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

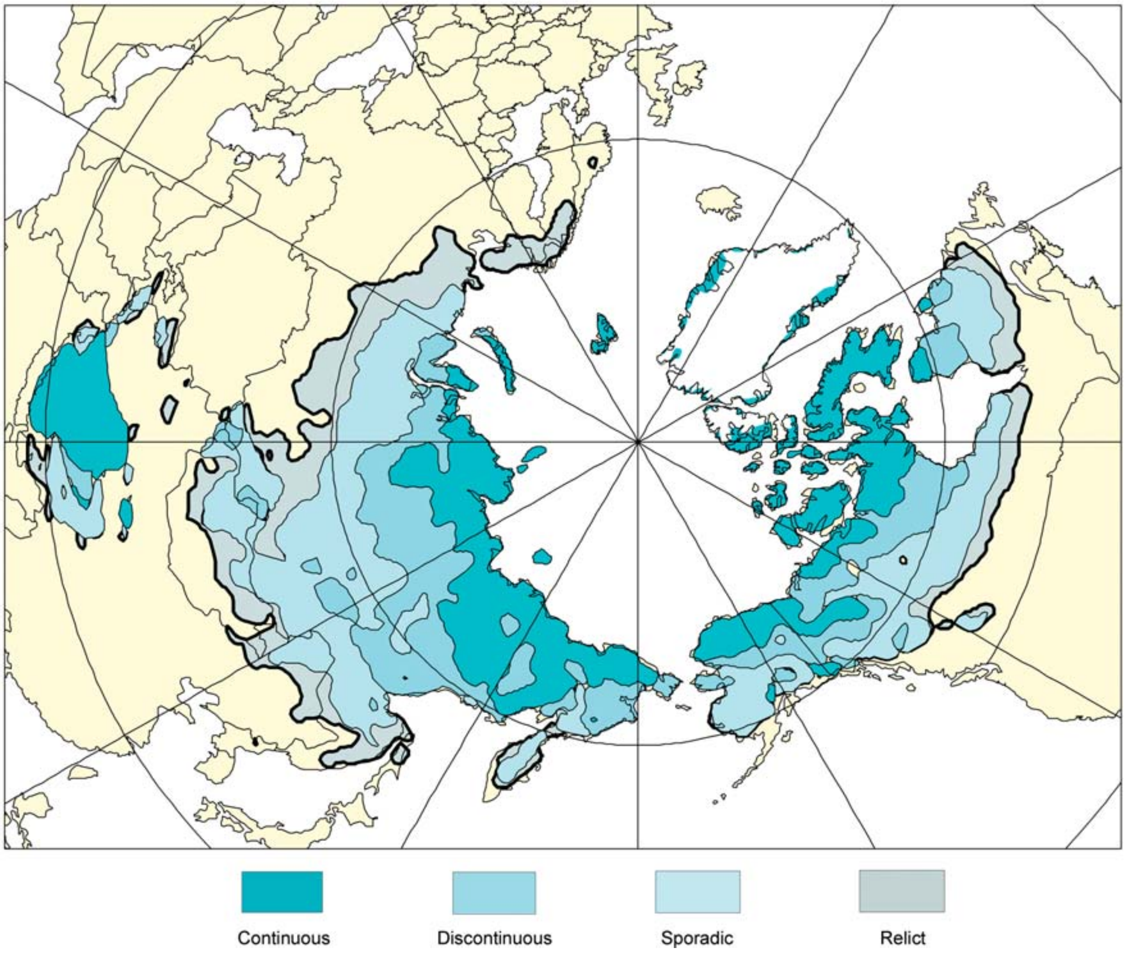

Figure 10. Distribution of permafrost in 2050 according to the UKTR general circulation model, based on calculations by Ansimov and Nelson (1997, Figure 2). Zonal boundaries were computed using criteria for the "surface frost number," a dimensionless index based on the ratio of freezing and thawing degree-days (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.

