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GIS assessment of climate-change impacts in permafrost regions

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ABSTRACT: An information system was designed specifically for the management of geocryological data and investigation of the impacts of contemporary and future climate change in permafrost regions. The system uses climatic, soil, and permafrost data, in association with models of climate-permafrost interaction of various complexity. Utilising different scenarios for global climate change, the model was used to predict contemporary climate changes in the Arctic, to compute maps of permafrost distribution, soil temperature, active layer thickness under modern and predicted climate, and to study the thawing of relict permafrost. For a prescribed global warming of 1°C, empirical predictions are for a 5–6°C increase in annual air temperature over continental Siberia, southern Alaska and central Canada, a 3–4°C increase on the North Slope of Alaska, and 1–2°C in most other parts of the Arctic. By 2050, a 10–17% reduction in the permafrost area and a 10–50% deeper seasonal thaw is predicted.

1 INTRODUCTION

Results from many scientific studies suggest that global climate change will have a serious environmental impact in the Arctic region (Anisimov & Fitzharris 2001). A progressive increase in the depth of seasonal thawing of permafrost could be a relatively short-term reaction to climatic warming (Anisimov et al. 1997). At the global scale, deeper seasonal thawing could facilitate further climatic change if more greenhouse gases are released when the upper layer of the permafrost thaws. At regional and local scales, changes in the active layer (layer of seasonal thawing) may produce substantial effects on vegetation, soil hydrology and runoff, as the water storage capacity of near-surface permafrost is altered.

Changes in active-layer thickness are of critical importance for the evaluation of hazards to existing facilities and infrastructure. Thermokarst and other degradation processes are detrimental to the infrastructure built upon ice-rich permafrost. Destructive cryogenic processes may become more intensive under future climatic conditions. The most severe impacts involve deformation and even collapse of buildings, resulting in economic costs and potential human injury.

Such detrimental processes are not necessarily abrupt and may instead evolve gradually. Destructive impacts on the environment and human infrastructure may therefore be predicted using permafrost scenarios that are based on monitoring data and modelling. To assist such efforts, a geographical information system (GIS) specifically designed to address the impact of climate change in permafrost regions was developed. The role of the information system is threefold:

- it serves as a geocryological and climatic database.
- it includes models of different complexity that can be used to predict distribution, temperature, and the depth of seasonal thaw of permafrost through climatic, vegetation, and subsurface data.
- depending on the availability of forcing data it makes automatic adjustment of permafrost models and enables construction of predictive permafrost maps at a variety of geographical scales, from local to hemispheric.

1.1 *Methods*

Our climatic database uses century-long records of mean monthly air temperature and precipitation from nearly 8000 weather stations from around the world (Peterson & Vose 1997). Information system has built-in tools for multi-criteria data filtering that could be used to produce subsets of stations with records of approximately equal duration, homogeneity and quality of data. Data can be filtered using criteria based on the station name, location (station coordinates or lat/long window), WMO code, elevation, population (rural or urban), and topographic unit (plain, highland, mountain valley, or mountain).

Gridded data have a 0.5° spatial resolution over the global continental areas and include climatic norms (Leemans & Cramer 1991), 1950–2000 monthly temperature and precipitation data (Willmott & Robeson 1995), a digital elevation model (Global ecosystems database 1992), soil texture (Staub & Rosenzweig 1987), permafrost conditions and ground ice content (Brown et al. 1997).

The input of the information system uses scenarios of climate change for 2050 derived from three equilibrium (GFDL, GISS, UKMO) and three transient (GFDL, ECHAM, HadCM) general circulation models. Data from palaeoclimatic reconstructions of the most recent interglacials in the geological past – the Holocene and the Eemian (Borzenkova 1992) are also used.

Details of the climate models may be found in the IPCC WG 1 report (McAvaney 2001).

The information system includes data on interannual variability of active-layer thickness from 69 locations characterising typical landforms in the circumpolar Arctic. Systematic measurements of the active-layer thickness were conducted under the auspices of the Circumpolar Active Layer Monitoring (CALM) program (Brown et al. 2000).

