plan for Terrestrial Climate-related Observations (GCOS, 1997; WMO, 1997). Permafrost observation sites and networks will play an important role in the developing Circumarctic Environmental Observatories Network (CEON).

2.4 Organizational Issues

Standardized collection of basic environmental parameters is essential to all large-scale scientific and engineering endeavors. With respect to permafrost, there is a clear need to establish a systematic data-reduction protocol in accordance with identified and established user needs. For example, hourly air temperature data collected by an individual field researcher may not be necessary for climate modelers and engineers. Instead, such data could be processed to produce average daily air temperatures or accumulated degree-days of frost, thaw, heating, or cooling. Implicit in such an approach is the recognition that basic aspects of data collection would be standardized (e.g., all air temperature measurements would be made at the same height above the ground surface using a standard radiation shield) and that metadata files would also be available. These data, if properly collected, provide the foundation upon which all efforts ultimately depend, and they are used to refine and validate climate modeling efforts.

A specific measurement protocol should be developed for monitoring permafrost. This protocol should be established by the scientific and engineering community for obtaining the appropriate measurements at the necessary temporal frequency and spatial resolution. The protocol should cover the scale of instrumentation ranging from site to satellite. Inherent in the protocol is the requisite accuracy and precision of thermistors, the optimal depth of soil temperature measurements, and site descriptions. These efforts should be coordinated and integrated with those of the GTN-P to ensure the collection of data useful for global climate observation (Burgess et al., 2000; GTN-P web site). Similarly, methods of monitoring active layer thickness and thaw subsidence should be integrated with those of ongoing and developing international projects (e.g., CALM, PACE, IPY) following discussion and modification of the protocols currently in place. In all cases, an effort should be made to assess the spatial variability of thaw depth and soil temperature and to collect ancillary data. A comprehensive list of recommendations regarding permafrost-related activities and their coordination was issued recently (IPA Council, 2003).

The 24-member International Permafrost Association (IPA) and several of its working groups and data committees coordinate GTN-P activities, including input to GTOS/TEMS. The Geological Survey of Canada (Ottawa) maintains the GTN-P web site and borehole metadata files and coordinates thermal data management and dissemination The NSIDC acquires, stores, and processes data. Data collected by funded projects in the U.S. should be archived in the Frozen Ground Data Center (FGDC) within an appropriate time period. FGDC is a subunit of the U.S. National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, which is an affiliate of the World Data Center for Glaciology (WDC). Details of site characteristics and measurements should be presented in standardized metadata files.

A strategy developed by the IPA facilitates data and information management to meet the needs of cold regions science and engineering. One focus of this strategy is the Global Geocryological Data (GGD) system, which provides an international link for scientific investigators and data centers. In collaboration with the International Arctic Research Center (IARC), WDC and NSIDC serve as a central node for GGD. Every five years NSIDC prepares a CD-ROM containing information and data acquired in the previous five-year interval. Known as the Circumpolar Active-Layer Permafrost System (CAPS), this product is a comprehensive compilation of data related to permafrost and frozen ground from a global perspective. Detailed information can be found on the FGDC web site.

Data sets representing spatially intensive measurements, such as satellite imagery or thaw depths interpolated over large regions, should be prepared in a format conducive to generation of descriptive statistics and standardized mapping. Digital mapping at regional, continental, and circumpolar scales has been facilitated greatly by the development of the Equal-Area Scalable Earth Grid (EASE-Grid) at NSIDC (Armstrong et al., 1997). Use of this flexible system of projections is recommended at these scales.

Chapter 3

IMPACTS ON INFRASTRUCTURE IN ALASKA AND THE CIRCUMPOLAR NORTH

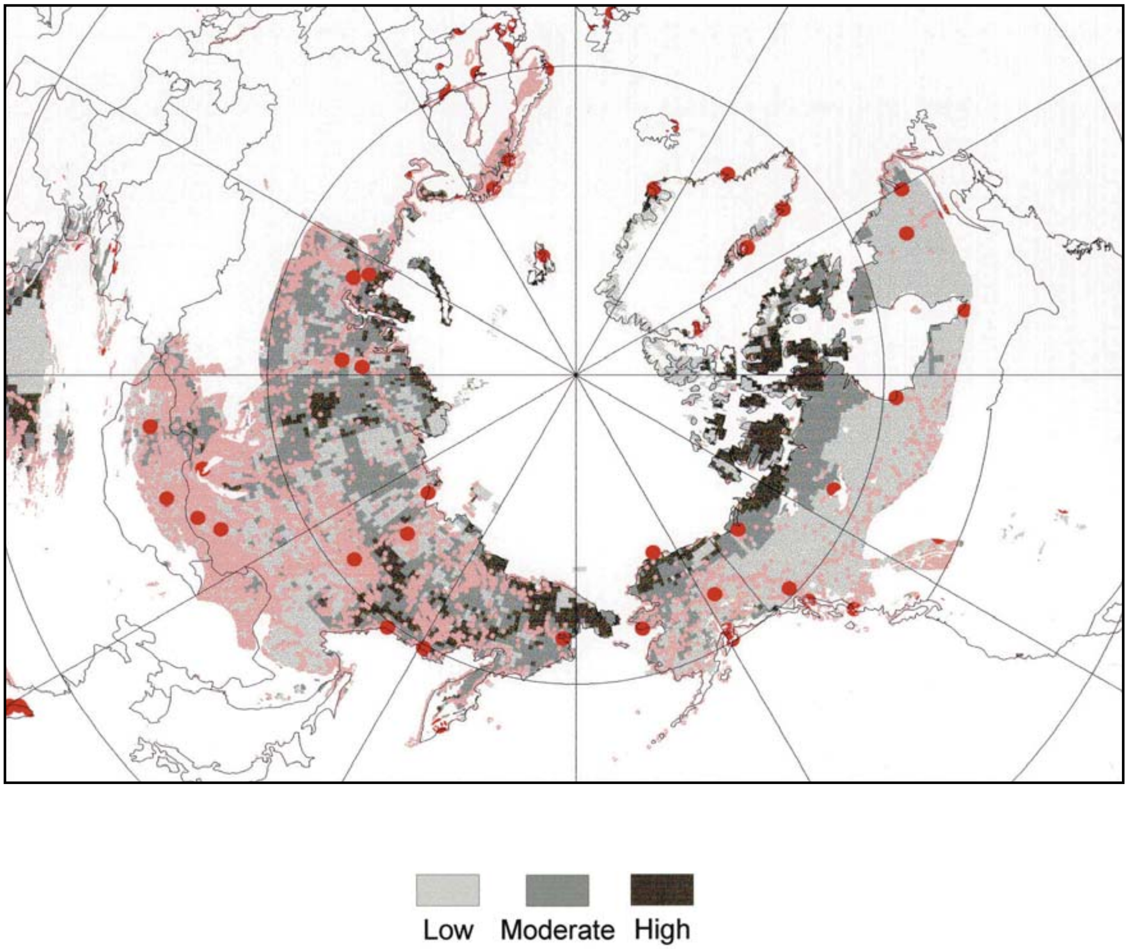
3.1 Introduction

Evidence presented in the preceding chapters documents widespread warming of permafrost, which in some cases is showing very clear evidence of thawing. Warming and thawing of permafrost will have significant effects on infrastructure (Instanes, 2003). Local sources of anthropogenic heat and surface modifications associated with urban land uses may exacerbate problems related to thaw and settlement (Hinkel et al., 2003b; Klene et al., 2003). After presenting a general overview of the possible effects of climate warming on permafrost in the Northern Hemisphere, this chapter discusses the existing infrastructure in Alaska with special reference to its relation with permafrost.

3.2 Northern Hemisphere Hazards

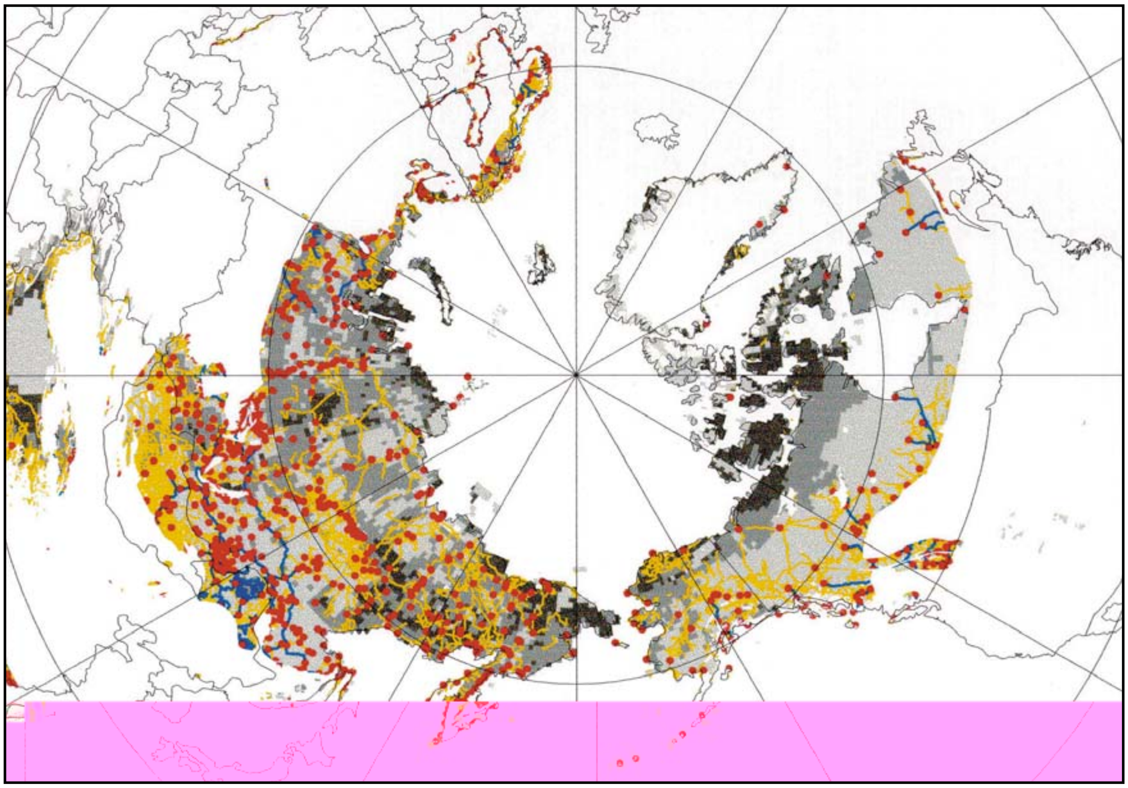
Nelson et al. (2001, 2002) used output from three transient-mode general circulation models (GCMs), in conjunction with a digital version of the International Permafrost Association's *Circum-Arctic Map of Permafrost and Ground Ice Conditions* (Brown et al., 1997, 1998; Brown and Haggerty, 1998), to map the hazard potential associated with thawing permafrost under conditions of global warming. The maps were created using a simple, dimensionless thaw-settlement index, computed using the relative increase in active layer thickness and the volumetric proportion of near-surface soil occupied by ground ice. Computational details are provided in Nelson et al. (2002). The resulting maps depict areas of low, moderate, and high hazard potential. In Figure 13 the location of existing infrastructure has been superimposed on the hazard map, providing a general assessment of the susceptibility of engineered works to thaw-induced damage under the UKTR climate-change scenario. Figure 13a indicates the risk to infrastructure in northern Canada, Alaska, and Russia. Russia has more population centers and infrastructure in the higher risk areas, but Alaska and Canada also have population centers, pipelines, and roads in areas of moderate and high hazard potential. Major settlements are located in areas of moderate or high hazard potential in central and northern Alaska (e.g., Nome and Barrow), northwestern Canada (Inuvik), western Siberia (Vorkuta), and the Sakha Republic in Siberia (Yukutsk). The potential for severe thaw-induced disruptions to engineered works has been reported from each of these areas, and problems are likely to intensify under conditions of global warming.