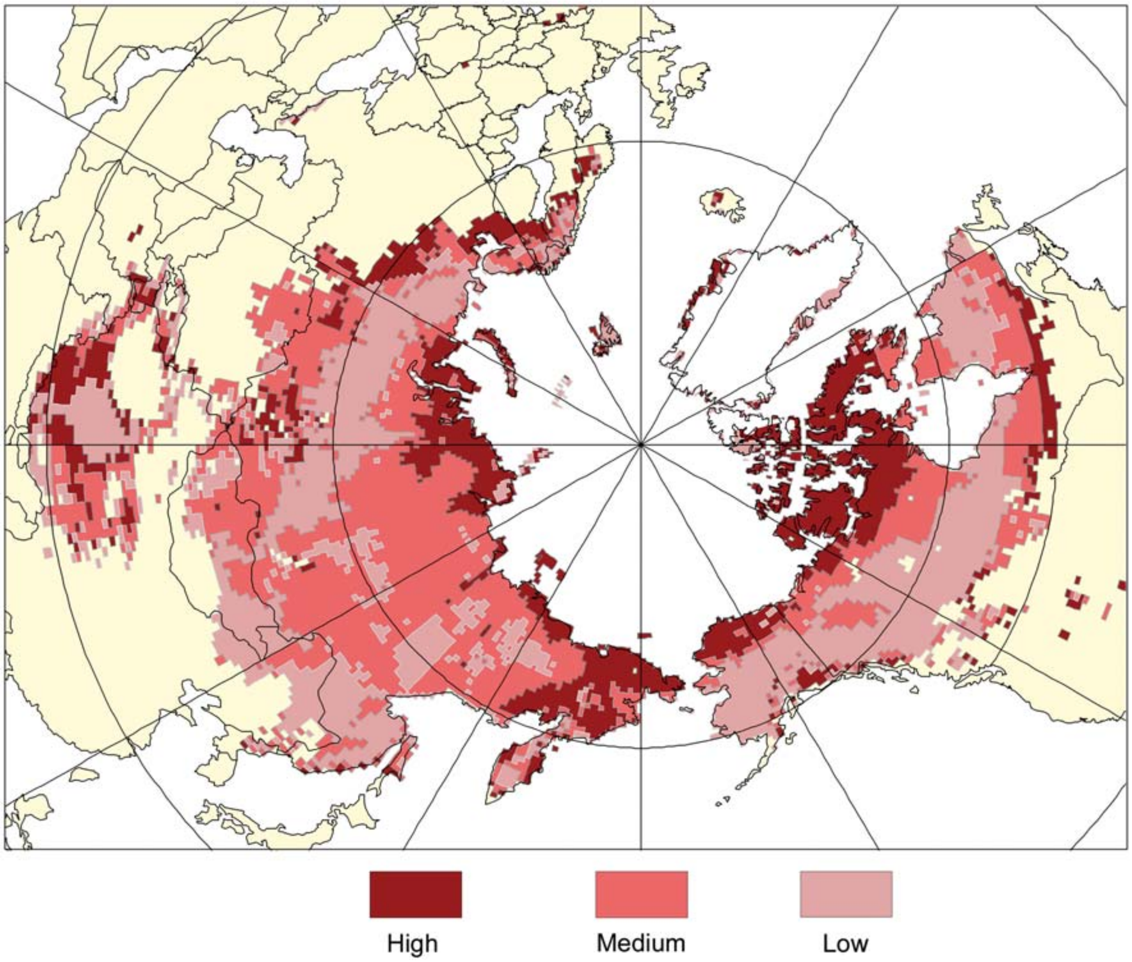

Figure 11. Relative changes in active-layer thickness in 2050 according to the UKTR general circulation model, reclassed from Ansimov et al. (1997, Figure 6): low: 0–25%; medium: 25–50%; high: >50%.