1.2 *Permafrost models*

Models of varying complexity were used to predict ground temperature, the areal distribution of permafrost, the depth of seasonal thawing, and the thaw of relict permafrost under changing climate. The simplest are semi-empirical models that employ climatic parameters to calculate predictive indexes, which are then used to derive conclusions about the properties of permafrost. Two such models based on the N-factor approach (Lunardini 1978), and frost-index (Anisimov & Nelson 1996, Anisimov et al. 1997, Nelson & Outcalt 1987) were used.

Another model of intermediate complexity is based on a simplified approximate solution of the conductive heat transfer equation in a medium with water phase changes. This model is driven by mean monthly air temperature and uses few other parameters accounting for the effects of snow cover and vegetation (Anisimov et al. 1997). It allows calculation of the mean annual permafrost temperature at the level of seasonal thawing, and the seasonal thaw depth.

The third dynamic model of greatest complexity uses the one-dimensional conductive heat transfer equation in the snow-vegetation-permafrost system with the boundary conditions derived from climatic data, the water balance equation and the surface energy balance equations (Anisimov 1989). Inputs to the full-scale variant of the model include air temperature, precipitation, air humidity, incoming solar radiation, and cloudiness. These are used to calculate the depth of seasonal thawing and temperature at several depths in the snow and permafrost with a prescribed temporal increment, typically from hours to several days. The complete set of input parameters for the full-scale model is available for only a few sites, including Barrow, Alaska, and four locations in Siberia: Yakutsk, Marre-Sale, Parisento, and Soleninskaia (Pavlov 1996). Data from these sites were used to validate the dynamic and equilibrium models. We used the dynamic model and the model of intermediate complexity to calculate seasonal thaw depth for the period 1989–1997 and then compared the results with field measurements. The difference between the ensemble-mean active-layer thickness calculated used various combinations of soil conditions (thermal properties, water/ice content, organic layer thickness) and the measured data did not exceed 10% for each model, being on average about 6%.

The dynamic model successfully reproduced the seasonal cycle and interannual variations of permafrost temperature and thaw depth in Barrow. The model was forced by 1949–1995 input data and the results were compared with the field measurements conducted in the 1960s and 1990s (digital data archive from CAPS-1 CD ROM, International Permafrost Association 1998). In 1963–1966 permafrost temperatures and thaw depth were measured on several plots along the 2-km long transect characteristic of the ice-wedge dominated Arctic Coastal Plain (Brown et al. 2000). Field data for 1993–1994 were obtained using a Campbell data logger connected to a rigid thermistor probe anchored in permafrost to the depth of 1.2 m. Temperatures at 12 depths (with a 10 cm increment) were read at hourly intervals. Comparison of the results obtained from the dynamic permafrost model and the field data were discussed in more details by Anisimov & Poliakov (1998).

The full-scale dynamic model requires a complete set of input parameters that are rarely available over large regions. A simplified version that requires only two input parameters, air temperature and precipitation was therefore developed. The energy budget equation was removed assuming that the surface temperature could be roughly approximated by the air temperature. Numerical experiments using the full scale and simplified models indicated that this assumption has a minimal effect on the calculated active-layer thickness.

The databases and the models of the information system were used to study the changes of the Arctic climate and the impacts they may have on permafrost temperature, distribution, and seasonal thaw depth.

2 CLIMATE CHANGE IN THE ARCTIC

2.1 *Observed changes of climate*

Empirical data from standard climate stations on land and measurements taken on drifting ice floes in the Arctic Ocean show a consistent trend towards warming of the northern hemisphere high latitudes. In northern Siberia and Alaska mean annual air temperatures have increased by 2–4°C since the beginning of the 20th century, and selected locations show a warming trend of up to 5°C/100 yrs (Anisimov & Fitzharris 2001).