Figure 13b shows the risk to transportation facilities. The network of seismic trails in northern Alaska, the Dalton Highway between the Yukon River and Prudhoe Bay in Alaska, the Dempster Highway between Dawson and Inuvik in western Canada, and the extensive road and trail system in central Siberia all traverse areas of high hazard potential. Numerous airfields occupy ice-rich terrain in Siberia, and the Trans-Siberian, Baikal-Amur Mainline, Hudson Bay, and Alaska Railroads span regions of lesser hazard potential, although they extend into areas in which localized problems have been reported. A dense network of secondary roads and trails occupies areas of moderate risk in Mongolia, and northeastern China has an

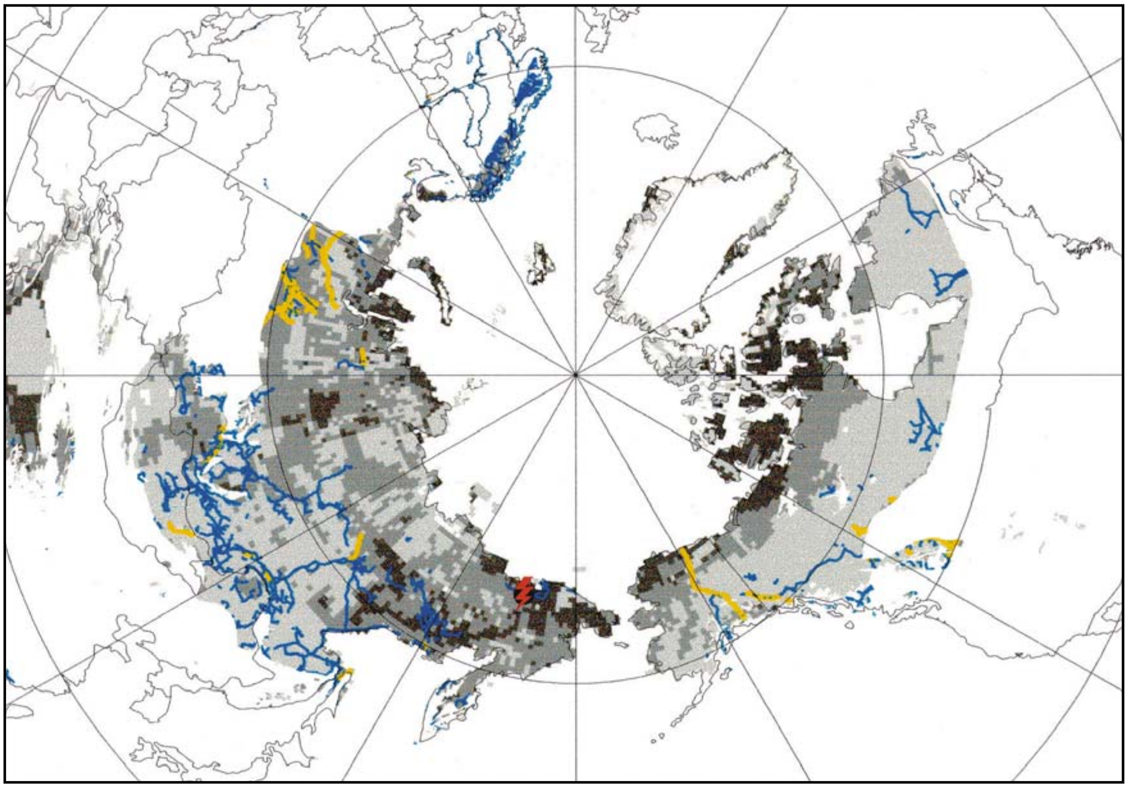


a. Risk to infrastructure. The red dots indicate population centers; the pink shading indicates areas of human settlement.

Figure 13. Areas at risk for infrastructure damage as a result of thawing of permafrost.



b. Risk to transportation facilities. The yellow lines indicate winter trails, the blue lines indicate railroads, and the red dots indicate airfields.



c. Risk to major electrical transmission lines and pipelines. The blue lines indicate electrical transmission lines, the yellow lines indicate pipelines (yellow), and the black dot with red lightning is the location of the Bilibino nuclear powerplant in Russia.

extensive railway system developed in areas underlain by permafrost.

The risk to major electrical transmission lines and pipelines is shown in Figure 13c. Most electrical facilities, including the extensive networks in northern Scandinavia and south-central Siberia, are located in areas of moderate risk. The Bilibino nuclear station and its grid, extending from Cherskiy on the Kolyma River to Pevek on the East Siberian Sea, occupy an area in which increased thaw depth and abundant ice-rich permafrost combine to produce high hazard potential. The Trans-Alaska Pipeline System spans two areas of moderate hazard potential. The network of pipelines associated with the West Siberia oil and gas fields is of particular concern because it is located in the ice-rich West Siberian Plain and is vulnerable to freeze–thaw processes (Seligman, 2000).

Figure 13 provides a generalized delineation of regions in the Northern Hemisphere to which high priority should be assigned for monitoring permafrost conditions. At the circum-arctic scale, maps such as these are useful for developing strategies to mitigate detrimental impacts of warming and adaptation of the economy and social life to the changing environment of northern lands. Maps at such scales cannot, of course, resolve the local factors involved in the development of thermokarst. Rather, they point to geographic areas where hazard scientists, policy analysts, and engineers should focus attention and prepare more detailed maps at local and regional scales.

3.3 Geocryological Hazards in Alaska

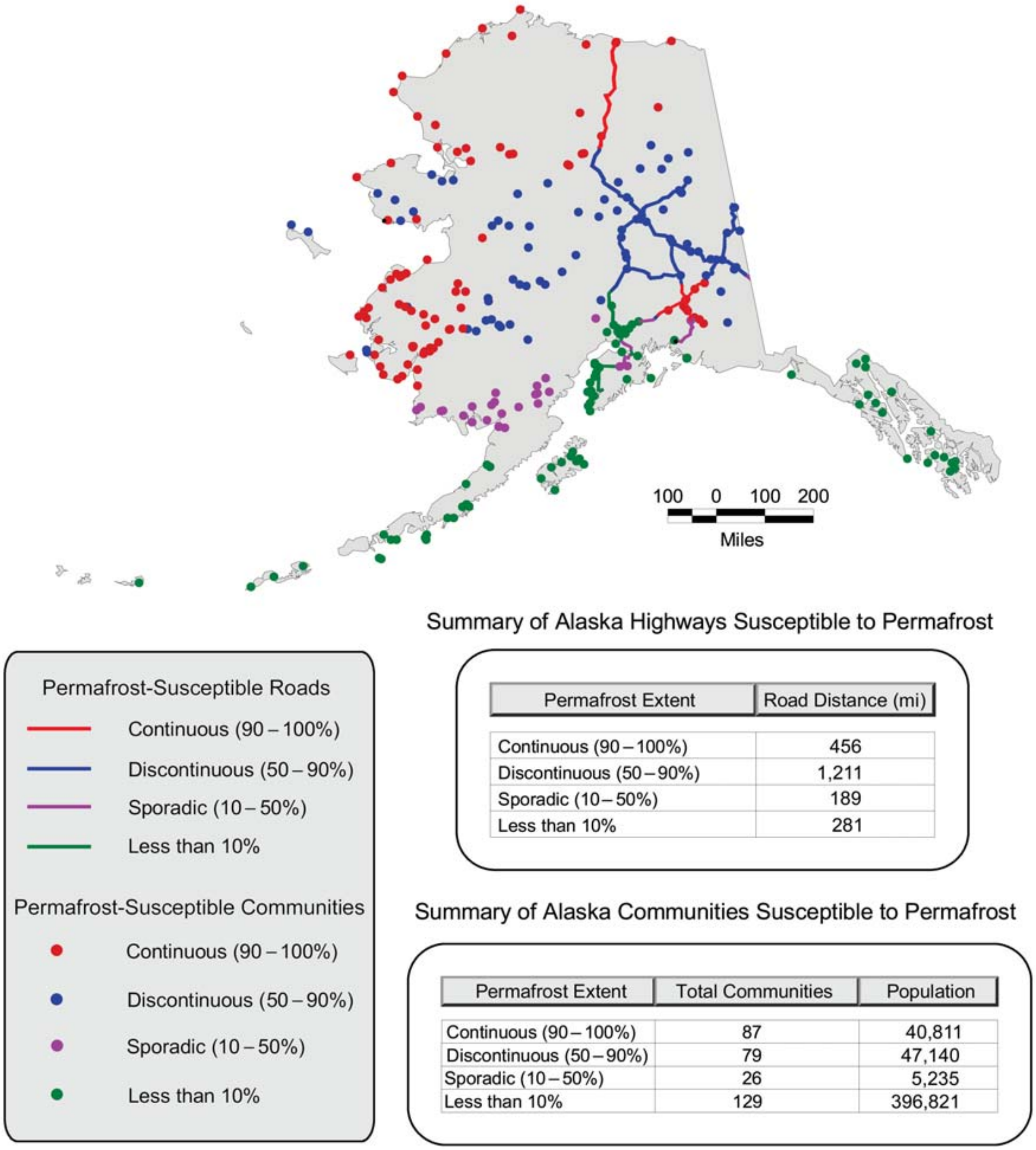
Figure 14 shows the population centers and major roads in areas of Alaska that are presently affected by permafrost. Although a majority of the population resides in permafrost-free areas of the state, sizeable towns and settlements are located in areas that are susceptible to permafrost degradation; nearly 100,000 Alaskans live in areas vulnerable to permafrost degradation (Fig. 14). Moreover, many of the state's highways traverse areas underlain by permafrost. The remainder of this chapter updates earlier reviews by Muller (1947), Ferrians et al. (1969), and Péwé (1954, 1983b) by considering how warming permafrost may affect transportation, the Trans-Alaska Pipeline, and community infrastructure.

