

temperature were evaluated by using Kudryavtsevs formulas. According to these formulas, mean annual air temperatures and seasonal air amplitudes as well as mean annual snow thickness; morphophysical properties of the soils (heat capacity and thermal conductivity) determine active layer thickness and mean annual ground temperatures. Hadley 2 Scenario based on actual measurements of meteorostations was used as a reference point for the evaluation of the permafrost dynamics over the past 100 years. Other five scenarios from Arctic Climate Impact Assessment (ACIA) project were used to evaluate the permafrost dynamics in the future. For each of these scenarios, maps of active layer thickness and mean annual ground temperature in Alaska and East-Siberia were created. Similarities and differences in future and past permafrost dynamics have been found. This analysis will let us interpolate the permafrost data between two transects and include three or four other transects to get the whole picture of the permafrost dynamics for the entire circumpolar region.

B11E MCC: 132 Monday 1020h

Interactions of Permafrost With Climatic, Hydrologic, and Ecosystems Processes II (joint with C, H, GC)

Presiding: F E Nelson, University of Delaware; J M Kimble, USDA
Natural Resources Conservation Service

B11E-01 1025h INVITED

Recent Permafrost Warming in Northwest Canada

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Ground temperature records, mostly collected by industry, are available for the Mackenzie delta area and western Arctic coast of Canada from the late 1960s and early 1970s. At Garry Island, the mean annual ground temperature (MAGT) is -6C, 2C warmer than previously. Similar data are available for northern Richards Island, and at the Illisarvik drained lake site, on Richards Island, MAGT in the early 1980s was -7C. At Herschel Island, the MAGT is -8C. There are no prior records from Herschel, but similar sites in the region distant from the Mackenzie River discharge plume previously recorded -9 to -10C. These data point to a relatively rapid response of near-surface permafrost temperatures to regional climate warming, due to the minimal phase change at these relatively cold temperatures in the continuous permafrost zone. In contrast, permafrost temperatures close to 0C in central and southern YT show relatively little response to climate warming due to the large amount of latent heat required for a small increase in ground temperature, and to the cooling achieved in separate winters with little or late snowfall.

B11E-02 1045h INVITED

Effect of Climate Change on Permafrost in Alaska: Short-Term (Decadal) Variability and Long-Term (Millennial) Changes.

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Permafrost, in general, is a product of cold climates, which are typical for high latitudes or high elevations. Hence, the air temperature is one of the most important parameters, which determine the existence of permafrost and its stability. However, because of the effects of intervening snow cover, vegetation, and active layer and because of the effects of possible changes in other climatic variables, particularly precipitation, somewhat different changes are generated at the surface of permafrost. Our recent study shows that permafrost temperatures reflect the longer time scale changes in climate (air temperatures) much better than the inter-annual variations. The recent climate warming brought soil temperatures at the North Slope sites to a surprisingly high level, about 3°C warmer than long-term averages. In Interior Alaska recent permafrost temperatures are 1°C to 1.5°C warmer than they were in the 1970s. At the same time, comparison between borehole temperature measurements in Barrow from the 1950s and recently measured temperatures at the same boreholes shows a significant similarity in the temperature profiles within the upper 20 meters of permafrost. Application of our calibrated numerical model shows that measured 1°C difference at 15 meters in permafrost

temperatures between 1950 and 2001 is the result of very recent warming during the late 1990s. Much colder permafrost temperatures (up to 2 to 3°C colder) were typical for Barrow during 1970s.

In the long-term perspective, the recent climate is somewhat cooler than it was during the Holocene Optimum (six to eight thousands years ago in Alaska). However, there is much evidence based on proxy climatic data, that the climate in 1980s and 1990s was the warmest during the last millennium. Moreover, several researchers reported thawing of permafrost from the surface at several undisturbed locations in Alaska. It is important from the ecological and engineering point of view to understand what is the age of this recently thawing permafrost. In this paper, some speculations on possible long-term (millennial time scale) changes in permafrost as a reaction to the long-term climatic variations will be presented.

B11E-03 1105h

A Trend of Fast Climate Warming in Northern Quebec Since 1993. Impacts on Permafrost and Man-made Infrastructures.

