Uncertainties in gridded air temperature fields and effects on predictive active layer modeling

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[1] Several model-based assessments predict a discernible increase in the depth of seasonal thawing and circumpolar-scale warming of permafrost by the mid-21st century. Quantitative estimates of the environmental and socioeconomic impacts of changing climate in northern regions require robust projection of changes in permafrost, which in turn depend on the availability of appropriate models and forcing data. We examined four high-resolution, hemispheric-scale gridded sets of monthly temperature and precipitation constructed using different interpolation routines and reanalysis of data from a large number of weather stations. At many of 455 Russian weather stations, the four data sets depart from empirical mean annual air temperatures averaged over the 15-year period by 1–2°C and in cumulative daily positive temperature sums (degree days of thawing) by more than 200°C days. A permafrost model, forced with the gridded climatic data sets, was used to calculate the large-scale characteristics of permafrost in northern Eurasia. We analyzed zonal-mean air and ground temperatures, depth of seasonal thawing, and area occupied by near-surface permafrost in Eurasia north of 45°N. The 0.5–1.0 °C difference in zonal-mean air temperature between the data sets translates into a range of uncertainty of 10–20% in estimates of near-surface permafrost area, which is comparable to the extent of changes projected for the following several decades. We conclude that more observations and theoretical studies are needed to improve characterization of baseline climatic conditions and to narrow the range of uncertainties in model-based permafrost projections.

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1. Introduction

[2] Results from many scientific studies indicate that global climate change will be especially pronounced in the Arctic, and will have serious impacts on permafrost [*Anisimov and Fitzharris*, 2001; *Symon*, 2005]. Permafrost is a key element of the northern environment, exerts substantial influence on soil temperature and soil moisture [*Frauenfeld et al.*, 2004], surface and subsurface hydrology and fluvial processes [*Vandenberghe and Woo*, 2002], ecosystem stability [*Kaplan et al.*, 2003], biochemical cycles [*Christensen et al.*, 2004; *Walker et al.*, 1998], and land use and human infrastructure [*Chapin et al.*, 2004; *Nelson et al.*, 2001; *Nelson et al.*, 2002].

[3] A progressive increase in the thickness of the uppermost layer of seasonal freezing/thawing (the active layer) could be a relatively fast response of permafrost to climatic warming [*Kane et al.*, 1991; *Kane et al.*, 1992]. Such a change could facilitate further climatic evolution in response to decomposition of the large amounts of organic material sequestered in the northern soils and increased emission of greenhouse gases [*Christensen et al.*, 2004; *Friborg et al.*, 2003]. Models project that the northern regions are likely to become a weak sink of CO_2 during climate warming, and a net source of methane [*Callaghan et al.*, 2004; *Sitch et al.*, 2003]. Significant methane emissions can lead to positive forcing, because CH_4 has a much stronger greenhouse effect than does an equal amount of CO_2 [*Callaghan et al.*, 2004; *Friborg et al.*, 2003]. Recent research indicates that under the climatic conditions projected for the mid-21st century, annual emission of methane from wetlands in Russian permafrost regions may increase by 6–10 Mt [*Anisimov et al.*, 2005a; *Anisimov et al.*, 2005b].

[4] The increase in soil temperature, progressive thickening of the active layer, and melting of the excess ground ice common in upper layers of permafrost in the high latitudes

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will favor development of potentially disruptive geomorphological processes. Subsidence at the surface induced by melting of ground ice (thermokarst) and mass movements (e.g., active layer detachment slides) may lead to widespread ecological disturbances [*Forbes and Sumina*, 1999; *Jorgenson et al.*, 2001] and disruption of existing infrastructure [*Garagulia and Ershov*, 2000; *Nelson et al.*, 2001; *Nelson et al.*, 2002]. This problem is particularly important for the Russian north. The Russian population living in permafrost regions consists of more than 10 million people, with a substantial portion concentrated in large cities and industrial centers. In Russia, 93% of natural gas and 75% of oil are produced in permafrost areas. Overall, the Russian permafrost regions contribute up to 70% of total Russian exports [*Il'ichev et al.*, 2003]. Predictive assessment of permafrost-related risks indicates that in many areas residential buildings and industrial infrastructure could become unstable by the middle of the 21st century [*Nelson et al.*, 2001; *Nelson et al.*, 2002].

[5] Permafrost scenarios are needed to evaluate the environmental and socioeconomic impacts of changing climate in the northern regions and to develop appropriate strategies for adaptation. At the scale of the circumpolar Arctic, this task may be addressed using predictive permafrost models. A wide range of algorithms for evaluating permafrost parameters geographically have been developed. Substantial efforts have been made recently to incorporate these algorithms into General Circulation Models (GCMs) [*Christensen and Kuhry*, 2000; *Takata and Kimoto*, 2000; *Malevsky-Malevich et al.*, 2001; *Tilley and Lynch*, 1998, *Lawrence and Slater*, 2005], hydrologic [*Rawlins et al.*, 2003; *Zhang et al.*, 2000], and ecosystem simulators [*Zhuang et al.*, 2003; *Zhuang et al.*, 2001]. The accuracy of these assessments over large regions is, however, limited significantly by model constraints [*Burn and Nelson*, 2006; *Smerdon and Stieglitz*, 2006] and uncertainties in available forcing data.