3.3.1 Transportation Network

The State of Alaska agency primarily responsible for transportation infrastructure is the Department of Transportation and Public Facilities (ADOT&PF). The ADOT&PF discusses the history, present status, and plans for road, rail, air, and marine transportation infrastructure in its *Vision 2020 Update, Statewide Transportation Plan* (ADOT&PF, 2002). With respect to the present status of roads, this report notes that "…Alaska is twice the size of Texas, but its population and road mileage compare more closely with Vermont…." The state has approximately 12,700 miles of roads, about 30% (less than 4,000 miles) of which are paved. Gravel and dirt roads are by far the most common design. The majority of the state's roads are in the south-central region, where permafrost is discontinuous and sparse. Roads in the interior, particularly north of Fairbanks (i.e., the gravel Dalton Highway), traverse areas underlain by ice-rich permafrost and may require substantial rehabilitation or relocation if thaw occurs.

The Alaska Railroad extends from Seward to Fairbanks, crosses permafrost terrain, and has been affected by differential frost heave and thaw settlement in places (Ferrians et al., 1969). The railroad does not extend northward into the zone of continuous permafrost. Thaw of ice-rich permafrost will increase railway maintenance costs but should not require major relocations of the existing track. Plans to extend the track to Canada across the interior will involve routing through permafrost areas. Selecting a route that avoids ice-rich permafrost foundations will increase the track mileage and construction cost.

Alaska has 84 commercial airports and more than 3,000 airstrips. The state has 285 publicly owned airports, 261 of which are owned by the state government, including 67 paved airstrips, 177 gravel airstrips, and 41 seaplane ports. Many of the state's rural communities depend exclu-



Summary of Alaska Highways Susceptible to Permafrost

Permafrost Extent	Road Distance (mi)
Continuous (90 – 100%)	456
Discontinuous (50 – 90%)	1,211
Sporadic (10 – 50%)	189
Less than 10%	281

Summary of Alaska Communities Susceptible to Permafrost

Permafrost Extent	Total Communities	Population
Continuous (90 – 100%)	87	40,811
Discontinuous (50 – 90%)	79	47,140
Sporadic (10 – 50%)	26	5,235
Less than 10%	129	396,821

Figure 14. Exposure of communities and major roads in Alaska to permafrost. (Source data: U.S. Geological Survey, International Permafrost Association, and Alaska Department of Natural Resources GIS database.

sively on a local airstrip for transporting passengers and freight, including heating fuel. A significant number of airstrips in communities of southwest, northwest, and interior Alaska are built on permafrost and will require major repairs or complete relocation if their foundations thaw.

The vulnerability of Alaska's network of transportation infrastructure to thawing of permafrost can and should be assessed systematically. Roads, railways, and airstrips placed on ice-rich continuous permafrost will generally require relocation to well-drained natural foundations or replacement with substantially different construction methods. Roads through discontinuous permafrost will require this reinvestment for reaches built on ice-rich permafrost. Roads and airstrips built on permafrost with a lower volume of ice will require rehabilitation, but perhaps not relocation, as the foundation thaws.

Site-specific information is most desirable for this purpose, but the information contained on permafrost maps can be applied to compute an expected value of road miles over each category of permafrost. Figure 14 shows the major road routes of the state and the locations of communities, shaded to indicate whether they are situated in areas of continuous, discontinuous, or sporadic permafrost. Thawing of various types of permafrost is predictable by analyses based on knowledge of soil conditions and air temperature warming projections. A timeline for serious permafrost-related problems could be derived from projections of general circulation models in a manner similar to that of Nelson et al. (2001). Expected values of relocation and rehabilitation can be developed, given estimates of per-mile design and construction costs. A master plan of climate-change-induced major relocation and rehabilitation projects can be formed with this information. The information can also be applied efficiently to locate stations to monitor permafrost warming where it matters most. This effort could best be accomplished comprehensively through the combined resources and efforts of the state and federal governments.

3.3.2 Community Infrastructure

Community infrastructure includes facilities in urban and rural communities that are not associated with the transportation network or the Trans-Alaska Pipeline. Examples of community infrastructure include private and public buildings, landfills, sewer and water facilities, solid waste facilities, electrical generating facilities, towers, antennas, and fuel storage tanks. Figure 14 shows the locations of settlements in Alaska with regard to permafrost susceptibility. Although the major population center in the Anchorage area is largely free of permafrost, over 160 communities lie in areas of continuous or discontinuous permafrost. Alaska has four large military bases, two of which must contend with discontinuous permafrost. Alaska also has 600 former defense sites. Russia has an even greater problem, with a significant number of population centers, industrial complexes (including one nuclear power plant), and military bases in permafrost areas (Ershov et al., 2003). The continuous permafrost in the far north forces essentially all facilities to be constructed on permafrost. Farther south, in areas of discontinuous permafrost, land ownership and needs often force facilities to be developed on permafrost.

The permafrost underlying most of the state is the key reason why Alaskan infrastructure will be affected by a warming climate far greater than any other region of the U.S. Thawing permafrost poses several types of risks to community infrastructure. Most are associated with the thawing of ice-rich permafrost, which, when thawed, loses strength and volume. The most basic risk is caused by the loss of mechanical strength and eventually thaw settlement or subsidence. Thaw settlement causes the failure of foundations and pilings, affecting all types of community infrastructure. Bond strengths between permafrost and piles are greatly reduced by rising temperatures. Increases in the thickness of the active layer can cause frost heaving of pilings and structures. Warming will also accelerate the erosion of shorelines and riverbanks, threatening the infrastructure located on eroding shorelines. Thawing of permafrost or increasing the thickness of the active layer can also mobilize pollutants and contaminants that are presently confined (Snape et al., 2003).

Thawing permafrost and changes in the active layer across Alaska will bring potentially adverse impacts to building foundations and support structures. The past is replete with examples of public and private facilities that have failed due to warming and subsidence of the underlying permafrost because of improper siting, design, and construction methods. Thaw subsidence has resulted in numerous cases of expensive fixes or abandoned facilities. During new construction, if ice-rich permafrost cannot be avoided, it can be addressed with proper design and construction techniques. Methods include digging out the permafrost if it is relatively shallow and thin, raising the structure on piles, or otherwise assuring that the substrate remains frozen through active or passive refrigeration. Mitigating existing problems is difficult and expensive, requiring reconstruction of the building support system, as well as repairing the damage to the structure. Warming creates further problems, however. If mean annual air temperatures rise above the freezing point, it will be impossible to maintain permafrost over the long term without expensive artificial refrigeration. The largest problem will be for those areas where the upper permafrost layers are already near the freezing point, primarily in regions of discontinuous permafrost. Larger facilities, such as schools and tank farms, will be affected first. Continued warming will cause problems even for those facilities that were properly designed to maintain the underlying permafrost in its frozen state. New approaches for maintaining existing structures and building new structures on permafrost must be developed to account for increases in soil temperatures.

Thaw subsidence is also a problem for utility distribution networks and communications facilities. These facilities are usually based on foundations or pilings. Frost heaving of piles can result from increased active-layer thickness. One of the major effects of thawing ice-rich permafrost is the development of thermokarst terrain. Uneven surfaces created by differential thaw settlement will cause problems with above-ground power lines, water, sewer, and fuel piped systems. Piped systems are especially susceptible to settlement and subsequent leakage (Williams, 1986).

In many arctic communities, modern sewer and water facilities are non-existent. Many villages still use “honeybucket” (storage and haul) systems in which human waste is emptied into a pit or lagoon in or near the town. Many of the towns with more modern facilities also have lagoons where waste is dumped or piped. Sewage disposal systems that are designed for subsurface discharge may benefit from less extensive permafrost, increased water table depth, and increased groundwater flow rates. For systems that discharge into streams or rivers, increased stream flow and reduced ice cover will help aerate and dilute the effluent. Landfills containing solid waste pose problems in that contaminants confined by the frozen ground may be released and transported as the permafrost thaws. The problem is amplified because there is often far more than solid waste in landfills and at many other locations near villages. Past practice throughout the north has ignored proper disposal of contaminants because of the associated expense and the perception that permafrost acts as an impermeable barrier.

Some villages or facilities located on riverbanks or exposed coastlines are facing major problems with erosion (Walker and Arnborg, 1966; USACE, 1999; Walker, 2001). Warming has contributed to longer ice-free seasons in arctic areas. Riverbank erosion has destroyed homes and public infrastructure in some villages (USACE, 1999). Increased storminess and higher waves are eroding arctic coasts at greater rates than in the past (Brown et al., 2003). The combination of increased wave action and warming permafrost especially threatens low-lying coastal villages (Walker, 2001). Several villages in Alaska have lost buildings to the sea (Callaway et al., 1999). In some cases, entire villages may have to be relocated. Abandoning and rebuilding communities will have the secondary effect of generating large amounts of solid waste.

