

## **Climate Change and Hazard Zonation in the Circum-Arctic Permafrost Regions**

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**Abstract.** The permafrost regions currently occupy about one quarter of the Earth's land area. Climate-change scenarios indicate that global warming will be amplified in the polar regions, and could lead to a large reduction in the geographic extent of permafrost. Development of natural resources, transportation networks, and human infrastructure in the high northern latitudes has been extensive during the second half of the twentieth century. In areas underlain by ice-rich permafrost, infrastructure could be damaged severely by thaw-induced settlement of the ground surface accompanying climate change. Permafrost near the current southern margin of its extent is degrading, and this process may involve a northward shift in the southern boundary of permafrost by hundreds of kilometers throughout much of northern North America and Eurasia. A long-term increase in summer temperatures in the high northern latitudes could also result in significant increases in the thickness of the seasonally thawed layer above permafrost, with negative impacts on human infrastructure located on ice-rich terrain. Experiments involving general circulation model scenarios of global climate change, a mathematical solution for the thickness of the active layer, and digital representations of permafrost distribution and ice content indicates potential for severe disruption of human infrastructure in the permafrost regions in response to anthropogenic climate change. A series of hazard zonation maps depicts generalized patterns of susceptibility to thaw subsidence. Areas of greatest hazard potential include coastlines on the Arctic Ocean and parts of Alaska, Canada, and Siberia in which substantial development has occurred in recent decades.

**Key words:** active layer, frozen ground, ground ice, hazard, mapping, mass movement, permafrost, polar regions, subsidence, thaw settlement, thermokarst, zonation

## 1. Introduction

Many of the potential environmental and socioeconomic impacts of global warming in the high northern latitudes are associated with *permafrost*, defined as any subsurface material that remains frozen continuously for more than two consecutive years. Owing to 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 extensively in both specialist literature and textbooks (e.g., Brown and Grave, 1979; Péwé, 1983; 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 provide adequate consideration of issues related to permafrost.

Climate-change scenarios indicate that anthropogenic warming will be most pronounced in the high latitudes. Changes have been detected in many parts of the globe (Hansen et al., 1998; Serreze et al., 2000); in the northern high latitudes they have involved air temperature (Pavlov, 1997), 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), ground temperature (Lachenbruch and Marshall, 1986; Majorowicz and Skinner, 1997), and thawing of permafrost (Jorgenson et al., 2001). If anthropogenic warming evolves over the next several decades, it could produce substantial impacts in polar environments. The effects of climatic warming on permafrost and the seasonally thawed layer above it (the *active layer*) can lead to severe disruption of human activities, and to intensified global warming (Brown and Andrews, 1982; Nelson et al., 1993; Fitzharris et al., 1996). Accordingly, the International Union of Geological Sciences has included frozen ground on its list of “ge indicators,” phenomena that are important for assessing environmental change over relatively short periods (Berger and Iams, 1996).

Although the permafrost regions are not densely populated, their economic importance has increased substantially in recent decades, owing to 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, 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. Figure 1 illustrates several common geomorphic manifestations of ice-rich permafrost terrain and the effects of its degradation on engineered works.

[Figure 1 near here]

The role of permafrost in climatic change is threefold (Nelson et al., 1993): (1) it serves as a *recorder* of climatic change through its ability to track temperature trends over long periods (e.g., Lachenbruch and Marshall, 1986); (2) it can act as a *facilitator* of further climate change through release of greenhouse gases (Michaelson et al., 1996; Goulden et al., 1998; Rivkin, 1998); and (3) it can be an effective *translator* of environmental change through its effects on natural and human communities (Williams, 1995). After a brief review of the hazard potential of permafrost in the context of global warming, this paper focuses on the latter role by presenting a

generalized geographic perspective on the potential effects of permafrost degradation on human infrastructure and activities in the Northern Hemisphere.