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 60º and 70ºN. 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

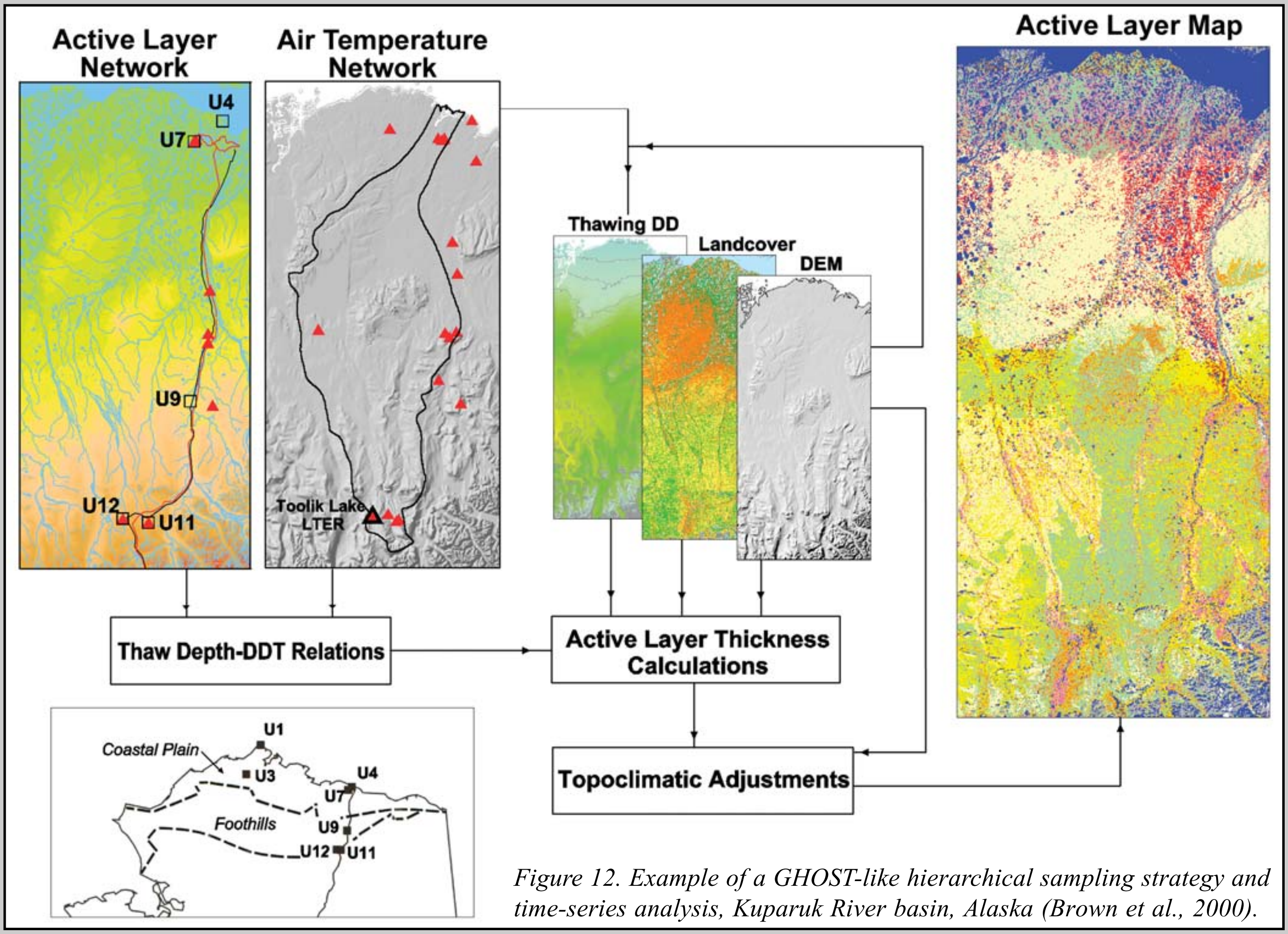

Figure 12. Example of a GHOST-like hierarchical sampling strategy and time-series analysis, Kuparuk River basin, Alaska (Brown et al., 2000).

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.