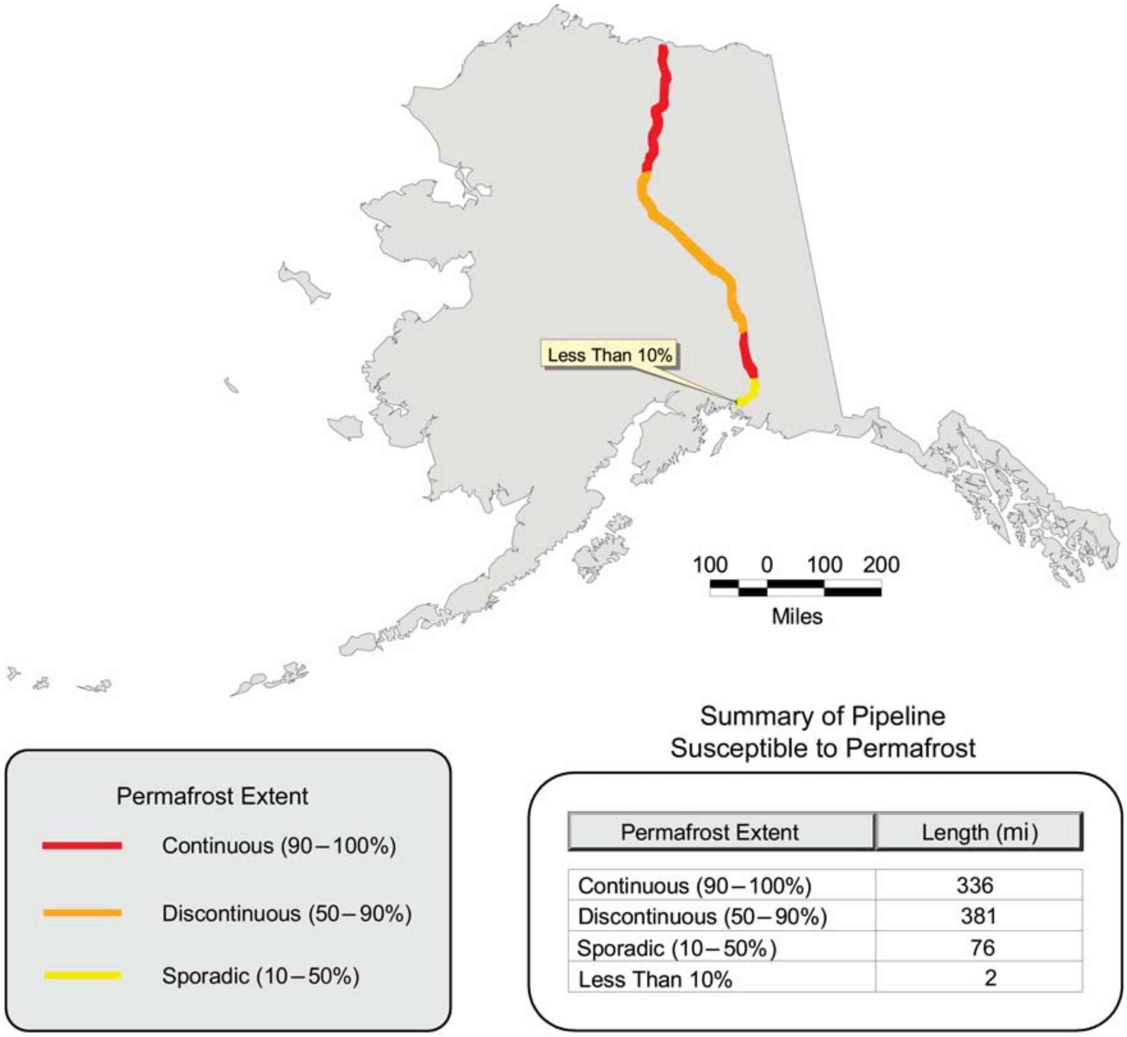
The costs associated with rehabilitating or abandoning community infrastructure damaged by thawing permafrost will be high. Even buildings that have been designed for ice-rich permafrost will not survive unscathed if the temperature rises to the point that systems designed to maintain permafrost in its frozen state no longer function adequately. Electrical distribution systems and pipe and utilidor systems will be subject to failure from subsidence or frost heaving. Contaminants could be released from landfills and other contaminant storage sites once thought to be safe. Huge costs will be associated with villages that must be relocated. In one case study by the Corps of Engineers in 1998, the costs of moving the village of Kivalina, Alaska, to a nearby site were estimated at $54,000,000

(USACE, 1998). Other coastal and river villages can be expected to have problems with warming permafrost and may require additional relocations.

The military has extensive facilities in Alaska. Two of its largest bases and a major training facility are located in areas of discontinuous permafrost, and they must constantly cope with problems caused by thawing permafrost (Cole, 2002). There are also 600 formerly used defense sites in Alaska. Alaska is also used extensively for training, requiring access by military vehicles and live firing of munitions. The development of thermokarst terrain would make some training lands unusable. Additional precautions will be necessary for contaminants generated by the military, some of which are associated with the use of live munitions. Permafrost must be considered in Department of Defense plans for new facilities, including the National Missile Defense sites being contemplated for Alaska.

3.3.3 The Trans-Alaska Pipeline

The Trans-Alaska Pipeline System (TAPS), the only large-diameter hot-oil pipeline to traverse environmentally sensitive permafrost terrain (Fig. 15), has been called an engineering marvel.



Summary of Pipeline Susceptible to Permafrost

Permafrost Extent	Length (mi)
Continuous (90–100%)	336
Discontinuous (50–90%)	381
Sporadic (10–50%)	76
Less Than 10%	2

Figure 15. Exposure of the Trans-Alaska Pipeline to permafrost. (Source data: U.S. Geological Survey, International Permafrost Association, and Alaska Department of Natural Resources GIS database.

The TAPS encounters a wide variety of permafrost soil and temperature conditions (Kreig and Reger, 1983). To avoid permafrost degradation, soil liquefaction, and subsidence, pipeline along 434 of the 800 miles of the TAPS was elevated on vertical support members (VSMs) (Fig. 16). The VSMs represented a new approach to engineering when they were designed in the early 1970s. Design standards were based on the permafrost and climate conditions of the period 1950–1970. The objectives of the design were to eliminate thawing of permafrost soils and maintain soil stability (Williams, 1986, Chapter 4).

About 61,000 of the 78,000 VSMs are equipped with pairs of thermosyphons (heat pipes), which were installed to remove heat from the permafrost by releasing it to the atmosphere. They are designed to operate between a range of temperatures in summer and winter and were installed mainly in areas of warm permafrost. Alyeska Pipeline Service Company's *Environmental and Technical Stipulation Compliance Assessment Document* provided the geotechnical justification for the design mode for each of the 1000 individual design segments in the 800-mile pipeline. The pipeline includes 200 elevated segments, where the thermosyphon function is particularly important because local soils have high liquefaction potential. An assessment of the long-term performance of the TAPS heat pipes is provided by Sorensen et al. (2003).

The Federal/State Joint Pipeline Office (JPO) has identified 22,000 VSMs as having possible problems caused by climate change along the pipeline route (JPO, 2001). It has also identified more than 50,000 of the heat pipes that have experienced some malfunction or blockage over the 25-year life of the TAPS. Some VSMs have required replacement. A thawing south-facing slope first identified in 1990 at the Squirrel Creek crossing resulted in one VSM tilting seven degrees by 1993. VSMs at this site were replaced in 2000. Other VSMs are being evaluated for replacement (Golder Associates, 2000). Proper functioning of the VSMs is critical to the future reliability of the TAPS.

At present, neither Alyeska Pipeline Service Company nor the JPO regard permafrost degradation as a problem. This interpretation is based, however, on the present permafrost and climate conditions and does not consider the Arctic Climate Impact Assessment predictions for the next 30 years. It is important to note that the 20-year period used to determine design standards was one of the coldest periods in recent Alaskan history.

The TAPS right-of-way leases from the federal and state governments terminate in 2004, and the owner companies plan to ask for a 30-year renewal. The original VSM design represented a coordinated effort by the Alyeska owners with strong oversight by the TAPS Federal Inspectors Office. That office relied

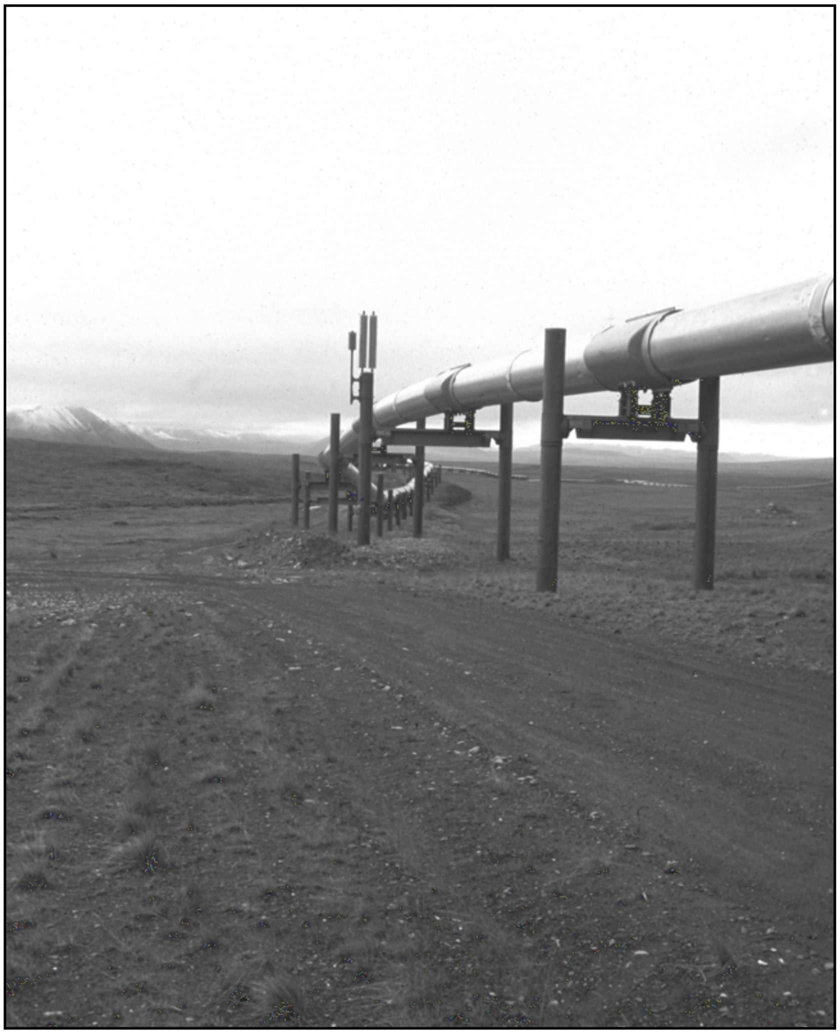


Figure 16. Vertical support members (VSMs) along the Trans-Alaska Pipeline System.

upon the expertise of the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and the USGS for identification of soil and permafrost problems; continuing operations should incorporate similar cooperative efforts.