[6] Active layer thickness (ALT) is one of the key environmental parameters in permafrost regions. ALT is controlled by many factors [*Brown et al.*, 2000; *Hinkel and Nelson*, 2003; *Zhang et al.*, 2005], including air temperature, vegetation, snow cover, soil moisture, the physical and thermal properties of the surface cover and substrate, thickness of the organic layer, and surface morphology. These variables interact across a range of spatial and temporal scales, resulting in large variations in ALT.

[7] Several global and continental scale data sets of major atmospheric parameters (e.g., air temperature and precipitation) have been developed over the last 3 decades [*Mitchell and Jones*, 2005; *Matsuura and Willmott*, 2005a, 2005b; *Serreze et al.*, 2005; *Serreze and Hurst*, 2000; *Kallberg et al.*, 2007]. These resources use different input sources (e.g., station observations, remote sensing products, and climate model simulations) and have been made available to the scientific community. In this paper, we examine the ability of four gridded data sets to reproduce spatial and temporal variations in the air temperature field over the Russian permafrost region and evaluate them in the specific context of continental scale permafrost modeling.

2. Gridded Climate Data Sets

[8] In this study we use monthly air temperature and precipitation data from the four gridded data sets spanning the circum-Arctic permafrost region. Two data sets were produced by interpolating observational data into regular grids using different methods and two are results from reanalysis of atmospheric data.

[9] The School of Environmental Sciences, University of East Anglia, UK Climatic Research Unit data set (CRU TS 2.1) is composed of monthly grids of observed climatic characteristics for the period 1901–2002 and covers the global land surface at 0.5 degree resolution [*Mitchell and Jones*, 2005]. Nine climate variables are available: mean, minimum, and maximum temperature, diurnal temperature range, precipitation, wet day frequency, frost day frequency, vapor pressure, and cloud cover. The data set was produced by interpolating station anomalies of climatic parameters relative to the 1960–1991 normals as a function of latitude, longitude, and elevation using thin-plate splines [*New et al.*, 1999]. The anomaly grids were combined with the gridded 1961–1990 normals (CRU CL 1.0 [*New et al.*, 1999]) to obtain absolute values. The CRU TS 2.1 data set is publicly available [*Climatic Research Unit*, 2007].

[10] The Willmott and Matsuura Arctic climate data set (W&M) was developed in the Department of Geography, University of Delaware. Monthly mean air temperatures and precipitation calculated for 4517 land surface weather stations located north of 43°N [*Matsuura and Willmott*, 2005a, 2005b] were used to produce a gridded archive with 0.5° latitude/longitude resolution. Traditional interpolation was accomplished with the spherical version of Shepard's algorithm, which employs an enhanced distance-weighting method [*Shepard*, 1968; *Willmott et al.*, 1985]. To increase the accuracy of spatial air temperature fields Digital Elevation Model (DEM)-assisted interpolation of air temperature was employed [*Willmott and Rawlins*, 1999]. Station air temperature was first translated to sea level using an average environmental lapse rate (6.0°C km^{-1}). Traditional interpolation then was performed on the adjusted-to-sea-level station air temperatures. Finally, the gridded sea level air temperatures were translated back to DEM-grid height, again at the average environmental lapse rate. The accuracy of this interpolation exercise was assessed by station-by-station cross validation. The resulting data set provides monthly means of air temperature and precipitation for the 1930–2004 period.

[11] Monthly air temperature and precipitation output from atmospheric reanalyses were obtained from the European Centre for Medium-Range Weather Forecast (ECMWF) 40-Year Re-Analysis (hereafter ERA-40) and the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR, hereafter NCEP-1). The atmospheric reanalysis projects provide long-term time series of analyzed atmospheric fields and modeled surface fields based on "frozen forecast and data assimilation systems" [*Serreze et al.*, 2005]. Analyzed fields, such as tropospheric pressure heights, represent an optimal blend of short-term forecast and observation. Modeled (or forecast) fields, such as surface radiation fluxes, are not directly influenced by observations of that variable. Use of frozen forecast and data assimilation systems removes spurious jumps and trends associated with changes in data assimilation techniques and models, often present in the archives of operational numerical weather-prediction systems. Temporal inconsistencies attributable to

changes in observing networks (e.g., rawinsonde and satellite remote sensing data products) may remain.