Changes in climate were most distinct in the last three decades. Figure 1 compares winter temperature (averaged over December, January and February) for the period 1986–1997 with the reference period 1951–1975. Greatest increases in winter temperature over this

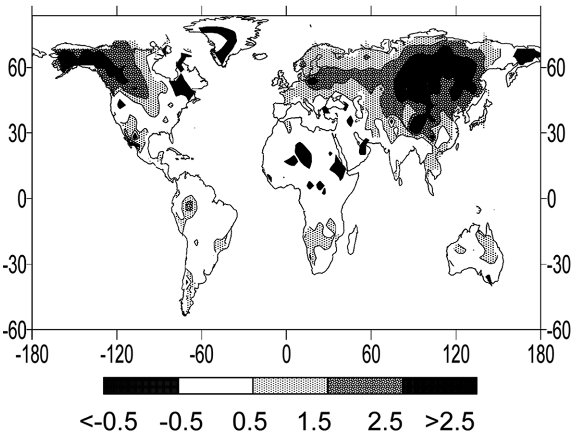

Figure 1. Observed changes of winter temperature.

period are in Siberia and Alaska. Unlike Alaska, the greatest increases in Siberia occurred in the interior of the continent. A similar but less pronounced pattern is observed in Central Canada.

In the last few decades, temperature changes in winter were greater than in summer. Summer warming did not exceed 1°C at high latitudes in the northern hemisphere, whereas winter temperature at selected locations increased by 3°C. Changes were not geographically uniform and regional cooling occurred in Eastern Canada, the North Atlantic and Greenland (Anisimov 2001). The overall effect is warming over most permafrost regions and a decrease in the amplitude of seasonal temperature variation.

Warming in high latitudes has been confirmed by indirect indicators including later freezeup (5.8 days/100 yrs) and earlier breakup (6.5 days/100 yrs) of ice on lakes and rivers (Magnuson et al. 2000). Maximum annual snow cover extent has decreased by 10% since 1972 (Serreze et al. 2000) while precipitation has increased. An inverse relationship was found between the changes in the extent of snow and near-surface spring temperature averaged over snow-covered areas (Folland & Karl 2001). Arctic sea ice extent has reduced by 10% since 1970, ice has become thinner, and the fraction of the multiyear ice has decreased (Anisimov & Fitzharris 2001). Runoff of northern rivers flowing to the Arctic Ocean has increased by 10% in the last three decades, and surface waters in the northern seas have become fresher (Shiklomanov et al. 2000).

2.2 *Predicted climate change*

General circulation models (GCMs) consistently predict that future climate in the circumpolar Arctic region will be markedly warmer and wetter than present. The magnitude of temperature and precipitation estimates varies widely between models however. Predicted changes in air temperature over the high latitude continental areas for the second half of the 21st century vary from +2.5 to +14.0°C for winter months and from +4.0 to +7.5°C for the summer (Anisimov & Fitzharris 2001). Predictions of precipitation increase vary from 10–20% to more than 50%. Although often perceived as the most robust tool for predicting climate change, GCMs have a large inherent uncertainty because they are very sensitive to variations of several climatic parameters that are difficult, if not impossible, to describe deterministically. One example is cloudiness, which strongly affects radiative forcing. Depending on the parameterisations of cloudiness the same model may generate quite different patterns of climate (Meleshko et al. 1999). Most comprehensive GCMs attempt to address this and other similar problems by empirical adjustment of radiative fluxes using comparison of control integrations with observed climate (McAvaney 2001). Such inherent uncertainty questions the dominant role of GCMs in predicting climate change in the next few decades (Anisimov 2001, Shackley et al. 1998). An alternative method is to base predictions of air temperature on empirical data.

The idea behind the empirical approach is to study the correlations between regional and global temperature using century-scale meteorological records and to evaluate the regional pattern of future climate using regression analysis and the global-mean air temperature as a predictor (Anisimov 2001). This approach implies that (1) changes of the global-mean air temperature may be predicted with reasonable accuracy using a simple one-dimensional climate model with prescribed climate sensitivity; (2) regional temperature is predictable in those parts of the world where it exhibits strong correlation with global-mean temperature; (3) as long as the changes in global atmospheric and oceanic circulations resemble that of the last hundred years, regional changes of the air temperature may be predicted by downscaling projections of the global-mean temperature, and (4) regional temperature changes can be represented in a linear manner over the time-scale of prediction. An examination of whether these assumptions impose stronger limitations to climate scenarios than flux adjustment in GCMs is beyond the scope of this paper. For constructing climatic projections in the Arctic over the period of a few decades it is likely that an empirical method is more robust than most currently available GCMs.