In addition to the TAPS segments elevated on VSMs, soil stability in non-permafrost areas where the pipeline is buried may be affected. While there was no permafrost located immediately adjacent to the buried pipeline, changes in freeze–thaw depth, water table location, and soil bearing capacity may cause degradation in downslope areas, river crossings, and other areas.

The TAPS cannot be discussed without mentioning the large infrastructure on the North Slope, which provides the oil to the pipeline. Literally tens of billions of dollars of construction is responsible for drilling pads, production installations, injection plants, pump stations, and hundreds of miles of feeder pipelines. Although these facilities are located on the colder permafrost north of the Brooks Range, which may not be as susceptible to thawing as is the warmer permafrost, their impacts have been substantial (Walker et al., 1987; Committee on Cumulative Environmental Effects, 2003, Chapter 6) and close monitoring is critical.

3.4 Summary

A significant proportion of Alaska's population and infrastructure is located in areas of permafrost, much of which may become unstable under conditions of global warming. Although much of this infrastructure was designed for permafrost, substantial retrofitting to accommodate warming conditions may be necessary. In many instances designs are clearly inadequate, and infrastructure could be severely damaged by differential thaw settlement.

The problems presented by climate warming in Alaska, although substantial, are not insurmountable. To achieve maximum effectiveness in an era of declining oil revenues and limited financial resources for both industry and government at all levels, a prevenient, well-informed, and coordinated response to the effects of global warming on permafrost is essential. The last chapter of this report provides a general prescription for the roles governmental agencies can and should play in permafrost research.

Chapter 4

FINDINGS AND AGENCY RECOMMENDATIONS

Members of the U.S. Arctic Research Commission Permafrost Task Force met in Salt Lake City, Anchorage, San Francisco, and Seattle between November 2001 and December 2003. Discussions were also held with scientists, private industry, the U.S. Permafrost Association, senior managers of federal agencies, and State of Alaska departmental personnel. An integration of these meetings and discussions with the background provided by Chapters 1 through 3 of this report resulted in the following findings and recommendations. The entire report with recommendations has been reviewed by the Commissioners and five independent, outside reviewers.

4.1 U.S. Federal Permafrost Research Programs

4.1.1 Permafrost: Equal Attention

Despite publication of several reports specifying needs and strategies (Committee on Permafrost, 1974, 1975, 1976, 1983; Brown and Hemming, 1980), permafrost research, both basic and applied, has received less attention within U.S. government research programs than it warrants. This situation may in part result from a perception that permafrost is very slow to respond to climate change. On the contrary, permafrost has significant roles in climate change: as a record keeper of past temperatures, as a translator of climate change through the effects of its degradation on ecosystems and human infrastructure, and as a facilitator through its potential for release of sequestered carbon. The importance of permafrost in the global system, combined with our incomplete understanding of the role and behavior of frozen ground and associated processes, dictates that permafrost research should have equal weight with other components of the cryosphere in climate-change research. *The Task Force believes it is critical that programs such as SEARCH, ACIA, PACE, ACD, Arctic-CHAMP, Land–Shelf Interactions, the Fourth International Polar Year, and others have permafrost research as one of the critical elements of their science plans.* ***The Task Force recommends*** *that all responsible funding agencies review their interdisciplinary Arctic programs to ensure that permafrost research is appropriately integrated in program planning and execution.*

4.1.2 Lack of a Visible U.S. Federal Research Program

The Task Force found no focused federal research program dedicated to permafrost. The National Science Foundation funds investigators in a wide range of disciplines and, under the Office of Polar Programs (mostly through its Arctic System Science Program), makes awards in permafrost science. The two components of GTN-P are examples of highly successful research programs that have received recent support from NSF. Another good example is the development of a Permafrost Observatory at Barrow by the International Arctic Research Center, University of Alaska Fairbanks. In past decades, particularly during the Cold War and the construction of the DEW Line and the Trans-Alaska Pipeline, CRREL and USGS had viable and robust long-term research programs on permafrost science and engineering. These once highly visible federal programs no longer exist. ***The Task Force recommends*** *that the USGS, because of its key responsibilities in Alaska, should develop a long-term permafrost research program with emphasis on field programs. Recognizing DOD's responsibilities in the areas of contaminants on formerly used defense sites and future military construction in Alaska,* **the Task Force recommends** *enhanced funding for permafrost research and continued development of permafrost expertise at CRREL.*

4.2 Data Collection, Protocols, Monitoring, and Mapping

4.2.1 Standardized Collection of Basic Environmental Parameters

Standardized collection of basic environmental parameters is essential to all scientific and engineering endeavors in cold regions. Effectively designed and implemented monitoring programs and sampling strategies provide data that form the foundation upon which all efforts ultimately depend. Moreover, the data derived from such programs are invaluable for modeling efforts (e.g., general circulation models). ***The Task Force recommends*** *that the WMO GHOST (Global Hierarchical Observing Strategy) hierarchical monitoring scheme discussed in Chapter 2 be implemented in its current or a modified format in permafrost monitoring programs.* Effort should be made to support the instrumentation deemed necessary to collect basic data, in addition to the information collected for process-based field studies. At the lowest level of instrumentation, air, near-surface, and upper-permafrost temperature measurements should be collected at subdiurnal frequencies. Complete meteorological instrumentation at the higher end of the spectrum should include measurements of wind speed and direction, insolation, surface albedo, soil moisture, and snow cover thickness, and it should include a dense vertical array of thermistors extending from the soil surface, through the active layer, and deep into the underlying permafrost. The basic aspects of data collection at these sites should be standardized (e.g., all air temperature measurements should be made at the same height above the ground surface using a standard radiation shield). Such sites should be linked via satellite to provide real-time data to users. Further, a concerted effort should be made to assess the degree to which instrumented sites are representative of the landscape. At this scale, timely acquisition of current and historical remotely sensed imagery is essential. In this way, a standardized set of basic environmental measurements, representative of a larger region, can be collected and incorporated into a spatially extensive data set that can serve the needs of the national and international cold-regions science and engineering communities.

4.2.2 Measurement Protocols for Permafrost Monitoring

A specific set of measurement protocols should be developed for monitoring permafrost and closely related phenomena. The protocols should be established by the scientific and engineering communities for the purpose of obtaining appropriate measurements at appropriate spatial and temporal frequencies and resolution. These protocols should cover the scale of instrumentation, ranging from site to satellite. Inherent in these protocols are the requisite accuracy and precision of thermistors, optimal depth of soil measurements, and requisite ancillary data. This effort should be coordinated and integrated with the GTN-P to ensure collection of data useful for global climate observation (Burgess et al., 2000; GTN-P web site). Similarly, methods of monitoring active-layer thickness and thaw subsidence should be integrated with those of ongoing international projects (e.g., CALM, PACE) following discussion and any appropriate modification of those protocols currently in place. In all cases, effort should be made to assess the spatial variability of thaw depth and soil temperature and to collect ancillary data.

4.2.3 Permafrost Data Management

Data collected by federally funded permafrost projects should be archived in the Frozen Ground Data Center at NSIDC within appropriate time periods. Details about data-collection sites and meteorological and ground measurements should be available in metadata files with standardized formats. Some data would be processed in accordance with identified and established user needs (e.g., modelers and engineers may make better use of average daily temperatures or accumulated degree-days of freezing, thawing, heating, and cooling rather than hourly air temperatures). Spatially intensive measurements, such as satellite imagery or thaw depths collected on a regular grid, should be available in a format conducive to generation of descriptive statistics and rapid mapping. Ultimately, these data will become part of an international cold regions environmental data directory with links to other databases.

4.2.4 NSIDC Frozen Ground Data Center

A recent initiative at the National Snow and Ice Data Center (NSIDC) in Boulder has been to archive permafrost and seasonally frozen ground data (for example, borehole data, Arctic Coastal Dynamics program data, and maps and soils data from Russia and China). These activities are partially funded by the International Arctic Research Center at the University of Alaska Fairbanks. The data activities are an outgrowth of the International Permafrost Association's data rescue program, the Global Geocryological Database. Long-term funding for the Frozen Ground Data Center is required. *Recognizing that NSIDC is funded primarily by NOAA, **the Task Force strongly recommends** that additional funding be provided by both NOAA and USGS to fully develop and sustain the Frozen Ground Data Center (an estimated $300,000 annually is required for adequate support).*

4.2.5 Baseline Permafrost Mapping

***The Task Force recommends** that U.S. and international funding be sought to update the International Permafrost Association's* Circum-Arctic Map of Permafrost and Ground Ice Conditions *(Brown et al., 1997), using the most recent international databases and maps. In addition, **the Task Force recommends** the funding and production of a high-resolution permafrost map for Alaska, a critical requirement for the state's future with regard to climate change. Federal and state agencies and, potentially, the private sector should jointly fund this effort (USGS; Army Corps of Engineers, Alaska District; Alaska State agencies; and industry).* The evolving Arctic Coastal Dynamics (ACD) program, a joint effort of the IASC and IPA, could also be a vehicle for facilitating data collection and mapping of coastal erosion and flooding regimes. A continuing research theme should be the integration of existing permafrost maps with elements of Arctic infrastructure, using GCMs and GIS. These products should include new information on the distribution and properties of offshore and alpine permafrost.