[12] The original ERA-40 2 m air temperature output contains temperature at 6-hour intervals in a reduced Gaussian grid (N80) with approximate resolution of 125 km and covers the period September 1957 through August 2002 [*Kallberg et al.*, 2007]. A broad overview of ERA-40 can be found in the extended abstracts from the 2001 ERA-40 workshop [*European Centre for Medium-Range Weather Forecasts*, 2002] and the ECMWF Web site (http://www.ecmwf.int). The 6-hour air temperatures are averaged arithmetically into daily and monthly values. ERA-40 air temperature from forecasts for the 2 m level are postprocessed, interpolated between the lowest model level and the surface, and assimilated with ground-based measurements [*Betts et al.*, 2003]. In this sense, ERA-40 air temperature is an analyzed field produced by the atmospheric reanalysis. However, the assimilated air temperature is not used as an initial condition for the forecast in the next time step. The primary ERA-40 archives also provide 6-hour accumulated precipitation fields in the N80 grid. ERA-40 precipitation data were processed into monthly precipitation sums by year. We used total precipitation, which is the sum of the large-scale and convective components. ERA-40 precipitation is a modeled (or forecast) field not influenced by ground-based measurements. The ERA-40 reanalysis data are available from the ECMWF Web site (http://www.ecmwf.int).

[13] The NCEP-1 reanalysis starts in 1948 and is updated continuously. The NCEP-1 system, based on a T62 Gaussian grid with a spatial resolution of about $1.875° \times 1.875°$ and 28 vertical sigma levels, was described by *Kalnay et al.* [1996], *Kistler et al.* [2001], and in references cited by them. *Serreze and Hurst* [2000] also provided a brief overview of the NCEP-1 system. The NCEP-1 2 m air temperature is a standard modeled field, produced by linear interpolation between the surface skin temperature and the temperature at the lowest model sigma level (0.995). It is therefore influenced strongly by the modeled surface energy budget. Air temperature at the lowest sigma (0.995) level is not influenced as strongly by the modeled surface energy balance and should provide for relatively realistic temperature variability [*Oelke et al.*, 2003]. Unlike the ERA-40 2 m air temperature, the NCEP-1 2 m air temperature is not assimilated with ground-based measurements. NCEP-1 precipitation is also a standard modeled field of the NCEP reanalysis [*University Consortium for Atmospheric Research*, 2007].

[14] This study is focused on analysis of gridded air temperature data and the effect of differences in air temperature fields on permafrost modeling results. Data sets are not compared with respect to differences in precipitation. In soil freeze/thaw models, precipitation data are used primarily to calculate snow depth, which has a pronounced effect on ground temperature. Continental-scale permafrost models do not take into account localized snow depth variability due to snow redistribution by wind, topography, and vegetation. As a result, uncertainties introduced by precipitation are marginal compared to inherent limitations of snow-depth calculations.

[15] To provide consistency of spatial resolution between the four gridded data sets, monthly air temperature and precipitation data were interpolated to the 25×25 km NSIDC EASE-grid [*Armstrong and Brodzik*, 1995] using inverse-distance weighting involving the five nearest grid nodes, i.e., the Cressman interpolation method [*Cressman*, 1959]. Transformation of the native grid (regridding), which is often used in the scientific studies to harmonize the data sets with different resolution and geographical referencing, may introduce error or bias. In this study we did not analyze the impact of regridding on the temperature data. *Fekete et al.* [2004] studied the impact of regridding on the quality of precipitation data and found that, although it could cause substantial local differences, the technique preserves large-scale patterns of the original fields adequately.

3. Evaluation of Grids

3.1. Air Temperature Fields

[16] Monthly gridded air temperature fields were compared with monthly 1990–2000 air temperatures time series from 455 stations located throughout Russia and the former Soviet Union. The 1990–2000 period was selected as representative of contemporary climatic conditions, for which data are available in all four data sets. Within the scope of our study, three temperature characteristics, mean annual air temperature (MAAT), annual temperature amplitude (ATA), and degree days of thawing (DDT), are particularly important because these characteristics largely govern the interannual variability of ALT. ATA is defined as half of the difference between the monthly maximum (July) and minimum (December) air temperature of the year. DDT is defined as the cumulative number of positive degree days. DDT is generally estimated by summing mean daily air temperatures during the warm season; such data are not readily available for many locations in high-latitude permafrost regions. In this study, DDT was estimated using monthly air temperature. Data from the four grid nodes surrounding each station were interpolated into the station location using inverse linear distance weight averaging and compared with the observations. The magnitude and the spatial pattern of differences between the gridded data and observations characterize the currently existing uncertainties in our knowledge of baseline climatic conditions in the study region.

[17] Data quality can be discerned by the frequency distribution of differences between air-temperature parameters (MAAT, ATA, and DDT) calculated from the four gridded fields and from 1990–2000 observations at 455 Russian stations. Departures from observation are significant in all four data sets (Figure 1). Departures of MAAT and DDT show distinct geographical patterns (Figures 2 and 3). Further analysis in this study is focused on the permafrost regions.