## **2. Impacts of Climate Change in Permafrost Regions**

### **2.1. PERMAFROST ZONATION**

The permafrost regions currently occupy about one-fourth of the earth's land area (Brown et al., 1997; Brown and Haggerty, 1998; Zhang et al., 1999). At geographical scales involving regions of continental or hemispheric dimensions, the distribution of permafrost is usually represented as a series of quasi-concentric zones in which permafrost is *continuous*, *discontinuous*, or *sporadic*. Although precise definitions for these terms have not been accepted universally (Nelson, 1989) their general meanings correspond, respectively, to regions in which permafrost underlies all terrestrial surfaces (except large, deep bodies of water), those in which climate is conducive to permafrost but details of its geography are influenced by local factors (vegetation, thermal properties of the substrate, etc.), and those in which permafrost occurs only under localized circumstances favorable to its formation or preservation (e.g., peat deposits). A circum-Arctic map of permafrost distribution, compiled recently for the International Permafrost Association (IPA) with standardized criteria (Brown et al., 1997), uses values of 90-100%, 50%-90%, and below 50%, respectively, to delineate the southern margins of these zones (Figure 2). The map also indicates ground-ice content in a generalized fashion (Figure 3).

[Figures 2 and 3 near here]

Changing climatic conditions in the polar regions may cause increases in ground temperature and thickening of the active layer, reduce the area underlain by near-surface permafrost, and cause extensive settlement of the ground surface, (e.g., Woo et al., 1992; Nelson et al., 1993). Warming of permafrost in several regions is documented (e.g., Lachenbruch and Marshall, 1986; Majorowicz and Skinner, 1997; 2001). Disappearance of permafrost (French and Egorov, 1998) and northward shifts in its distribution (Thie, 1974; Kwong and Gan, 1994; Beilman et al., 2001) were also observed over the course of the twentieth century.

Anisimov and Nelson (1996, 1997) and Anisimov et al. (1997) investigated the impact of changing climatic conditions on permafrost distribution at the hemispheric scale, using equilibrium and dynamic models driven by modern climatic data and several scenarios of climate change derived from general circulation models (GCMs) and palaeoclimatic reconstructions. Predictive maps of the areal extent of near-surface permafrost in the Northern Hemisphere were constructed using results obtained by linking GCM scenarios to a permafrost-distribution model that uses the ratio between freezing and thawing degree-day sums to form a "frost index" that evaluates the likelihood of the presence of permafrost under the specified climatic conditions (Nelson and Outcalt, 1987) The frost-index approach has been tested extensively using modern permafrost and climate data for Alaska (Nelson and Outcalt, 1983), central Canada (Nelson, 1986), and Russia (Nelson and Anisimov, 1993; Christensen and Kuhry, 2000). Boundaries calculated for the continuous, discontinuous, and sporadic permafrost zones are in good agreement with empirical mappings of contemporary permafrost for the entire Northern Hemisphere. Anisimov and Nelson (1997) found a high degree of correspondence between results from the frost index and a preliminary version of the IPA permafrost map (Brown et al., 1997).

The primary conclusion of the GCM-based permafrost mapping experiments is that climate changes of the magnitude hypothesized by GCM experiments could reduce the area of near-surface permafrost in the Northern Hemisphere substantially over the next several decades.

Figure 4 shows the permafrost zonation derived from the ECHAM1-A general circulation model (Cubasch et al., 1992; Greco et al., 1994). Use of zonal boundaries to depict changes in permafrost distribution is a cartographic representation well-suited to the circum-Arctic scale. Changes in the positions of these lines, however, represent a composite of many local changes involving thinning of permafrost and an increasingly patchy distribution (Halsey et al., 1995).

Changes in the thickness of the seasonally thawed layer above permafrost may also be substantial. Anisimov et al. (1997) used the IPCC (Intergovernmental Panel on Climate Change) transient scenarios, in conjunction with Kudryatsev's solution for the depth of seasonal thaw (Yershov, 1998), to examine changes in the thickness of the seasonally thawed layer in the Northern Hemisphere. Relative increases of 20-30% were predicted for many regions, with the largest relative increases in the northernmost areas. Figure 5 shows relative changes in active-layer thickness, obtained using the ECHAM1-A GCM scenario, for a soil with silt texture and moderate moisture content. An observational network has also been implemented to monitor long-term changes in the thickness of the active layer and near-surface temperatures in permafrost regions. Known as the Circumpolar Active Layer Monitoring (CALM) program (Nelson and Brown, 1997), this network now includes more than 80 stations in 12 countries and Antarctica.

[Figures 4 and 5 near here]

## 2.2. THAW SUBSIDENCE AND THERMOKARST

Climate-induced changes in the thickness and geographical extent of permafrost have considerable potential for disruption of human activities if substantial amounts of *ground ice* are present. The origin and morphology of ground ice are varied (Mackay, 1972; Mackay and Black, 1973), ranging from thick layers of buried glacier ice, through horizontally oriented ice lenses formed by 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).