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From about 1945 to the early 1990s, the climate of the Ungava Peninsula and Ungava Bay area followed a cooling trend that was documented both in Environment Canada stations and in permafrost temperatures measured with the thermistor cables spread across the region. This trend was also invoked to explain the observed increase of ice-wedge cracking and the thinning of the active layer. Despite some logistical difficulties, continued monitoring of permafrost temperatures in many communities now document a radical change of trend. In summer, the warming trend began in 1993 while winters started to become warmer in 1995. Winters 1997-1998 and 1998-1999 were particularly warm. The temperature increases at climatic stations such as Kuujuaaraapik and Kuujuaq are unprecedented in the instrumental record. In the continuous permafrost zone, this recent and fast warming is translated into the shifting of permafrost temperature profiles by as much as 1.9°C at depths down to 20 m and into an important increase in active layer depth. A smaller number of ice wedges are now apparently active. In the discontinuous zone, palsas in particular are degrading and thermokarst landscape in wetlands is expanding. As a result of the fast climate change, one dimensional thermal modelling suggests that permafrost thickness in the discontinuous zone is now greater than what it should be at equilibrium with present atmospheric temperatures. On some of the monitoring sites, an increase in snow cover thickness was probably also a contributing factor; precipitation data, however, are insufficient to assess that factor at the regional scale. One active layer slide provoked the moving of 20 houses in a community. Signs of thaw settlement under roads and airstrips are gradually showing up. Continued monitoring will determine coming trends and variations.

B11E-04 1120h

Large Permafrost Warming in Northern Alaska During the 1990's Determined from GTN-P Borehole Temperature Measurements

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The U.S. Department of the Interior currently maintains 9 automated active-layer monitoring stations and an array of 21 deep boreholes in northern Alaska as part of the Global Terrestrial Network for Permafrost (GTN-P). The GTN-P network is used both for climate change detection and for documenting the sensitivity of permafrost to climate change; GTN-P is one component of the Global Terrestrial Observing System (GTOS), which in turn is part of the long-term Global Climate Observing System (GCOS).

During August 2002, temperatures were re-measured in the majority of the DOI/GTN-P boreholes

to determine the present thermal state of deep permafrost in northern Alaska. A preliminary comparison with earlier temperature logs from the borehole array shows that permafrost on the Alaskan Arctic Coastal Plain and Alaskan Arctic Foothills has warmed ~ 3 K since the late 1980's. This warming of the Arctic cryosphere coincides with the shift in atmospheric dynamics described by the Northern Hemisphere Annular Mode (NAM) that also began in the late 1980's.

B11E-05 1135h

European Mountain Permafrost: Geothermal Change and Associated Geomorphological Impacts

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Geothermal measurements are reported from six recently drilled permafrost boreholes that form a transect extending from the European Alps, through the Scandinavian mountains to Svalbard. Boreholes were drilled in frozen bedrock to depths of at least 100 m by the EU PACE Project (Permafrost and Climate in Europe). In each borehole, 30 thermistors were installed at standard increasing down-hole depth intervals. All boreholes show non-linear thermal profiles with near-surface warm-side temperature deviations from the deeper thermal gradient. A first estimate of ground temperature change is made by assuming constant bedrock properties and comparing the observed thermal profile with linear extrapolation of the deeper geothermal gradient. At 20m depth the largest permafrost temperature deviation from the extrapolated thermal gradient is +0.51°C at the most northerly location (Janssonhaugen, Svalbard). In mainland Scandinavia the deviation decreases southwards, being +0.35°C at Tarfalarýgg, Sweden and +0.29°C at Juvasshøe, Norway. In the European Alps, the steeper topography and greater influence of aspect is reflected in greater variation in thermal profiles, with 20 m warm-side deviations ranging from +0.10°C to +0.40°C.

Inversion modeling offers the potential for estimating the evolution of former surface temperatures. However, a realistic parameterization of the complex three-dimensional topography at each of the drill sites is a critical component of such inversion modeling. We are presently developing this analysis by (a) numerical simulation of summits with assumed surface temperatures and (b) measuring surface temperatures around specific summits in order to calibrate our rock-wall temperature models.

Permafrost is sensitive to thermal change and warming will likely lead to increased slope instability in mountain terrain. Field studies of thaw-related slope instability are hampered by the natural variability of geomorphic processes, both in space and time. An alternative approach, using scaled geotechnical centrifuge modeling of degrading permafrost slopes, was developed within the PACE project, and results are briefly reviewed in the context of process-based permafrost hazard assessment.

URL: <http://www.cf.ac.uk/earth/pace/>

B11E-06 1150h

Climate-Change-Induced Emergent Behavior in Melting Permafrost

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Melting of permafrost owing to climate change commonly is treated as a linear reaction to change in mean temperature. However, it is broadly recognized that nonlinearities, such as geomorphic feedbacks, can dominate melting (IPCC, 2001). In polar lowland regions underlain by ice-rich permafrost, roughly 5% of Earth's land surface, growth of thaw lakes is thought to be a principal means by which permafrost melts.