[18] With respect to MAAT, good agreement (±0.5°C) between the gridded fields and observations was found for fewer than one-third of the 156 stations located in the Russian permafrost regions. MAAT from ERA-40 data set are higher than observations almost everywhere (Figure 2); CRU and W&M data sets overestimate MAAT in West Siberia, southern Yakutia, and Chukotka. Underestimates occur in central Siberia. MAAT departures from NCEP show an irregular geographic pattern.

[19] Values of DDT calculated using gridded monthly air temperature depart significantly from each other and from

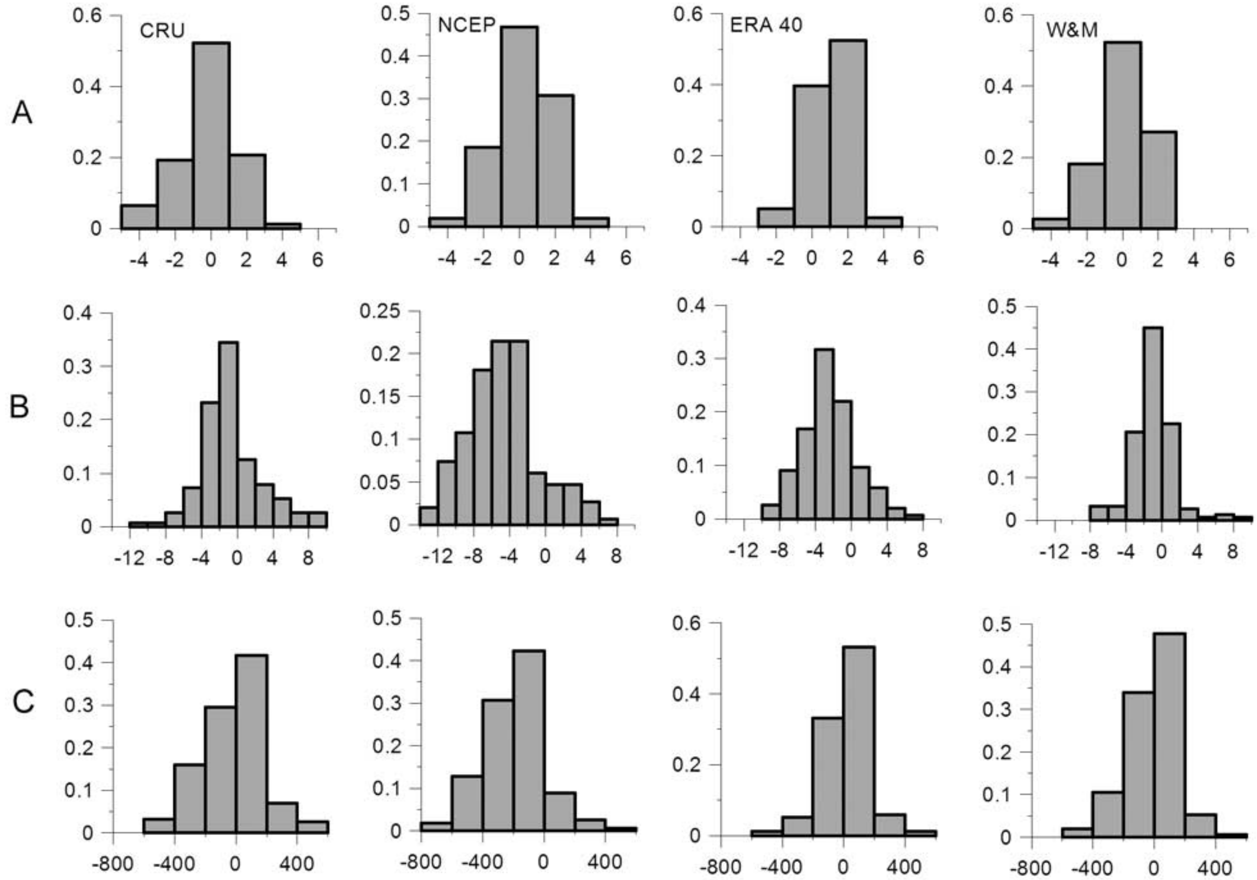

Figure 1. Frequency distribution of differences between gridded data and observations at 455 Russian weather stations. (a) Mean annual air temperature (°C); (b) annual air temperature amplitude (°C); (c) degree days of thawing (°C days).

weather-station data (Figure 3). NCEP data underestimate summer warmth by more than 200 degree days at almost every location in the Russian permafrost regions. The CRU, W&M, and ERA-40 data sets overestimate DDT primarily for stations located in the westernmost portion of the Russian permafrost region and have a small, randomly patterned, positive bias in Yakutia and Chukotka.

[20] Departures of ATA from observations at weather stations are significant, exceeding those for MAAT, and show an irregular geographic pattern. Decade-mean 1990–2000 temperature characteristics calculated using four data sets are noticeably different in regional details. Differences in the southernmost, sporadic permafrost zone are discernable in all three examined variables. Differences in temperature gradients along the north-south axis are particularly important, complicate delineation of the southern boundary of permafrost distribution, and lead to large divergences in model-based estimates of total permafrost area.