4.2.6 Measurement Technologies and Remote Sensing

Typical measurements for the different hierarchies of permafrost sites are provided in Section 2.3. Measurements range from probing the active layer once annually to observing soil temperature approximately hourly; annual to semi-annual permafrost temperatures have also been taken at 100-m depths. A fully instrumented single site for examining temporal variability would include measurements of soil temperature, soil moisture, active-layer thickness, thaw settlement, and near-surface permafrost temperatures. Air temperature, wind speed, precipitation, and snow depth are also high-priority measurements. With the exception of soil moisture, off-the-shelf instrumentation can make these measurements automatically and relatively inexpensively. Presently, data are typically recorded on a datalogger downloaded during an annual visit to the site. Retrieval of data by satellite uplink would mitigate the need for large data storage capacity on-site and would allow sites to be monitored in near-real time. A critical instrumentation issue that needs to be addressed is the development of advanced technology for monitoring soil moisture. ***The Task Force recommends** support for the development of instrumentation for sensors in cold-regions terrain by NSF's Office of Polar Programs and Directorate of Engineering and by NASA.*

Satellite remote sensing offers the greatest opportunity for large-scale monitoring of the state of ground. The capability of current sensors for permafrost monitoring needs to be fully evaluated and exploited, as the study of permafrost by satellites has been a low-priority issue in the remote sensing community. ***The Task Force recommends*** *that NASA continue development of new satellite sensors optimized for monitoring state of the surface, temperature, moisture, and ground ice in cold regions.* A greater capability to detect ground ice would have additional planetary applications. All remote sensing techniques will require thorough field validation. Until reliable permafrost sensors become available, methods that combine remotely sensed data with ground-based measurements and soil thermal modeling should be developed and tested. Further, much can be inferred about permafrost from combining digital elevation measurements (DEMs) with other remotely sensed parameters such as those concerning snow cover and vegetation. However, the DEMs currently available for much of Alaska are extremely coarse and sometimes inaccurate, limiting their utility. ***The Task Force recommends*** *support for advanced studies involving synthesis of remotely sensed data with other data sets, including model output.*

4.2.7 Monitoring and Analysis Requirement

The Task Force recommends *a new approach (via federal legislation) for funding the monitoring of cold-regions environments in which federal projects are planned. Federal agencies that fund all or portions of major public works (in excess of $1M in cost) in Alaska should specify that 1% of the project planning, design, and construction costs for future Alaskan projects be invested in monitoring in the vicinity of the construction site.* In this way climate change can be more adequately monitored and observations analyzed and mapped into the future.

4.3 Basic Permafrost Research

4.3.1 Process Studies in Permafrost Research

Transfer functions: air–surface–permafrost, snow, vegetation. Quantitative estimation of the air–surface–permafrost transfer function remains a significant problem, because of non-linearity in the near-surface layer (air, snow, vegetation) and because of numerous feedback effects. Continued basic research on these processes is critical if a complete understanding of arctic energy flows is to be achieved.

Carbon cycle considerations. Greenhouse gases (carbon dioxide and methane) released from thawing permafrost into the atmosphere could create a strong positive feedback in the arctic system, and this topic is under investigation at several sites. Counterbalancing this prediction, there may be increased arctic ecosystem plant productivity, which could enhance the carbon sink (Kolchugina and Vinson, 1993). The carbon cycle in the nearshore zone of the Arctic Ocean has received less attention and requires significant investigation. Key questions remain: What is the major mechanism regulating the distribution and associated rates of carbon transfer, transformation, and burial in the arctic land–shelf system? How do biogeochemical processes on the Arctic Ocean margins influence the chemistry and biology of surface waters and associated fluxes of CO_2 between the air–water (or air–ice) interface? Answers to such questions require much more research on the state of offshore and onshore permafrost in the atmosphere–land–shelf system in the Arctic.

Hydrology and hydrogeology. Although Arctic hydrology has received serious attention in many science planning documents, little attention has been devoted to subsurface hydrologic and hydrogeologic processes. This is a critical omission because subsurface flow and subsurface storage are extremely important in the arctic hydrological system and in the arctic water cycle as a whole. Studies of permafrost hydrogeology are practically nonexistent in the U.S., a serious gap in research for the high Arctic and Subarctic. ***The Task Force recommends*** *that NSF's new arctic programs, Arctic-CHAMP and Land–Shelf Interactions, fully incorporate permafrost hydrology and hydrogeology in their science plans.*

Permafrost degradation. Stratigraphic and paleogeographic evidence indicates that permafrost will degrade if recent climate warming continues. Degradation of ice-rich permafrost has been documented under contemporary conditions in central Alaska and elsewhere (Osterkamp and Romanovsky, 1999; Osterkamp et al., 2000; Jorgenson et al., 2001). Little is known, however, about specific processes associated with the thawing of permafrost, either as a function of time or as a three-dimensional process affecting the geometry of permafrost distribution over a wide spectrum of geographic scale. There is urgent need to conduct theoretical and numerical studies and additional field investigations to address these critical issues; stratigraphic and paleoclimatic studies incorporating stable isotope dating should be included, as has been done in the field of glaciology.

Geomorphic investigations. The study of landforms and geomorphic processes is a critical component of permafrost science but has received little attention in Alaska in recent decades. Process-based and modeling investigations focused on the evolution of slopes and other geomorphic features are urgently needed. Particular attention should be given to how processes interact over a spectrum of geographic scale. Studies focused on landscape evolution over extended periods are also critical and can contribute to existing programs (e.g., SEARCH, Arctic-CHAMP) concerned with hydrological and sediment budgets over extensive areas. Geomorphological studies should, where possible, employ a systems approach that combines expertise from closely related disciplines.

4.3.2 Permafrost Modeling

Modeling is a powerful tool in permafrost research. Although significant progress has been achieved during the last three decades, the importance of permafrost in a global context has been underestimated. Until recently, GCMs did not incorporate permafrost and permafrost-related processes. The modeling community has begun to understand that unless permafrost and permafrost-related processes are incorporated, there is little reason to expect that GCMs will produce physically reasonable results for the Arctic (Slater et. al., 1998a, b). Inclusion of permafrost in GCMs is a major challenge to both modelers and permafrost researchers, and continued cooperative research between the two communities is a necessity. Funding of modeling efforts for arctic and subarctic regions must require that permafrost be incorporated in the research plans.

Another important issue related to GCMs is how well they can predict the extent, duration, and thickness of snow. Permafrost degradation under a changing climate scenario is strongly influenced by the regional snow cover. To date, GCMs do not provide an adequate predictive capability for snow.

Analytical models. Many methods have been proposed to calculate active-layer thickness and mean annual permafrost surface temperatures using simplified analytical solutions (Pavlov, 1980; Zarling, 1987; Romanovsky and Osterkamp, 1995; Smith and Riseborough, 1996). For work involving point locations where subsurface data are available, the importance and utility of analytical solutions is diminished. Numerical models are widely available for permafrost problems and can be used with some confidence when adequate information about climatic, boundary layer, and subsurface parameters is available. Serious problems arise, however, when complex models are employed in a spatial context, particularly when little is known about the spatial variability of parameters important to geocryological investigations. In such cases, stochastic modeling (Anisimov et al., 2002) or analytic procedures in a GIS environment (Nelson et al., 1997; Shiklomamov and Nelson, 1999; Klene et al., 2002) often yield results superior to complex, physically based models. Analytical equations can also be helpful in providing insights into the physics of the coupling between permafrost and the atmosphere. However, these simple equations are presently limited in their usefulness because they do not include the effects of inhomogeneous active layers with multiple layers, variable thermal properties, unfrozen water dynamics, and non-conductive heat flow. Deterministic models must be transformed to probabilistic models if the risk of permafrost degradation is to be assessed under a changing climate scenario (Bae and Vinson, 2001; Vinson and Bae, 2002). More research on refining analytical models (both deterministic and probabilistic) for use in permafrost environments is a necessity.

4.4 Applied Permafrost Research

4.4.1 Synthesis for Cold-Regions Engineering Applications

Scientific research programs are not necessarily tailored to the needs of engineering practice and design criteria development. Predictions of frost effects and the behavior of frozen ground are highly empirical and are based on limited numbers of field and laboratory investigations. Far-reaching assumptions are necessary to arrive at any decisions regarding changes to the natural pattern of warming or cooling of foundations for buildings, roads, railways, or airstrips in a permafrost environment. Engineers tend to rely a great deal on the proven performance of past construction as essential validations of analytical predictions.

In a period of accelerating global warming, the recent past provides only partial guidance for predicting future permafrost conditions. Extrapolation of the recent air temperatures can be misleading. ***The Task Force believes*** *decisions regarding new infrastructure on permafrost will be more credible if they consider climate change, as predicted by global circulation models, weighed by associated probabilities.*

A history of seasonal temperature is represented through freezing and thawing indices, the annual sums of daily average temperatures below or above freezing, respectively. Freezing and thawing indices are translated to corresponding ground surface freezing and thawing indices for general categories of ground surface types, e.g., snow, turf, sand, and gravel. The transfer of atmospheric heat energy into lower layers of the soil is proportional to the soil thermal conductivity, which varies with soil grain size, dry density, water content, and water state (frozen or unfrozen). More precise computations of heat transfer are possible but impractical in all but carefully controlled research settings. Alaskan records of air temperature are sparse, and maps of soil characteristics are poorly resolved. ***The Task Force recommends*** *that a denser network of environmental monitoring stations be funded by NOAA, USGS, USDA, and responsible state agencies for Alaska.* Such a network of monitoring stations, along with the application of GIS mapping methods, will allow improved procedures to be developed for predicting permafrost behavior that can better account for natural variability and probabilistic considerations.

4.4.2 Cold-Regions Design Criteria Development

There is a significant requirement for a cold-regions engineering database to enhance the design, construction, and maintenance of infrastructure. Existing environmental atlases of Alaska are nearly twenty years old. A new database should take advantage of GIS technology and include geotechnical information, such as permafrost distribution, soil type, and soil properties, as well as climatic information including air temperature and snow depth. The system should allow standard calculations for practical engineering applications, such as freezing and thawing indices, active-layer thickness, and soil bearing capacity. There is also a need to establish a database or information clearinghouse on existing cold-regions transportation infrastructure (design, construction, and operations). Methods for site-specific forecasts of climate change must be developed. A rational approach to developing design criteria using GCM results will perhaps be more affordable than applying an arbitrarily large factor of safety to conventional design criteria. We cannot continue to treat forecasts of future climate deterministically (i.e. linearly extrapolating a rate of temperature change over a future time interval at a given location) and must move to a more probabilistic approach. Adaptating conventional statistical analyses of trends and extremes to apply GCM-predicted accelerated change is a challenging topic for researchers.