Owing to the volumetric reduction attending the phase transition from ice to water and expulsion of pore water 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, resulting in thawing of ice-rich layers and subsidence of the ground surface. 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).

Thermokarst can have severe effects on engineered structures, and in many cases can render them unusable. 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* 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 1e; 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 timescales. Removal or disturbance of the vegetation cover for agricultural purposes (Péwé, 1954), construction of roads or 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 near Fairbanks, Alaska produced up to 6.7 m of subsidence over a 26-yr period, simply by removing the insulating layer of vegetation (Linell, 1973). Even trampling can trigger thermokarst (Mackay, 1970), indicating that 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 to encourage 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) reviewed a wide range of anthropogenic disturbances affecting permafrost terrain.

Abundant geological evidence 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<sup>2</sup> or more (Soloviev, 1973; Koutaniemi, 1985; French, 1996). Kachurin (1962) and Czudek and Demek (1970) attributed development of the Siberian *alases* to warm intervals during the Holocene. In arctic parts of North America, thaw unconformities (Burn, 1997), sedimentary evidence (Murton, 2001), and widespread 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.

### 2.3. HUMAN INFRASTRUCTURE IN THE ARCTIC

Although often perceived in the popular imagination as a vast, unpopulated, and undeveloped wilderness, large tracts of the Arctic have already been affected by intense developmental pressures. According to Kryuchkov (1994, cited by Vilchek et al., 1996) approximately 31,000 km<sup>2</sup> of the Russian Arctic has been subjected to severe environmental disturbance. Large reservoirs of fossil fuels and ore deposits occur in the permafrost regions, and very substantial economic investments have been made in the Arctic. Clusters of economic development and infrastructure, many involving expensive state-of-the-art technology and complex decision-making and administrative processes, are associated with these activities (e.g., Flanders et al., 1998). Examples include the Prudhoe Bay development in the central part of Alaska's North Slope (Walker et al., 1980; Williams, 1986) and the oil and gas fields of western Siberia (Andre'eva et al., 1995; Kryukov and Shmat, 1995; Seligman, 2000).

With a few exceptions (Fairbanks, Barrow, Whitehorse, Yellowknife) human settlements in the permafrost regions of North America are relatively small, and are scattered widely. Engineered works are limited to air- and oilfields, transportation corridors, mining facilities, and pipelines. The impact of these facilities is substantial, however, and large areas that were

pristine fifty years ago are now traversed by seismic trails and scarred by abandoned petroleum-exploration facilities (e.g., Lawson and Brown, 1978; Walker et al., 1987). In northern Scandinavia several cities with populations of more than ten thousand are located in the contemporary zone of sporadic permafrost.

The developments described above are dwarfed by those in the Russian Arctic. In northern Russia large cities (Yakutsk, Noril'sk, Vorkuta) with populations of more than a hundred thousand exist in permafrost terrain. Several large river ports also occupy permafrost terrain in the lower Ob' (Salekhard), Yenisei (Igarka and Dudinka), and Lena (Tiksi) River valleys, each with a population of more than ten thousand. Smaller settlements are located around terminals on the arctic coast along the northern sea route from the Barents Sea on the west through the Kara, Laptev, and East-Siberian Seas, to the Bering Sea in the east. Several pipelines traverse the discontinuous and sporadic permafrost zones from the West Siberia oil and gas fields to the central parts of Russia. Conventional thermal and hydropower plants are located in several parts of the Russian Arctic, and a nuclear power station operates in permafrost terrain at Bilibino in the Russian Far East. Although the Bilibino station does not appear to be a major source of radionuclide contamination, the presence of permafrost has contributed to localized contamination problems in the plant's discharge zone (Cooper et al., 1996). The network of rudimentary trails and airfields in Siberia is extensive.