[21] Uncertainties in characterizing baseline climatic conditions arising from differences between the data sets can be compared with trends of MAAT, ATA, and DDT calculated using data from 156 weather stations located in permafrost regions (Figure 4). This exercise indicates that uncertainties associated with gridded climate fields are far beyond the level of decadal-scale changes. This situation complicates predictive permafrost modeling, especially in the zones of climatically sensitive discontinuous and sporadic permafrost.

3.2. Gridded Climate Data in Permafrost Modeling

[22] The effects of differences between four air temperature data products on predictive permafrost modeling were evaluated further by comparing the magnitude and geographic pattern of ALT and mean annual temperature at the base of the active layer. In this study we used an equilibrium permafrost model of intermediate complexity. Although sophisticated transient models can reproduce interannual variations of permafrost conditions more accurately (N. I. Shiklomanov et al., Analysis of model-produced permafrost active layer fields: Results for northern Alaska, submitted to *Journal of Geophysical Research*, 2007), the uncertainties introduced by the large number of required parameters severely restrain their applicability for studies over large areas.

[23] The equilibrium modeling algorithm used in this study was developed by V. Kudryavtsev [*Kudryavtsev et al.*, 1974], primarily for the practical needs of cold regions engineering. With slight modification, the modeling strategy has been used in many subsequent studies addressing changes in permafrost conditions at local [*Romanovsky and Osterkamp*, 1995], regional [*Shiklomanov and Nelson*, 1999; *Sazonova and Romanovsky*, 2003], and hemispheric

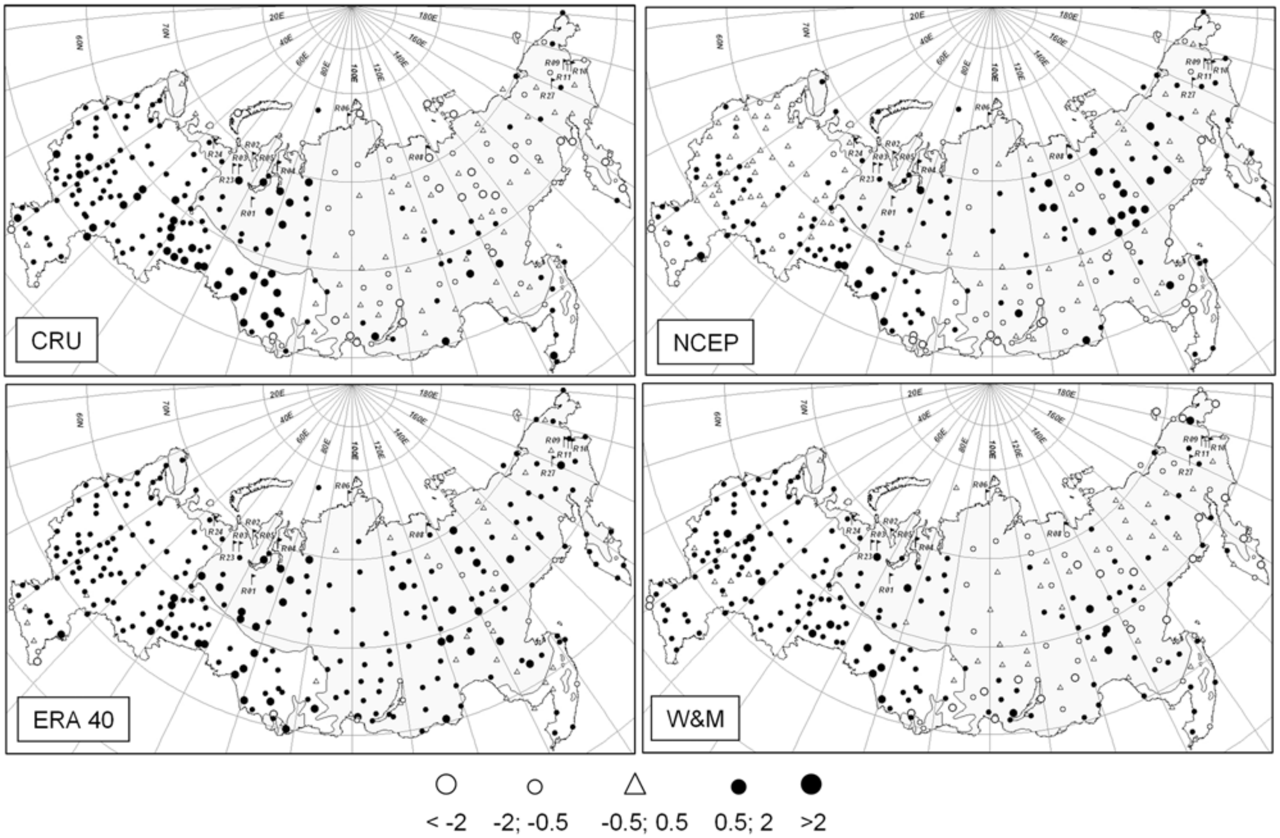

Figure 2. Differences between calculated and observed mean annual air temperatures, averaged over the 1990–2000 period. Circles indicate locations of weather stations and flags show locations of Circumpolar Active Layer Monitoring (CALM) sites in Russia.