An empirical model was developed using century-scale temperature records from the database of the information system. Using a prescribed 1°C increase in global temperature as the input, the resulting predictions are for a 5–6°C increase in annual air temperature over the continental Siberia, southern Alaska and central Canada, a 3–4°C increase on the North Slope of Alaska, and 1–2°C in most other parts of the Arctic.

3 IMPACTS OF CLIMATE CHANGE ON PERMAFROST

20th Century warming has resulted in measurable changes in the distribution, temperature, and depth of seasonal thawing of frozen ground. In the period between 1989 and 1998, temperatures of the upper permafrost layers increased by 0.5–1.5°C along a several hundred kilometre north-south transect in central Alaska, and by 0.5–1.0°C in the western Yamal Peninsula (Pavlov 1996, Pavlov 1998). Reduction of permafrost extent during the 20th century has been documented for central and western Canada and Alaska (Weller & Lange 1999). Thawing of permafrost under global warming can be studied using predictive models and scenarios of climate change. Such an approach was used to calculate transitions between the zones of continuous, discontinuous, and sporadic permafrost, the depth of seasonal thawing, and thawing of relict permafrost.

3.1 *Permafrost distribution*

The surface frost index (SFI), suggested by Nelson & Outcalt (1987), was used to calculate the distribution of permafrost in the northern hemisphere under the conditions of the modern climate and GFDL, ECHAM, and HadCM transient scenarios of climate change for 2050. In an earlier study (Anisimov & Nelson 1996) SFI isolines of 0.50, 0.60, and 0.67 accurately reproduced the positions of southern boundaries of sporadic, discontinuous, and continuous permafrost zones on an empirical map of permafrost and ground ice conditions (Brown et al. 1997). In this study we combined a similar approach with climate data from the information system to predict the distribution of permafrost over the continents of the Northern Hemisphere under the modern and projected conditions for mid-21st century climate.

We used the gridded monthly norms of air temperature and precipitation with a resolution of 0.5° lat/long (Leemans & Cramer 1991) as baseline data characterising modern climate. Scenarios for 2050 were constructed by superimposing the changes of climatic parameters predicted by several GCMs on the baseline data. Results are presented in Table 1.

Reductions in permafrost area from the present to 2050 vary from 10% to 17%, depending on the climatic scenario. Because of the geometry of the continents, the southernmost zone occupies a smaller fraction of the continental permafrost area in North America than in Eurasia. Relative reduction of the areal extent will therefore also be smaller, as indicated in Table 1, although northward displacement of the boundaries may be roughly equal on both continents.

Table 1. Calculated areas of continuous (C), discontinuous (D) and sporadic (S) permafrost zones in the Northern Hemisphere (NH), Eurasia (EU), and North America (NA).

Region and climate scenario	Total area, mln km^2 and % from present	Areas of permafrost zones, mln km^2		
		C	D	S
NH, modern	26.9	8.7	6.1	12.1
NH, GFDL	23.6 (88%)	8.3	5.1	10.3
NH, ECHAM	24.2 (90%)	7.9	5.7	10.6
NH, HadCM	22.4 (83%)	8.0	8.5	5.9
EU, modern	16.7	5.9	4.3	6.5
EU, GFDL	13.8 (83%)	5.5	3.6	4.8
EU, ECHAM	14.6 (87%)	5.4	4.0	5.2
EU, HadCM	13.1 (78%)	5.4	3.6	4.1
NA, modern	10.2	2.8	1.8	5.6
NA, GFDL	9.8 (96%)	2.8	1.5	5.5
NA, ECHAM	9.6 (94%)	2.5	1.7	5.4
NA, HadCM	9.3 (91%)	2.6	4.9	1.8