4.4.2 Trans-Alaska Pipeline System (TAPS)

In its *2001 Comprehensive Monitoring Report* (a series of three reports dealing with

TAPS operations, construction, and operation), the Joint Pipeline Office (JPO) of the U.S. and the State of Alaska indicated a range of problems regarding changing permafrost. The following conclusions were reached:

- The warming trends could have some effect on the foundations of the elevated portions of the pipeline, some 423 miles with 78,000 vertical support members (VSMs).
- More than 25,000 VSMs are currently subject to movement. Of those VSMs having heat pipes (because they are located in areas of warm permafrost), 84% have some degree of blockage that could affect the structure's load-bearing capacity.
- A long-term maintenance and reconstruction program is necessary for the VSMs.

The pipeline owners and their operating consortium, Alyeska, have contracts underway to determine the scope of the operating and maintenance program that will be necessary over the next 30 years, the period requested for a right-of-way renewal. The current lease expires in 2004 for both the federal and state rights of way.

When the present lease was issued, scientific and engineering decisions were based on the permafrost and climate regimes of the previous three decades. Permafrost engineering applications were limited until World War II and reached their peak during the construction of the DEW Line from 1948 to 1962. The expertise of CRREL and the USGS was made available to the TAPS design team, which spent four years working out the present design of the VSMs. ***The Task Force recommends** that a similar effort be made today that closely coordinates the efforts of the TAPS and JPO with a significantly upgraded federal research effort on permafrost.* Linkages with the Arctic Climate Impact Assessment (with its secretariat at the University of Alaska Fairbanks) should be established early in this effort.

4.4.3 Contaminants in Permafrost Environments

Past practice favored burial of contaminants in permafrost because it was assumed to be impermeable and therefore a safe and effective method for isolating contaminated wastes. Contaminants are mobile in the active layer, however, and some can even be mobile within frozen ground. Moreover, when permafrost thaws, the ground becomes permeable, allowing contaminants to spread laterally and to reach deeper unfrozen and frozen layers. The Arctic contains a significant number of contaminated sites; in Alaska DOD has responsibility for formerly used defense sites, some of which are contaminated. To determine the extent of the problem, sites known to be contaminated must be assessed individually, identifying the contaminants as well as the physical characteristics of the site. The potential for diffusion of contaminants will require an estimate of the impact of regional climate warming on the specific sites. To develop models to predict the transport of contaminants, the hydrological connections between the near-surface and deeper layers or ground water systems must be established. Research is also required on the chemical interaction of contaminants with the thawed soils, as well as on such mitigation techniques as bioremediation. CRREL is the logical federal laboratory for this research, and the University of Alaska (Fairbanks and Anchorage campuses) has experienced research groups in this field. ***The Task Force recommends** substantially increased federal funding for contaminants research in cold regions by DOD, EPA, and NSF, as this research is deemed critical to the Nation's cleanup effort in Alaska.*

Federal Agency, State of Alaska, and National Research Council Recommendations

U.S. Geological Survey
(Department of the Interior)

- Develop a long-term permafrost research program with emphasis on field work and monitoring of deep boreholes; formulate the program as a contribution to SEARCH.
- Adopt the WMO GHOST hierarchical monitoring program for environmental data collection for new boreholes and mapping.
- Jointly fund with NOAA the Frozen Ground Data Center at NSIDC.
- Participate in joint funding of a high-resolution permafrost map of Alaska.
- Fund (with NOAA, USDA, and state agencies) a denser network of environmental monitoring stations for Alaska.
- Provide technical expertise (on permafrost and other cold-regions issues) to the TAPS JPO during the right-of-way renewal process.
- Develop jointly with the Minerals Management Service a study of offshore undersea permafrost.
- Expand stratigraphic investigations and mapping of Quaternary permafrost in Alaska and the contiguous states.
- Expand investigations of periglacial landforms and processes (both contemporary and relict) in Alaska and the contiguous states.

U.S. Army Corps of Engineers
(Department of Defense)

- Provide enhanced funding for permafrost research and support the continued development of permafrost expertise at CRREL.
- Participate in joint funding of a high-resolution permafrost map of Alaska.
- Increase funding for research on contaminants in cold regions at CRREL.
- Plan for climate change and permafrost degradation at existing and new military facilities to be built in Alaska.
- Rescue past agency data and contribute present and future data to national archives.
- Expand the role of the National Permafrost Test Site [a node in the National Geotechnical Experimentation Sites (NGES) network] on Farmer's Loop Road outside Fairbanks.

National Science Foundation

- Review all interdisciplinary arctic programs to ensure that permafrost research is appropriately integrated in program planning and execution.
- Within the Office of Polar Programs, restructure the Glaciology program under the heading Cryosphere, which would include snow, ice, and permafrost.
- Adopt hierarchical, spatially oriented monitoring strategies (preferably variants of the WMO/GHOST approach) as appropriate for all arctic research programs.
- Fund proposals for the development of instrumentation for sensors in cold regions (e.g., an autonomous soil moisture sensor) (Office of Polar Programs and Directorate of Engineering).
- Incorporate permafrost hydrology, hydrogeology, and geomorphology in arctic programs such as Arctic-CHAMP and SEARCH; incorporate permafrost research in global carbon programs.
- Increase support for research on permafrost-related geomorphic processes and terrain/landform analysis.
- Increase support for geocryological hazards research at local, regional, and circumpolar scales.
- Increase funding for proposals dealing with research on contaminants in cold regions.
- Support international permafrost activities, including conferences and workshops.
- Integrate the use of the Permafrost National Test Site at Fairbanks into U.S. Arctic research logistics planning.
- Include permafrost research at the Barrow Global Climate Change Research Facility.

National Aeronautics and Space Administration

- Continue the development of satellite sensors optimized for monitoring the state of the surface, temperature, moisture, and ground ice in cold regions.
- Explicitly include geocryological applications in competitive grants programs concerned with the use of satellite remote sensing data.
- Include the development of frozen ground sensors in NASA contributions to SEARCH.
- Support the Barrow Global Climate Change Research Facility as a satellite sensor validation site; use the facility to ground-truth satellite frozen ground sensors.

National Oceanic and Atmospheric Administration
(Department of Commerce)

- Jointly fund with USGS the Frozen Ground Data Center at NSIDC.
- Jointly fund with USGS, USDA, and the State of Alaska a denser network of environmental monitoring stations around Alaska.
- Adopt the WMO GHOST hierarchical monitoring program for environmental data collection.

Environmental Protection Agency

- Increase funding for research on contaminants in cold regions, and fully develop a program in Alaska.
- Make funding available for permafrost-related hazards research, particularly in urban areas.

U.S. Forest Service
(Department of Agriculture)

- Increase the number of soil moisture and temperature monitoring stations in Alaska.
- Formalize and extend existing programs in soil physics and carbon sequestration.

U.S. Natural Resources Conservation Service
(Department of Agriculture)

- Refine and extend activities devoted to characterizing, classifying, and mapping cryosols in Alaska and the contiguous states.
- Formalize and extend existing programs related to carbon sequestration in tundra regions of Alaska and the contiguous states.
- Formalize and extend existing programs investigating soil physics and ground temperature in Alaska, the western cordillera of the contiguous states, and the northern Appalachians.

State of Alaska

- Review the arctic engineering certification process for knowledge of permafrost under changing climate conditions.
- Seek federal support for test programs for nonstandard pavements for roads and airport runways.
- Review building codes with a view to near-term changes in the permafrost regime.
- Intensify and extend geological and geophysical investigations of permafrost and its role in Quaternary history by the Division of Geological and Geophysical Surveys (DGGS).
- Survey community infrastructure located in permafrost environments, with specific emphasis on rural sewage and ground water systems.

National Research Council
(National Academies of Science and Engineering)

- Have the Transportation Research Board (TRB), in cooperation with the Polar Research Board (PRB), develop a proposal for a study on the impacts of changing permafrost on transportation systems in Alaska.
- Have the Polar Research Board (PRB) include global permafrost monitoring and research in the U.S.-supported programs for the International Polar Year, 2007–2008.

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Glossary

Most of the definitions given below were taken from the *Multi-Language Glossary of Permafrost and Related Ground-Ice Terms* (van Everdingen, 1998). This source should be consulted for more extensive definitions. Updates, modifications, or new definitions are indicated by inclusion of additional references.

Active layer

The layer of ground subject to annual thawing and freezing in areas underlain by permafrost.

Active-layer detachment slide

Shallow landslides that develop in permafrost areas, involving reduction in effective stress and strength at the contact between a thawing overburden and underlying frozen material. Active-layer detachment slides can occur in response to high seasonal air temperature, summer rainfall events, rapid melting of snowcover, or surface disturbances. See Lewkowicz (1992).

Active-layer thickness

The thickness of the layer of ground subject to annual thawing and freezing in areas underlain by permafrost (Also see **thaw depth**). See Nelson and Hinkel (2003).

Alas

A large depression of the ground surface produced by thawing of a large area (e.g., > 1 ha) of very thick and exceedingly ice-rich permafrost.

Cryoturbation

(a)A collective term used to describe all soil movements due to frost action.

(b)Irregular structures formed in earth materials by frost penetration and frost action processes, and characterized by folded, broken, and dislocated beds and lenses of unconsolidated deposits, included organic horizons, or bedrock.

Degree-day

A derived unit of measurement used to express the departure of the mean temperature for a day from a given reference temperature. Also see **freezing index** and **thawing index**.

Depth of zero annual amplitude

The distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature.

Excess ice

The volume of ice in the ground that exceeds the total pore volume that the ground would have under natural unfrozen conditions.

Freeze–thaw cycle

Freezing of material, followed by thawing. The two fundamental frequencies involved are *diurnal* and *annual*.

Freezing index

The cumulative number of degree-days below 0^{o}C for a given time period (usually seasonal).