[*Anisimov et al.*, 1997] scales. The model is forced by mean monthly temperature and precipitation data and takes into account the effects of snow cover, vegetation, soil moisture, and soil thermal properties. We modified Kudryavtsev's algorithm to account for the presence of an organic layer. Owing to substantially lower thermal conductivity when unfrozen, organic soils attenuate seasonal temperature variations and effectively preserve ground from warming and permafrost from thawing. The resulting model is based on evaluation of the annual temperature wave as it propagates through consecutive layers of vegetation, snow, organic and mineral soil. The computational design of the model is presented in Figure 5.

[24] The core of the model is an equation for calculating the depth of seasonal thawing (Z_{thaw}), derived under the assumption that the soil is a homogeneous medium with constant thermal properties and that for a period of 1 year the influence of geothermal heat is small and can be neglected [*Kudryavtsev et al.*, 1974]:

$$Z_{thaw} = \frac{2(A_s - T_z)\cdot\left[\frac{\lambda\cdot P_{sn}\cdot C}{\pi}\right]^{1/2} + \frac{\left(2A_z\cdot C\cdot Z_c + Q_{ph}\cdot Z_c\right)\cdot Q_{ph}\left[\frac{\lambda\cdot P_{sn}}{\pi\cdot C}\right]^{1/2}}{2A_z\cdot C\cdot Z_c + Q_{ph}\cdot Z_{thaw} + \left(2A_z\cdot C + Q_{ph}\right)\cdot\left[\frac{\lambda\cdot P_{sn}}{\pi\cdot C}\right]^{1/2}}}{2A_z\cdot C + Q_{ph}} \quad (1)$$

where

$$A_z = \frac{A_s - T_z}{1\text{n}\left[\frac{A_s + Q_{ph}/2C}{T_z + Q_{ph}/2C}\right]} - \frac{Q_{ph}}{2C} \quad (2)$$

and

$$Z_c = \frac{2(A_s - T_z)\cdot\sqrt{\frac{\lambda\cdot P_{sn}\cdot C}{\pi}}}{2A_z\cdot C + Q_{ph}}. \quad (3)$$

[25] Here, A_s is the annual amplitude of soil-surface temperature (°C), T_z is mean annual temperature at the depth of seasonal thawing (°C), λ is the thermal conductivity of soil in the thawed state ($Wm^{-1}\ K^{-1}$), C is the volumetric heat capacity of soil in the thawed state ($Jm^{-3}\ K^{-1}$), P_{sn} is the period of the temperature wave (s), and Q_{ph} is the volumetric latent heat of phase changes ($J\ m^{-3}$). Owing to the effects of snow cover, vegetation and the organic layer, T_z differs from the mean annual air temperature. Calculation of this parameter is detailed elsewhere [*Kudryavtsev et al.*, 1974].

[26] The permafrost model defined by equations (1) through (3) has been tested in several studies and compared with observations at selected locations [*Romanovsky and Osterkamp*, 1995] and over regional transects in Alaska [*Shiklomanov and Nelson*, 1999] and Siberia [*Sazonova and Romanovsky*, 2003]. Results indicate that, although differ-