These results assume an equilibrium model for permafrost. The results are therefore the projected changes of near-surface permafrost extent, and the presence of relict permafrost below a few metres depth is implicitly assumed. The dynamic model was used to study the thawing of relict permafrost. Changes in the depth of permafrost table were calculated using climatic data from 12 selected locations in Siberia and Alaska within the sporadic, discontinuous and continuous zones. In the first 10 years of calculations the model was initialised using local monthly norms of air temperature and precipitation. In the following 80 years we gradually increased air temperatures by 0.1°C/yr and precipitation by 1 mm/yr. In the last 10 years the model was forced by monthly air temperatures 8°C warmer than at the beginning and with annual precipitation 80 mm higher. Thermal properties of subsurface layers were calculated through soil type and ground ice content using empirically adjusted parameterisations (Anisimov et al. 1997). Calculations were made for silt and sands overlain by a 10 cm thick organic layer. In Figure 2 the calculated depth of permafrost table is plotted against initial seasonal thaw depth. Triangles and inverted triangles correspond to low (10%) and high (30%) content of ice in the frozen ground, respectively.

3.2 *Permafrost temperature and depth of seasonal thawing*

The permafrost temperature and depth of seasonal thawing were estimated by forcing the model of intermediate complexity with gridded norms of monthly air temperature and precipitation and scenarios of climate change derived from GCMs. Results are presented in Table 2.

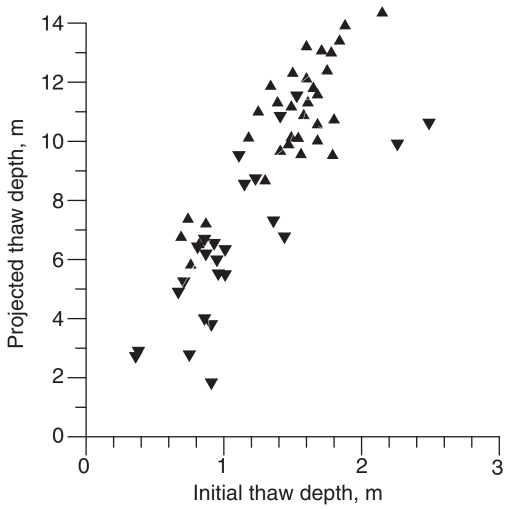

Figure 2. Projected depth to permafrost as a function of initial seasonal thaw depth.

Table 2. Changes in mean annual air temperature (ΔT_a), ground temperature (ΔT_s), and relative increase of the seasonal thaw depth (ΔZ_r) calculated for projected 2050 climate.

Region	ΔT_a, °C	ΔT_s, °C	ΔZ_r, %
Northern Scandinavia	1.5–2.0	1.0–1.5	10–20
West Siberia	2.0–3.0	1.5–2.5	20–30
Yakutia	2.5–4.0	2.0–3.0	30–50
Russian Far East	0–0.5	0–0.5	0–20
North Slope of Alaska	2.0–3.0	1.5–2.5	25–50
Western Canada	1.5–2.5	1.0–2.0	20–30
Central Canada	2.0–3.0	1.5–2.5	30–50
Northeastern Canada	0–0.5	0–0.5	0–10

The depth of seasonal thawing is strongly affected by soil type, water/ice content, and the thickness of the organic layer. Calculations were made for silt and sands overlaid by a 5 cm and 10 cm thick organic layer under different soil moisture conditions (10–40%) using GFDL, ECHAM, and HadCM climatic scenarios for 2050. Data in Table 2 includes the results obtained with different combinations of climatic and soil conditions.

4 CONCLUSIONS

One of the major conclusions from this and several preceding studies is that the response of permafrost to climatic warming depends on the nature of the climatic scenario, properties of vegetation, snow, organic layer, and ground ice/water content. Many of these factors in the Circumpolar Arctic are poorly understood and uncertainties remain large. Results of the earlier studies therefore need to be updated when new data comes into existence. A geographic information system with integrated databases and climate impact models is an effective instrument that may be used to achieve such a goal. Besides the effects on natural systems, anthropogenic global warming may have adverse impacts on human environments in high latitudes. Consequences of permafrost thawing are detrimental for the engineered structures built upon it (Nelson et al. 2001). The information system presented here may be used to assist investigations of engineering and social adaptation strategies to mitigate the adverse impacts of climatic warming in permafrost regions.

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