Rates and spatial distribution of thawing permafrost owing to climate change are estimated for scenarios derived from IPCC projections with a model that

abstracts the fast-time-scale processes of small-scale heat conduction, subsidence of melting permafrost and lake-margin collapse. The creation, growth and draining of thaw lakes and associated terrain is modeled in two horizontal dimensions on a grid. In each grid cell, the surface elevation, depth of permafrost and ice content are specified. Lakes are created preferentially where permafrost is undisturbed or has recovered following draining of a lake and grow at a rate determined by lake level, lake size, permafrost depth in surrounding terrain, and climatic factors. Lake level depends on catchment area and precipitation/evaporation balance. Lakes drain, either partially or fully, when their increasing size causes them to intersect a lake, lake basin or river valley lying below their lake level. Ice-rich permafrost recovers at a rate determined by climatic and hydrological factors.

Modeled terrain matches both qualitatively and quantitatively the patterns of intersecting lake basins observed in permafrost lowlands of the Seward Peninsula and Arctic Coastal Plain. The time scale over which modeled lakes evolve and react to perturbations far exceeds that of the fundamental heat conduction, subsidence and erosion processes, and the time scale over which the terrain evolves far exceeds that of lake evolution, suggesting at least two levels of self-organization and associated emergent behavior. The bulk rate at which permafrost melts is sensitive to the climate history of modeled terrain; rates are significantly different for terrain subjected to rapid change from one climate to a second than for terrain developed solely under the second climate regime, for example, suggesting that projections of melt rates must take into account the properties of thaw lake terrain that evolve over millennia, especially morphology.

Supported by Natural Science and Engineering Research Council and the Andrew W. Mellon Foundation.

B12A MCC: Hall C Monday 1330h

Interactions of Permafrost With Climatic, Hydrologic, and Ecosystems Processes IV Posters (joint with C, H, GC)

Presiding: D L Kane, University of Alaska, Fairbanks; L D Hinzman, University of Alaska, Fairbanks

B12A-0773 1330h POSTER

A tool for modeling permafrost and snow in CCSM

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High-latitude terrestrial variables and processes (e.g., permafrost, soil freezing and thawing, snow, moss, lichen, heterogeneity on the micro-scale, interaction of soil moisture and soil temperature states, etc.) have received little systematic study in the context of global climate model simulations. The soil- and snow-components of the hydro-thermodynamic soil vegetation model (HTSVS) that are to be integrated in the NCAR Community Climate System Model will be introduced. These modules among other things describe (1) the insulating effect of snow and its retardation of infiltration, achieved by the inclusion of an explicit snow layer, (2) the heat conduction and water diffusion (including the Richards-equation) within the soil as well as the cross-effects (Ludwig-Soret-effect and Dufour-effect) generally generated by soil moisture and temperature gradients as postulated by the linear thermodynamics of irreversible processes, (3) soil freezing and thawing and the related release and consumption of latent heat, (4) the effects of frozen soil layers on the vertical fluxes of heat and moisture, (5) water vapor fluxes within the soil, (6) water uptake by plants including a vertically variable root distribution, dependent on vegetation-type, (7) a variable ground water depth responding to the previous meteorological conditions. The general performance of the modules and preliminary results will be discussed.

B12A-0774 1330h POSTER

Spatial Variation in Regional CO₂ Exchange for the Kuparuk River Basin, Alaska Over the Summer Growing Season

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Here we describe the spatial and temporal patterns in CO₂ flux for the Kuparuk River Basin during the 1994-95 growing seasons derived from the Regional Arctic CO₂ Exchange Simulator (RACES), which uses satellite imagery to scale chamber and tower eddy covariance measurements of net ecosystem CO₂ exchange to the regional scale. CO₂ flux estimates derived from non-linear models were scaled to the Kuparuk Basin using a geographic information system database consisting of the Normalized Difference Vegetation Index (NDVI) maps and dynamic temperature and radiation layers. The spatial and temporal patterns in the NDVI during both growing seasons suggest that ecosystem development occurred 2-4 weeks earlier and was relatively more rapid in the southern portion of the Kuparuk River Basin. Similarly, rates of gross primary production (GPP) and whole-ecosystem respiration (R_e) were 2-4 fold higher in the southern basin than along the arctic coastal plain depending on time of year. While GPP and R_e showed strong latitudinal trends, spatial and temporal trends in net ecosystem CO₂ exchange (NEE) were much more variable. Thus, while rates of carbon gain and loss closely linked, small spatial and temporal differences in these large fluxes (GPP and/or R_e) lead to large variations in the regional pattern of NEE.