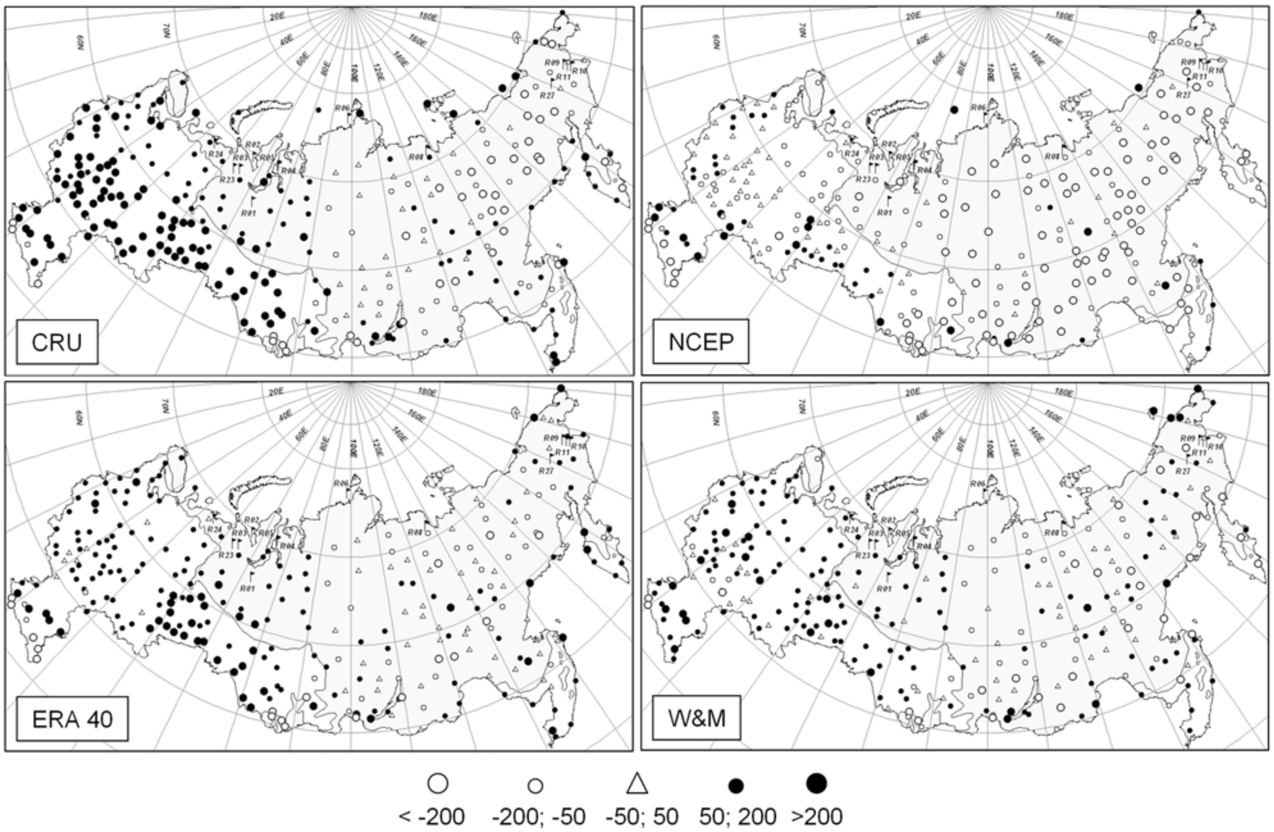

Figure 3. Differences between calculated and observed degree days of thawing, averaged over the 1990–2000 period. Circles indicate locations of weather stations and flags show locations of Circumpolar Active Layer Monitoring (CALM) sites in Russia.

ences between calculated and observed permafrost parameters for individual years can be quite large, when applied to long-term (decadal or longer time scale) averages this approach achieves accuracy of 0.2–0.4°C for permafrost temperature and 0.1–0.3 m for ALT calculations [*Sazonova and Romanovsky*, 2003]. At point locations, discrepancies with observations in individual years are attributable to the inherent limitations of the equilibrium modeling concept. The assumption of equality between air and ground-surface temperatures oversimplifies the atmospheric boundary layer processes that have significant effects on the thermal state of the ground and the depth of seasonal thaw propagation. The model assumes a thermal balance between climate and permafrost conditions, and when forced with annual climatic data does not account for the temperature inertia associated with deep, low-temperature permafrost layers that mitigate the propagation of heat from the surface. The annual imbalance between the thermal state of the upper layer of seasonal thawing and deeper permafrost created by the equilibrium approach leads to erroneous annual estimates of ground thermal regime parameters. This is particularly true for years that are significantly colder or warmer than the decadal mean

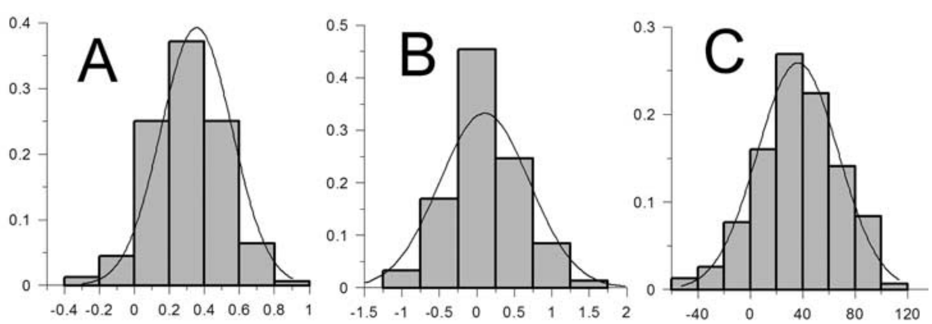

Figure 4. Frequency distribution of decadal changes in (a) mean annual air temperature (°C/decade); (b) annual temperature amplitude (°C/decade); (c) degree days of thawing (°C days/decade) for the 1970–2002 period, based on data from 156 weather stations in Russian permafrost region.