Frost action

The process of alternate freezing and thawing of moisture in soil, rock, and other materials, and the resulting effects on materials and on structures placed on or in the ground.

Frost creep

The net downslope displacement that occurs when a soil, during a freeze–thaw cycle, expands perpendicular to the ground surface and settles in a nearly vertical direction.

Frost heave
The upward or outward movement of the ground surface (or objects on or in the ground) caused by the formation of ice in the soil.

Frost mound
Any mound-shaped landform produced by ground freezing, combined with accumulation of ground ice due to groundwater movement or migration of soil moisture. Also see Nelson et al. (1992).

Frost penetration
The movement of a freezing front into the ground during freezing.

Frost-susceptible soil
Subsurface earth materials in which segregated ice will form (causing frost heave) under the required conditions of moisture supply and temperature.

Frozen ground
Soil or rock in which part or all of the pore water has turned into ice.

Gas hydrate
A special form of solid clathrate compound in which crystal lattice cages or chambers, consisting of host molecules, enclose guest molecules.

Gelifluction
The slow downslope flow of unfrozen earth materials over a frozen substrate. Also see **solifluction**.

Geocryology
The study of earth materials and processes involving temperatures of 0°C or below.

Geothermal gradient
The rate of temperature increase with depth below the ground surface.

Ground ice
A general term referring to all types of ice contained in freezing and frozen ground.

High-center polygon
An ice-wedge polygon in which melting of the surrounding ice wedges has left the central area in a relatively elevated position.

Ice lens
A dominantly horizontal, lens-shaped body of ice of any dimension.

Ice segregation
The formation of discrete layers or lenses of segregated ice in freezing mineral or organic soils, as a result of the migration and subsequent freezing of pore water.

Ice wedge
A massive, generally wedge-shaped body with its apex pointing downward, composed of foliated or vertically banded, commonly white, ice.

Ice-wedge polygon
A network of ice wedges defining the boundaries of a geometric polygon in plan view.

Intrusive ice
Ice formed from water injected into soils or rocks.

Latent heat of fusion
The amount of heat required to melt all ice (or freeze all pore water) in a unit mass of soil or rock. For pure water this quantity is 334 J g^{-1}.

Low-center polygon
An ice-wedge polygon in which thawing of ice-rich permafrost has left the central area in a relatively depressed position.

Mass wasting (mass movement)
Downslope movement of soil or rock on or near the earth's surface under the influence of gravity.

Massive ice
A comprehensive term used to describe large masses of ground ice, including ice wedges, pingo ice, buried ice, and large ice lenses.

Mean annual air temperature (MAAT)
Mean annual temperature of the air, measured at standard screen height above the ground surface.

Mean annual ground-surface temperature (MAGST)
Mean annual temperature at the surface of the ground.

Mean annual ground temperature (MAGT)
Mean annual temperature of the ground at a specified depth.

N-factor
The ratio of the freezing or thawing index at the ground surface to that derived from air temperature records.

Palsas
Permafrost mounds ranging from about 0.5 to about 10 m in height and exceeding about 2 m in average diameter, comprising (1) aggradation forms and (2) degradation forms. The term "palsa" is a descriptive term to which an adjectival modifier prefix can be attached to indicate formative processes. See Washburn (1983) and Nelson et al. (1992).

Patterned ground
A general term for any ground surface exhibiting a discernibly ordered, more or less symmetrical, morphological pattern of ground and, where present, vegetation.

Periglacial
The conditions, processes, and landforms associated with cold, nonglacial environments, regardless of proximity to past or present glaciers.

Permafrost
Earth materials that remains continuously at or below 0°C for at least two consecutive years.

Permafrost, continuous
Regions in which permafrost occurs nearly everywhere beneath the exposed land surface. At the circumpolar scale the term *continuous permafrost zone* refers to a broad area, crudely conformable with latitude, in which permafrost is laterally continuous. See Nelson and Outcalt (1987).

Permafrost, discontinuous
Regions in which permafrost is laterally discontinuous owing to heterogeneity of material properties, subsurface water, and surface cover.

Permafrost, dry
Permafrost containing neither free water nor ice.

Permafrost, ice-rich
Permafrost containing excess ice.

Pingo
A perennial frost mound consisting of a core of massive ice produced primarily by injection of water, and covered with soil and vegetation.

Retrogressive thaw slump
A slope failure resulting from thawing if ice-rich permafrost.

Seasonally frozen ground
Ground that freezes and thaws annually.

Solifluction

A general term referring to the slow downslope flow of saturated unfrozen earth materials over an impermeable substrate (also see **gelifluction**).

Thermokarst terrain

Irregular topography resulting from the melting of excess ground ice and subsequent thaw settlement.

Thaw depth

The instantaneous depth below the ground surface to which seasonal thaw has penetrated (also see **active-layer thickness**). See Nelson and Hinkel (2003).

Thaw lake

A lake whose basin was formed or enlarged by thawing of frozen ground. See Hopkins (1949) and Washburn (1980, p. 271).

Thaw settlement

Compression of the ground due to loss of excess ground ice and attendant thaw consolidation.

Thawing index (DDT)

The cumulative number of degree-days above 0°C for a given time period (usually seasonal).

Thaw consolidation

Time-dependent compression resulting from thawing of ice-rich frozen ground and subsequent draining of excess water.

Thermal erosion

Erosion of ice-bearing permafrost by the combined thermal and mechanical action of moving water.

Thermal conductivity

The quantity of heat that will flow through a unit area of a substance in unit time under a unit temperature gradient. In permafrost investigations thermal conductivity is usually expressed in $W\ m^{-1}\ {}^{o}C^{-1}$.

Thermal offset

Temperature depression in the upper layer of permafrost, resulting from the combined effects of seasonal differences of thermal conductivity and the operation of nonconductive processes in the active layer. See Williams and Smith (1989) and Nelson et al. (1985).

Zero curtain effect

Persistence of a nearly constant temperature very close to the freezing point of water during annual freezing (and occasionally thawing) of the active layer. See Outcalt et al. (1990).

List of Acronyms

ACD
Arctic Coastal Dynamics (IASC)

ACIA
Arctic Climate Impact Assessment

ADOT&PF
Alaska Department of Transportation and Public Facilities

ALT
active-layer thickness

ARCSS
Arctic System Science program (NSF/OPP)

Arctic-CHAMP
Community-wide Hydrological Analysis and Monitoring Program (U.S. National Science Foundation initiative)

BEO
Barrow Environmental Observatory

CALM
Circumpolar Active Layer Monitoring program

CEON
Circumarctic Environmental Observatories Network

CRREL
Cold Regions Research and Engineering Laboratory (U.S. Army Corps of Engineers)

DGGS
Division of Geological and Geophysical Surveys (Alaska Department of Natural Resources)

DOD
U.S. Department of Defense

EPA
U.S. Environmental Protection Agency

FAO
Food and Agriculture Organisation (of the United Nations)

FGDC
Frozen Ground Data Center (NSIDC)

GCOS
Global Climate Observing System

GCM
general circulation model (or global climate model)

GHOST
Global Hierarchical Observational Strategy (WMO)

GIS
geographic information systems (or geographic information science)

GSC
Geological Survey of Canada

GTN-P
Global Terrestrial Network for Permafrost

GTOS
Global Terrestrial Observing System

IASC
International Arctic Science Committee

ICSU
International Council of Scientific Unions

IPA
International Permafrost Association

IPCC
Intergovernmental Panel on Climate Change

IPY
International Polar Year

JPO
Joint Pipeline Office (U.S. federal and State of Alaska)

LTER
U.S. Long Term Ecological Research Network

MAAT
mean annual air temperature

MAGST
mean annual ground surface temperature

MAGT
mean annual ground temperature

NASA
U.S. National Aeronautics and Space Administration

NOAA
U.S. National Oceanic and Atmospheric Administration

NRCS
U.S. Natural Resources Conservation Service (USDA)

NSF
U.S. National Science Foundation

NSIDC
U.S. National Snow and Ice Data Center (Boulder, Colorado)

OPP
Office of Polar Programs (U.S. National Science Foundation)

PACE
Permafrost and Climate in Europe program

SEARCH
Study of Environmental Arctic Change (U.S. federal government multiagency initiative)

TAPS
Trans-Alaska Pipeline System

TDR
time-domain reflectometry

TEMS
Terrestrial Ecosystem Monitoring Sites network

TOPC
Terrestrial Observational Panel for Climate

UAF
University of Alaska Fairbanks

UNEP
United Nations Environment Programme

UNESCO
United Nations Educational, Scientific and Cultural Organization

USACE
U.S. Army Corps of Engineers

USDA
U.S. Department of Agriculture

USPA
U.S. Permafrost Association

USARC
U.S. Arctic Research Commission

USGS
U.S. Geological Survey

VSM
vertical support member

WMO
World Meteorological Organization

UNITED STATES ARCTIC RESEARCH COMMISSION

The U.S. Arctic Research Commission (USARC) was created by the Arctic Research and Policy Act of 1984 (as amended in November 1990). The Commission, whose seven members are appointed by the President of the United States, assesses national needs for arctic research and recommends to the President and the U.S. Congress research policies and priorities that form the basis for a national arctic research plan. Other key USARC functions include facilitating cooperation in arctic research between federal, state, and local governments; recommending improvements in arctic research logistics; recommending areas for enhanced international scientific cooperation in the Arctic; cooperating with the Governor of Alaska in formulating arctic research policy; and conducting special studies such as *Climate Change, Permafrost, and Impacts on Civil Infrastructure*. USARC biennially submits a strategic document, *Goals and Objectives for Arctic Research*, to the Interagency Arctic Research Policy Committee for its use in revising a national five-year Arctic Research Plan. The Commission normally meets four times annually (at least once each year in Alaska) to hear invited and public testimony on all facets of Arctic research. The USARC staff has offices at 4350 North Fairfax Drive, Suite 510, Arlington, Virginia 22203, and 420 L Street, Suite 315, Anchorage, Alaska 99501.

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Back Cover: South-facing view of the Trans-Alaska pipeline near Sukakpak Mountain, southern Brooks Range foothills. This area is in the zone of discontinuous permafrost. Nearly 80% of the Trans-Alaska pipeline lies within the state's permafrost regions (see Figure 15). Photo by F.E. Nelson, October 1982.