PERMAFROST IN THE 21ST CENTURY

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Summary

Large regions of the Northern Hemisphere, portions of the arctic continental shelf and Antarctica, and some mountainous regions of South America are underlain by permafrost. Because permafrost is a thermal condition of earth material, its distribution and behavior are sensitive to both short- and long-term changes in climate. Upon thawing, ice-rich permafrost becomes unstable, resulting in slope failures, accelerated erosion and subsidence (thermokarst). Frozen, organic-rich sediments are sources of trace gases, as are hydrates found within and beneath the onshore and offshore permafrost. Modeling results of climate-change scenarios predict increased seasonal thawing and reduction in the extent of permafrost during the 21st century. Coordinated networks of long-term measurements have recently been initiated in order to detect recent and future trends in the thermal regimes of the overlying seasonal thaw zone and near-surface permafrost. A brief summary and limited number of recent references to the extensive permafrost literature are presented in this short report.

Introduction

Approximately twenty-five percent of the land mass of the Northern Hemisphere, regions of the arctic continental shelf and the Antarctic continent, and some mountainous areas of South America are underlain by perennially frozen ground, commonly referred to as permafrost. Permafrost develops where the depth of seasonal freezing consistently exceeds the depth of summer thaw. Thick sections of permafrost formed during cold geological intervals attaining thicknesses in excess of 1500 meters in unglaciated parts of Siberia. The colder and deeper permafrost survived warmer interglacial periods. Relict permafrost can persist even under warm surface ground conditions. Ice-rich permafrost requires special engineering designs to insure stable foundations for buildings, roads, airfields, and pipelines. Warming and potential loss of permafrost conditions during the 21st century will have important economic, societal and environmental consequences.

Over the past decade there has been increased awareness that permafrost contributes to the consequences of global warming. The Intergovernmental Panel for Climate Change (IPCC) assessments on potential environmental and economic impacts forecasts degradation of permafrost terrains in many regions, with resulting influences on landscapes, the atmosphere and adjacent waters. These forecasts are based on numerous published modeling exercises and field investigations that assess changes in permafrost regimes at local, regional or global scales, and on field projects to measure trace gas fluxes between the atmosphere, vegetation, soil, and permafrost. Recent results were reported in June 1998 at the Seventh International Conference on Permafrost in Yellowknife, Canada (French 1998).

Distribution and Properties

Permafrost is not distributed uniformly across all land surfaces. At its southern margin in the Northern Hemisphere permafrost occurs as isolated bodies, usually under well-insulated peatlands. Its distribution and spatial continuity gradually increase northward from these isolated islands into zones of sporadic (10–50% of the surface underlain by permafrost), discontinuous (50-90%), and continuous (>90%) permafrost. In the mountains and plateaus of the mid- and low-latitudes, permafrost becomes more widespread with increased elevation, generally exceeding the areas occupied by adjacent modern glaciers.

The oldest permafrost may exceed 3 million years; however, its spatial extent over time has not remained constant. For example, the dynamics of permafrost distribution in Northern Eurasia during the last 20,000 years had its maximum extent during the Last Glacial Maximum, with the northernmost position of the southern permafrost limit occurring during the Holocene Optimum (Lisitsyna and Romanovskii 1998). It was during the former period that subsea permafrost developed on the exposed continental shelf, and that the massive "ice complex" accumulated both on land and the exposed shelf. During the warmer Holocene, thermokarst processes resulted in thaw-lake formation and depressions, inundation of the shelf, and partial decay of subsea permafrost. These processes are active today and will continue into the future.

The mean annual temperature of permafrost decreases poleward and is usually several degrees colder than the surrounding mean annual air temperature. Local spatial variations in permafrost temperatures and thicknesses are the result of differences in landform, snow cover, vegetation, slope, aspect, and substrate. Temperatures at depth integrate changes in surface climates over time; measurement and analyses permit reconstruction of recent climate-induced changes. For example, based on deep geothermal temperature measurements, Lachenbruch and Marshall (1986) estimated that permafrost had warmed 1–2°C over the past several decades to century in Arctic Alaska. Based on annual measurements in the upper permafrost present, warming of the permafrost in the discontinuous zone has been reported from interior Alaska (Osterkamp and Romanovsky 1999). In some cases this is accompanied by subsidence as ground ice melts.