That thermokarst can produce dramatic socioeconomic impacts is illustrated by a 1966 disaster in Noril'sk, where a building affected by differential thaw collapsed, killing 20 people. Yakutsk, a Russian city built over permafrost in central Siberia, has suffered severe damage to its infrastructure from thawing permafrost. Thaw of ice-rich layers caused differential settlement and severe damage to several large residential buildings. In all, more than 300 buildings have been damaged by thaw-induced settlement (Anonymous, 1998). A local power generating station was also affected, resulting in temporary loss of electrical service. Development of thermokarst has severely affected the Yakutsk airport, leading to closure of a runway and a 14-fold increase in the extent of water-filled depressions in surrounding terrain. In 1998 Yakutsk was declared a natural disaster area, in which substantial investments will be necessary to prevent catastrophic consequences arising from further damage to buildings and other engineered works. The magnitude of these problems is already beyond the capacity of government to address. Given the economic situation, the "solution" was to transfer responsibility for upkeep and repair to the private sector. Although some of these incidents were undoubtedly caused by improper management rather than changing climatic conditions, most structures built in Yakutsk after 1940 were engineered for conditions involving permafrost. An expert from the Melnikov Permafrost Institute in Yakutsk ascribed a large proportion of the city's recent problems to climatic warming (Anonymous, 1997).

As global warming continues to evolve, it may produce similar detrimental impacts on infrastructure throughout the permafrost regions, even under appropriate practices of environmental management. Although the infrastructure in the northern reaches of the USA and Canada is much less extensive than in Russia, thickening of the active layer in the course of global warming and development of thermokarst could have severe effects on engineered structures (Anisimov et al., 1997). Many facilities and structures were designed for current climatic conditions, and appreciable warming could introduce differential settlement beneath them. Engineering design for permafrost terrain under changing climatic conditions has received considerable attention in recent years (e.g., Paoli and Riseborough, 1998; Bobov, 1999).

### 3. Hazard Zonation in the Circum-Arctic Permafrost Region

In climate-change impact studies, contemporary development of thermokarst has been associated primarily with processes in the marginal, southernmost areas (e.g., Kwong and Gan, 1994; Osterkamp et al., 1998; Osterkamp and Romanovsky, 1999; Osterkamp et al., 2000; Zuidhoff and Kolstrup, 2000; Beilman et al., 2001; Jorgenson et al., 2001). Permafrost in the discontinuous and sporadic zones is relatively warm, with temperatures only a few degrees below the freezing point. It is also relatively thin (typically between several meters and a few tens of meters), and has a very small thermal gradient. Results obtained by Anisimov et al. (1997) and the widespread thaw unconformity associated with warm intervals in the Holocene (e.g., Burn, 1997) indicate, however, that climatic warming may also initiate development of thermokarst processes farther north, in the zones of discontinuous and continuous permafrost, where thermokarst may develop in near-surface sediments at localities with disturbed or thin organic layers. Substantial disturbances of the organic layer are produced by technogenic effects associated with engineering activities (Figure 1). Permafrost in the vicinity of mining facilities, pipelines, roads, and buildings may, therefore, be impacted adversely by climatic change, even in the continuous permafrost zone.

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The permafrost literature contains many general statements about and localized investigations into the possible adverse effects of climatically induced permafrost degradation on engineered works. Only a few studies have attempted to evaluate vulnerability over large areas. Smith and Burgess (1998, 1999), used a 2xCO<sub>2</sub> scenario and spatially referenced databases to delineate areas of relative sensitivity to thaw in Canada. Other studies at scales involving large areas (e.g., Chizhov et al., 1993; Vyalov et al., 1993; Chernyad'yev and Chekovskiy, 1994) were based on relatively simple assumptions about the nature and regional variability of both climatic change and geocryological conditions.

Potential environmental hazards associated with degradation of permafrost and development of thermokarst can be evaluated at continental or circumpolar scales using permafrost models, scenarios of climate change, and geographical information systems (GIS) technology. Predictive mapping facilitates identification of regions in which the environmental impacts of warming have the greatest potential for detrimental consequences. In this section we introduce the concept of *hazard zonation* (Carrara and Guzzetti, 1995; Brunori et al., 1996) in the context of degrading permafrost. We use the term "zonation" with respect to both the arrangement of physical-geographical phenomena in concentric latitudinal bands and the degree of severity associated with vulnerability of geographic areas to thermokarst subsidence.

Although settlement of the ground surface may occur anywhere that ice-rich permafrost exists, thermokarst subsidence will be most pronounced in locations at which both the relative volume of ground ice and increases in the depth of thaw are maximized. A dimensionless index was developed to characterize this relation, and to classify modern permafrost with respect to its potential for ground settlement under changing climatic conditions. This "settlement index" ( $I_s$ ), constructed using data on predicted changes of active-layer thickness and ground ice content, is given by:

$$I_s = \Delta z_{al} \cdot V_{ice} \quad (1)$$

where  $\Delta z_{al}$  is the relative increase of active-layer thickness, and  $V_{ice}$  is the volumetric proportion of near-surface soil occupied by ground ice. For present purposes, we assume that liquid water

generated by ablation of ground ice is drained from affected sites and that thaw subsidence is proportional to the thickness of ice lost from the substrate.