B12A-0775 1330h POSTER

Morphogenesis of Soils Associated With Frost Boils

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Frost boils are a kind of nonsorted circles commonly found in arctic and alpine regions. In early studies of the Northern Alaska Arctic Coastal Plain, frost boils were found more frequently on moist nonacidic tundra (MNT) than on moist acidic tundra (MAT). But a recent study indicates that frost boils are widespread on both land cover types. Although MNT has more frost boils with mineral soils exposed forming an easily recognizable circle that is generally free of vegetation (mud boils). Crossing the transition from MNT to MAT, there is increased vegetation cover on frost boils. In well-developed MAT, vegetation cover masks frost boils. Once the vegetation cover is removed, frost boils are clearly defined by ice ring ridges underneath the inter boil moss layer. These frost boils are active as indicated by chunks of cotton grass (*Eriophorum vaginatum*) in various stage of decomposition that are found frost churned in along the slopes of the ice ridges toward the upper permafrost. In the lower active layer and the upper permafrost there are concentrations of frost churned organic matter mixed with gleyed mineral horizons. Thus, frost boil process can be regarded as the controlling factor in the sequestration of surface produced organic matter through its incorporation into the upper permafrost for both MNT and MAT.

There are drainage differences due to micro relief across the frost boil sequence. In summer, the elevated center of the frost boil is drained well drained as compared with the poorly drained inter boil due to its depression position. The active layer depth in the center of the frost boil is generally more than twice that of the inter boil, thus the permafrost table surface forms a nearly perfect bowl shape. The lower active layer has strongly developed reticular cryogenic structure. The upper permafrost is ice-rich, generally containing more than 65% ice (vol.) and has ataxitic cryogenic structure. The thickness of the ice-rich layers in the ridges beneath the inter boil area is much greater than that beneath the boil center. In addition, the cracks and the ice veins are parallel to the slope of the ice ridge. Although there are different theories regarding the initiation of frost boils and different factors are involved in frost boil self-organization, morphological evidence in the field suggests that the thick ice formation under the inter boil causes long-term heave of the frost boil and forms its shape.

B12A-0776 1330h POSTER

Temporal and spatial variability of microclimate and permafrost conditions in Fairbanks region, Alaska.

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Permafrost is a product of cold climate and environment. Its dynamics is strongly affected by changes in climatic characteristics such as: air temperatures, amplitudes of seasonal fluctuations of air temperatures and amount of precipitation. The purpose of this research is to reveal the temporal and spatial variability of microclimate and permafrost conditions in Fairbanks region, Alaska. Our research combines fieldwork, laboratory measurements, analysis and interpretation of data at several study sites in Fairbanks area. The study area is approximately 100x150 km around Fairbanks. All the sites belong to various landscapes with varying permafrost conditions, relief features, slope exposition to solar radiation and amount of precipitation (especially thickness of snow cover during the winter). There are several sites on which measurements were being held for the period from 1 to 10 years. At study sites vertical temperature profiles in the air, ground surface, active layer and near-surface permafrost have been recorded at hourly intervals, using automatic data loggers. Measurements of snow cover thickness, density and snow surface temperature have been made at selected sites. Measurements and detailed sites descriptions have been made during visits of the sites to obtain information on the snow cover characteristics and the specific features of ground surface morphology and vegetation. Measured data were converted into daily, monthly and annual average temperatures. Depths of the active layer and amplitudes of seasonal variations of ground and air temperature were derived. The processed data were used to assess the effect of climate, especially air temperatures and snow cover characteristics (density and depth) and regional microclimatic factors, particularly vegetation, surface morphology and soil properties (soil composition, water content) on temperature field of the active layer and permafrost. On this basis it is possible to reveal the main factors that rule the permafrost conditions at each particular site. The obtained data will be used for calibration of a numerical model, and as an input data for the forecast of permafrost dynamics.

B12A-0777 1330h POSTER

Freezing Index as a Measure of Climate Change

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Global warming can be compared in several ways which give insight into magnitude and time extent. One measure of this involves the arctic thermal process of freezing measured by the freezing index or number of degree days below freezing.

Visual visualization of freezing index plotted linearly with time appears as a scatter of data giving difficulty with interpretation. One method developed uses freezing index accumulation as a deviation from the mean, which is a type of differentiation resulting in visible slopes or rates of change. These slopes give a reasonable visualization of warming or cooling trends as related to winter conditions. As opposed to ground temperature measurements, which tend to lag