A unique characteristic of permafrost is the presence of ground ice; which can form during initial freezing or be incorporated subsequently into the frozen ground over varying periods of time. Ground ice occurs in many forms and includes small lenses, large tabular masses and vertically foliated wedges. Ground ice may occupy as much as 80% of the upper ten meters or more of permafrost, as is the case for the "ice complex" of Siberia. During the 1990s, representatives of the International Permafrost Association (IPA) compiled existing information and published a generalized map of the Northern Hemisphere (1:10,000,000 scale) depicting estimates of ground ice and permafrost zonation by major landscape and physiographic regions (Brown et al. 1997) (Fig. 1). Statistics from the digitized version of the map provide qualitative estimates of ground ice and permafrost continuity in relation to overburden thickness or proximity to bedrock (Brown and Haggerty 1998). Employing both the digital database for permafrost and global elevation, it is estimated that approximately 60% of the permafrost occurs below 500m elevation in nonmountainous terrains possessing thick overburdens (T. Zhang, pers.comm.). The digital version of the map, is available both in ArcInfo (<ftp://ftp.ngdc.noaa.gov/SNOW_ICE/PERMAFROST/IPA_map/) and raster formats. A combination of these and other global databases are providing the basis for reassessing the distribution and regional susceptibility of ground ice and perma-

frost and their relationships to warming and related impacts for the 21st century. In addition, an English language edition of the detailed geocryological map of the Former Soviet Union at a scale of 1:2,500,000 is now available (Williams and Warren 1999).

Potential Changes and Hazards

Modeling results of permafrost distribution under several different climate scenarios, as well as other analyses, predict increases in active-layer thickness and decreases in the areal extent of the near-surface permafrost (Anisimov and Nelson 1997; Kettles et al. 1997). Where summer thaw exceeds winter freezing, unfrozen thaw zones (taliks) develop and persist. Taliks provide conduits for groundwater flow and heat transfer; and accelerate melting of ground ice, thermokarst development, and both thermal and hydraulic erosion. As some areas of warmer permafrost completely thaw, a reduction in the area of the land underlain by permafrost will occur. Depending on the physiographic region and thickness of the permafrost, dislocation northward of the permafrost boundaries is predicted. Since complete thawing of thick sections of even warm permafrost requires hundreds of years to millennia, only the upper several tens of meters of thick, warm permafrost are likely to disappear during this century (Osterkamp and Romanovsky 1999). An increase in active-layer thickness can cause disruption to human activities, even where appreciable thicknesses of permafrost remain.