The settlement index for permafrost areas in the Northern Hemisphere was calculated using Kudryavtsev's solution for the thickness of the thawed layer as detailed by Anisimov et al. (1997), digital maps of volumetric ice content (Brown et al., 1997, 1998) and soil texture (Staub and Rosenzweig, 1987), and the ECHAM1-A and UKTR scenarios of climate change for the middle of the twenty-first century (Cubasch et al., 1992; Murphy, 1994; Murphy and Mitchell, 1994; Greco et al., 1994). Data layers were interpolated to a common resolution ( $0.5^\circ \times 0.5^\circ$  latitude/longitude) and  $I_s$  was computed for each node using a specialized GIS software package (Anisimov and Polyakov, 2000). The result of these calculations are predictive maps (Figures 6 and 7) of potential environmental hazards associated with degradation of permafrost. Of the three transient GCMs selected for the IPCC's work on socioeconomic projections (Greco et al., 1994), the ECHAM1-A and UKTR scenarios provide lower and upper bounds, respectively, for the extent of hazard potential. Nelson et al. (2001) obtained mid-range values with the GFDL89 scenario. The calculations produced a relatively small number of negative values indicating areas where moderate cooling, thinning of the active layer, and encroachment of permafrost may occur (Anisimov and Nelson, 1997). These pixels were assigned to a "stable" category in which no degradation of permafrost is predicted.

[Figures 6 and 7 near here]

Hazard potential is partitioned geographically in Figures 6 and 7 into areas of "low," "moderate," and "high" susceptibility to thaw-induced settlement. After logarithmic transformation of  $I_s$  values from the ECHAM1-A, GFDL89, and UKTR climate-change scenarios (Greco et al., 1994), pixels with positive values were assigned to these hazard-zone categories by partitioning their pooled empirical frequency distribution using a nested-means procedure (Scripter, 1970). The number of class intervals produced by this method is constrained to  $2^n$ , where  $n$  is a positive integer; for this application  $n = 2$ , yielding four class intervals. The two lowermost categories were combined to yield a conservative estimate of the potential for hazard.

The settlement index yields its highest values in areas where the increase in thaw depth predicted under a GCM scenario coincides with high ice-content values on the IPA map. Mappings of  $I_s$  developed from the two climate scenarios depict similar patterns, although the degree of hazard potential diverges significantly between maps in some areas, notably central Siberia and the central Canadian Arctic. The UKTR scenario depicts much more extensive areas in the "high risk" category. Areas of high hazard potential appearing on both maps include the coastal zone around the Arctic Ocean, indicating susceptibility to severe coastal erosion. Much of Alaska's North Slope, parts of the Canadian Arctic Archipelago, the Chukotka Peninsula in the Russian Far East, the Lena River valley, and parts of the West Siberian Plain fall within the moderate- and high-risk categories. At this scale, areas of lower hazard potential are associated with mountainous regions (e.g., the Brooks Range in Alaska and the Central Siberian Plateau) and stable cratons in which bedrock is near or at the surface (e.g., the Canadian Shield). Localized areas of high risk may be numerous within areas depicted in the "low" category, but cannot be resolved at the map scale employed in Figures 6 and 7.

Figure 8 depicts the distribution of human infrastructure in the circum-Arctic region, superimposed on the maps of hazard potential. The locations of population centers, utility lines, pipelines, airfields, road networks, and railroads were obtained from a digital database (U.S. National Imagery and Mapping Agency, 1997) and plotted on the hazard maps, providing a

general assessment of the susceptibility of existing infrastructure to thaw-induced damage under the two climate scenarios.

[Figure 8 near here]

Major settlements (Figure 8a) 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 (Yakutsk). The potential for severe thaw-induced disruptions to engineered works has been reported from each of these areas in existing literature (Lawson and Brown, 1978; Yershov, 1998; Forbes, 1999; Dyke and Brooks, 2000), and problems are likely to intensify under conditions of global warming.

Figure 8b shows transportation facilities, including roads and vehicle trails, railroads, and airfields. The network of seismic trails in northern Alaska (Figure 1), 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 (e.g., Ferrians et al., 1969). A dense network of secondary roads and trails occupies areas of moderate risk in Mongolia, and northeast China has an extensive railway system developed in areas underlain by permafrost.