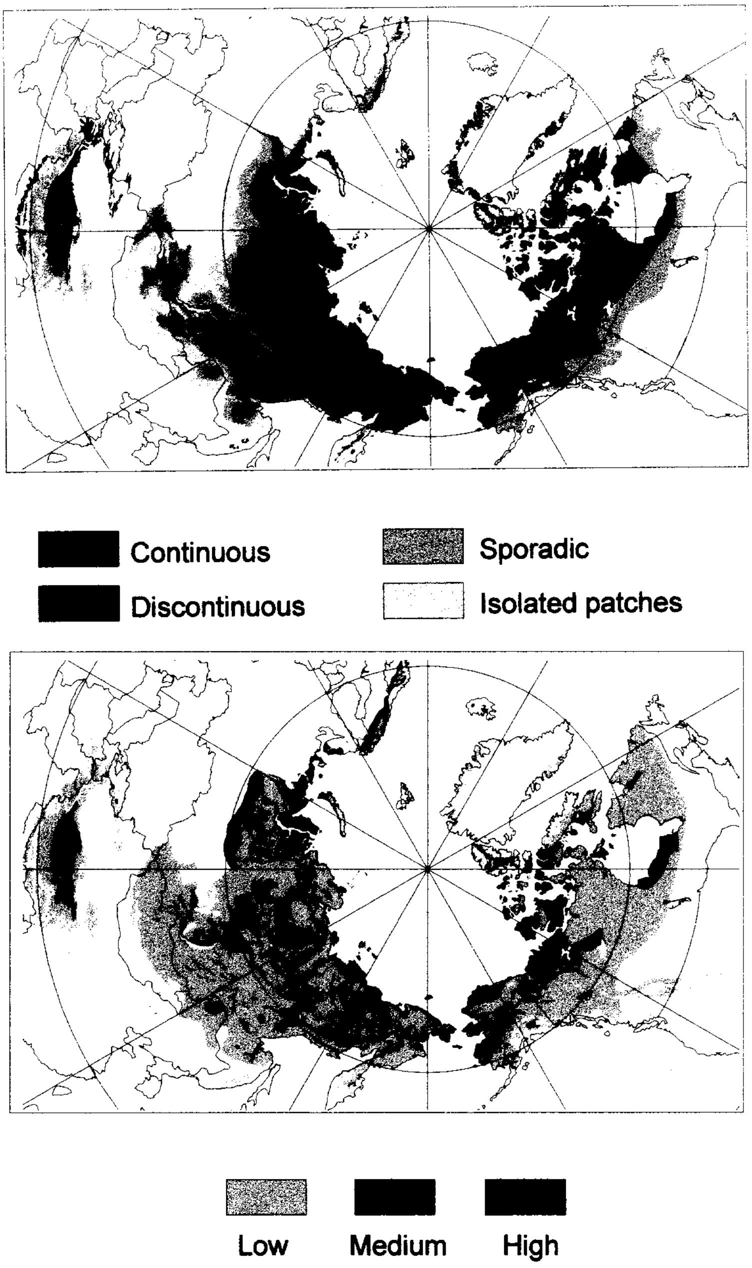

Figure 1. Maps of the Northern Hemisphere illustrate the distribution of permafrost (upper), and estimates of ground ice (lower), as derived froom the digital database (Brown et al. 1997, Brown and Haggerty 1998).

Activities related to resource extraction (e.g., oil and gas exploration and development and mining activities) in the Arctic and Subarctic provide ample evidence of the sensitivity of permafrost to disturbance and practices for restoration and mitigation. Human-induced, surface disturbances and thawing of warm permafrost terrains are more rapid, but analogous to natural processes; both produce increased thaw, soil destabilization, subsidence, accelerated erosion, and slope instability. Increased rates of mass movement and slope failures are of particular concern in mountainous regions. Permafrost degradation also affects sources and sinks of greenhouse gases, and results in changes to vegetation, surface hydrology, and ground water.

Ice-rich permafrost in coastal regions is subject to high rates of erosion during the relatively short, ice-free period. In some regions of the Arctic such as the Laptev Sea, sediment yield onto the continental shelf from eroding, ice-rich permafrost coastlines exceeds sediment input from the major rivers, such as the Lena (Are 1999). Under conditions of rising sea level or submergence, erosion rates of ice-rich coasts will increase (Shaw et al. 1998). Communities located along these coasts continue to be impacted by loss of land and water supplies, storm damage, and inundation.

Long-Term Observation Networks and Data Management

To evaluate the magnitude and consequences of changes in permafrost terrain, an international global observation program, known as the Global Terrestrial Network-Permafrost (GTN-P), is in development under the auspices of the Global Climate Observing System of WMO, FAO and the IPA. Initial parameters for measurement are depth of seasonal thaw (active layer) and the permafrost thermal state. The Circumpolar Active Layer Monitoring (CALM) network, begun in the early 1990s, is now part of GTN-P and, in addition to thaw, measures soil temperatures, moisture, and subsidence at selective sites. The CALM network currently comprises about 80 sites in the Northern Hemisphere and is being expanded to include additional locations in Southern Hemisphere. The GTN-P borehole program has identified approximately 300 existing boreholes for potential temperature measurements. Included are a limited number of sites in the mountain and plateau regions of the Northern Hemisphere, including a series of borehole observations under the European Community project Permafrost and Climate in Europe (PACE). To date there are no permafrost boreholes in the mountains of South America.

The results of the GTN-P are required to improve and validate predictive models and impact assessments, including those reported by the Intergovernmental Panel on Climate Change (IPCC), and to further our understanding of the responses of the permafrost and related processes to climate variability and change. Similarly, an international network of coastal sites is recommended to evaluate long-term response of coastal erosion and accretion and sediment yields in response to changes in sea level. Measurements at all these permafrost observatories must extend over many decades to adequately document and interpret the influences of decadal to secular variations in the climatic variables on permafrost.

As information and data from these observational programs become available they are posted on several web sites hosted by participating organizations:

CALM (University of Cincinnati): http://www.geography.uc.edu/~kenhinke/CALM/

GTN-P borehole (Geological Survey of Canada): http://sts.gsc.nrcan.gc.ca/permafrost/gtn-p.htm

PACE (Cardiff University): http://www.cf.ac.uk/uwcc/earth/pace/

Periodically, both metadata and data are transferred from these and other sources into the archives of the World Data Center A for Glaciology, co-located with the National Snow and Ice Data Center, Boulder, Colorado. The IPA Global Geocryological Database (GGD), serviced by CD ROMs and online access, will continue to provide comprehensive access to rapidly increasing data and information about onshore and offshore permafrost, as well as the growing interest in planetary permafrost.

Coordination

Permafrost and related frozen ground investigations encompass many scientific and engineering disciplines. As such, activities and individuals are widely dispersed. There are relatively few national or international organizations and institutions focused on the problems related to permafrost. To rectify this situation, the IPA continues to gather information on its activities and others, and disseminates it to many organizations and individuals around the world through an annual news bulletin and web site. Periodically, the IPA supervises the preparation of a CD-ROM containing retrospective information and data (Brown and Haggerty 1998). In recognition of the difficulties of organizing and communicating globally, those countries or organizations having common regional interests are encouraged to organize regional groups, and in turn to report on accomplishments and plans at international conferences and in other publications. Chinese and Russian geocryologists and engineers have been meeting biannually and will meet again in September 2000 in Lanzhou. The first European permafrost conference is planned for Rome in March 2001, and the third international conference on cryosols will be held in Denmark in August 2001. The international permafrost conferences are traditionally held every five years in different countries; the eighth international conference will be in Switzerland in 2003. Perhaps in the early decades of the 21st century we will see more utilization of community-wide, electronic conferencing and publishing as a supplement to these and other scheduled conferences.

As an affiliated member of the IUGS, the International Permafrost Association provides information and liaison with other IUGS organizations and programs. For example, IPA assisted in identifying "frozen ground" as a geoindicator of short-term environmental change. In the future, IPA should expand participation in other relevant IUGS activities. Future nominations of representative and unique permafrost phenomena or landscapes can be made to the Global Geosite program. The recently dedicated Gold Stream permafrost section near Fairbanks, Alaska, the "ice complex" of northern Siberia, and the pingos of the Mackenzie Delta are considered candidate Geosites or Permafrost World Heritage Sites.

Conclusions and Recommendations

Permafrost is a widespread thermal condition of the Earth's surface. Under a warming climate, the uppermost sections of warm permafrost and isolated masses of permafrost are more suspectible to thaw. The melting of large masses of ground-ice, whether due to human-induced surface modifications or climate, create unstable soil conditions that are conducive to slope failures, accelerated erosion, subsidence, and changes in the carbon balance of organic-rich, cold soils. Coordination of national and international programs is required to assess and validate the magnitude of future natural and anthropogenic impacts on permafrost terrain, and to develop acceptable procedures for their mitigation and restoration. Development and long-term support of a global network of permafrost observatories and related data management activities require national and international commitments.

Acknowledgments
Dr. F.E. Nelson provided critical comments and the two maps.

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