The routes of major electrical transmission lines and pipelines are shown in Figure 8c. 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 substantial hazard potential. The network of pipelines associated with the West Siberia oil and gas fields (Central Intelligence Agency, 1985) is of particular concern owing to its location in the ice-rich West Siberian Plain and because severe environmental problems have resulted from inadequate engineering and environmental standards (Seligman, 2000).

#### **4. Conclusions**

Terrain underlain by ice-rich permafrost is an environmental hazard of very high rank and spans a large range of spatial and temporal scale. Under conditions of global warming, permafrost constitutes a threat to human infrastructure of a magnitude similar to those posed by other elements of the cryospheric environment. Evidence for development of widespread thermokarst subsidence over large regions is abundant in the geological record of former warm intervals. Given the extent of contemporary infrastructure in the permafrost regions, initiation of a similar episode would constitute an engineering challenge involving many billions of dollars. To date, however, the literature of environmental hazards and policy pertaining to the polar regions does not reflect the extensive work on these problems that has been performed by permafrost scientists. Recognition of the magnitude of potential problems constitutes a critical first step toward mitigation. Collaboration between permafrost scientists, hazard specialists, and policy experts is critical for a timely and effective response to problems associated with thawing permafrost. A dispassionate and scientific approach is essential, given that the popular press has already begun to give uncritical, hyperbolic, and erroneous coverage to the topic (e.g., Gentleman, 2000; Linden, 2000; ABC News Online, 2001).

The maps of hazard potential presented in this paper provide 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 those in Figure 8 have direct implications 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 of this scale cannot, of course, resolve the localized factors involved in the development of thermokarst. Rather, they point to geographic areas upon which hazard scientists, policy analysts, and engineers should focus attention and prepare more detailed hazard maps at local and regional scales (e.g., Péwé, 1983; Parmuzin and Shamanova, 1986).

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## Figure Captions

Figure 1. Ground ice and its effects on arctic terrain. (a) Massive ground ice in the Yamal Peninsula, western Siberia; (b) active layer detachment slide, delineated below headwall with dashed lines, associated with the presence of massive ground ice, Yamal Peninsula; (c) network of ice-wedge polygons near Prudhoe Bay, Alaska; (d) thermokarst developed in terrain underlain by ice-wedges near Prudhoe Bay, resulting from inadequate amount of gravel fill in road construction; (e) severe thermokarst developed over one decade in winter road near Prudhoe Bay, constructed by stripping organic layer and stacking mats in intervening area; (f) building in Faro, Yukon Territory, Canada undergoing differential settlement due to thawing of ice-rich permafrost.

Figure 2. Map of permafrost zonation in the Northern Hemisphere. Adapted from Brown et al. (1997; 1998).

Figure 3. 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. Adapted from Brown et al. (1997; 1998).

Figure 4. (a) Distribution of permafrost under the ECHAM1-A general circulation model, based on calculations by Anisimov and Nelson (1997, Figure 2). Zonal boundaries were computed using criteria for the "surface frost number" (Nelson and Outcalt, 1987). The solid line shows the approximate southern limit of contemporary permafrost. Areas occupied by permafrost have been adjusted slightly from those in the original publication to account for marginal effects.

Figure 5. Relative changes in active-layer thickness under the ECHAM1-A general circulation model, reclassified from Anisimov et al., (1997, Figure 6). Low: 0-25%; Medium: 25-50%; High: >50%.

Figure 6. Hazard zonation map obtained using the ECHAM1-A climate scenario, computed using eq. (1) to operate on digital matrices represented by Figures 3 and 4. Shading density indicates susceptibility to disturbance under conditions of warming climate.

Figure 7. Hazard zonation map obtained using the UKTR climate scenario. Other parameters are identical to those of Figure 6.

Figure 8. Hazard potential maps of Figures 6 and 7, with the distribution of contemporary settlements and infrastructure (U.S. National Imagery and Mapping Agency, 1997) superimposed: (a) population centers (red) and settlements (pink), (b) undifferentiated major and secondary roads, including winter trails (yellow), railroads (blue), and airfields (red); (c) electrical transmission lines (blue) and pipelines (yellow). The location of the Bilibino nuclear station in the Russian Far East is indicated. Only settlement/infrastructure features within the contemporary permafrost zones (as defined by Brown et al., 1997) are shown.