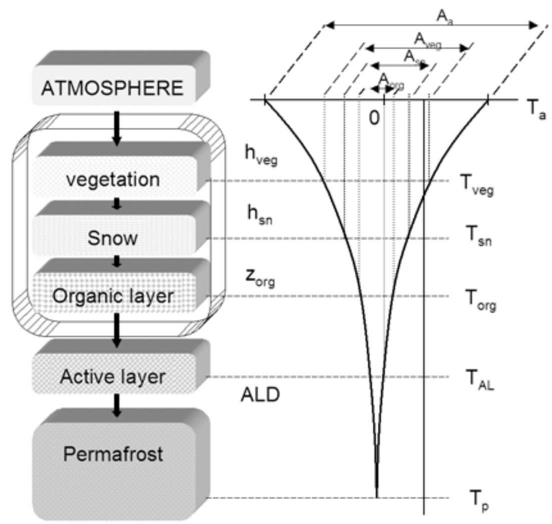

Figure 5. Computational design of the equilibrium permafrost model.

and during transitions from colder to warmer climatic conditions. These features of the model are apparent in Figure 6, which compares calculated ALT with observations at the R1 CALM site (Nadym). Nadym is the only Russian permafrost observation site with a continuous data record (ALT, air temperature, and precipitation) extending over more than 25 years. Although model results depart from observations in individual years, statistical parameters are in close accordance. Calculated and observed ALT, averaged over the 1975–2002 period, are 1.34 m and 1.32 m, respectively, and standard deviation in each case is 0.08.

[27] This study is concerned more with evaluating and comparing climatic fields in broad-scale permafrost applications than with achieving accurate estimates of permafrost parameters for individual years at particular locations. An important concern in this context is the high spatial heterogeneity of local climatic, surface, and subsurface conditions. To simulate the effects of small-scale variability in snow, vegetation, and soil moisture, we used an ensemble approach. In different calculations snow depth varied in the range ±50% from the mean climatological value; vegetation (moss) height varied between 5 and 10 cm, and organic layer thickness was in the range 5–20 cm. Moisture content in the organic layer varied between 0.3 and 0.5 m/m, and mineral soil moisture varied from 0.1 to 0.3 m/m.

[28] The permafrost model was forced with the CRU, M&W, ERA-40, and NCEP-1 gridded fields of monthly air temperature and precipitation. At each grid node we made 36 model runs using different combinations of the varying parameters to generate the ensemble of calculated results. Mean winter snow depth was calculated from winter precipitation using the approach detailed by *Anisimov et al.* [1997]. The density, thermal conductivity, and heat capacity of snow were prescribed at 300 kg m^{-3}, 0.23 W m^{-1} K^{-1}, and 2090 J kg^{-1} K^{-1}, respectively. The thermal properties of vegetation (moss) were set to 0.2 W m^{-1} K^{-1} for thermal conductivity and 2500 J kg^{-1} K^{-1} for heat capacity [*Kudryavtsev et al.*, 1974; *Sazonova and Romanovsky*, 2003]. Soils have a prescribed dry density of 200 kg m^{-3} for organic and 1400 kg m^{-3} for mineral soils. The thermal conductivities of organic and mineral soils were estimated using dry density and moisture content, as described by *Anisimov et al.* [1997]. Ensemble-averaged results from broad-scale modeling of several parameters obtained with the four sets of climatic data are presented in Figure 7.

[29] Permafrost characteristics, including areal extent, ALT, and mean annual ground temperature at the depth of maximum thawing were calculated for Eurasia north of 45°N, which includes discontinuous permafrost in the mountainous regions of southern Siberia. Permafrost area was estimated using the concept of "near-surface permafrost," which is the uppermost permafrost layer that adjusts its thermal regime to changing climate with a lag of only a few years. This uppermost layer can be sensitive even to short-term climatic variations, while centuries of sustained warming may be required for propagation of thaw to deeper

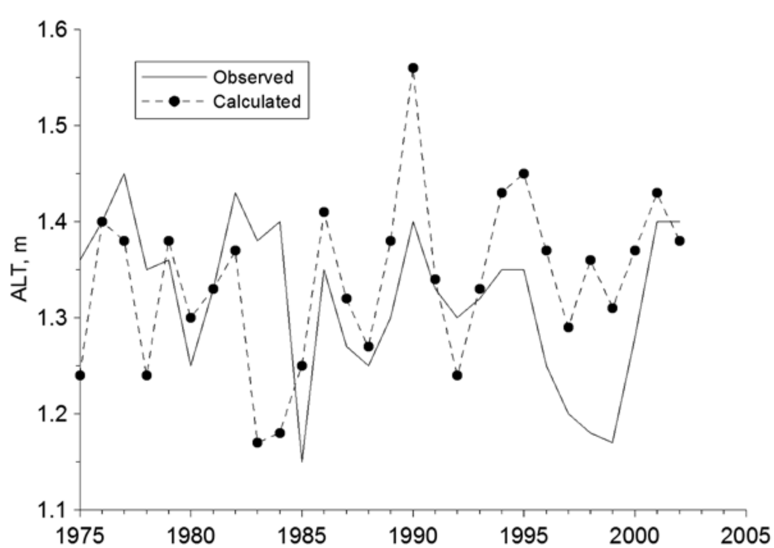

Figure 6. Comparison of results from permafrost model with observations at R1 CALM site (Nadym).

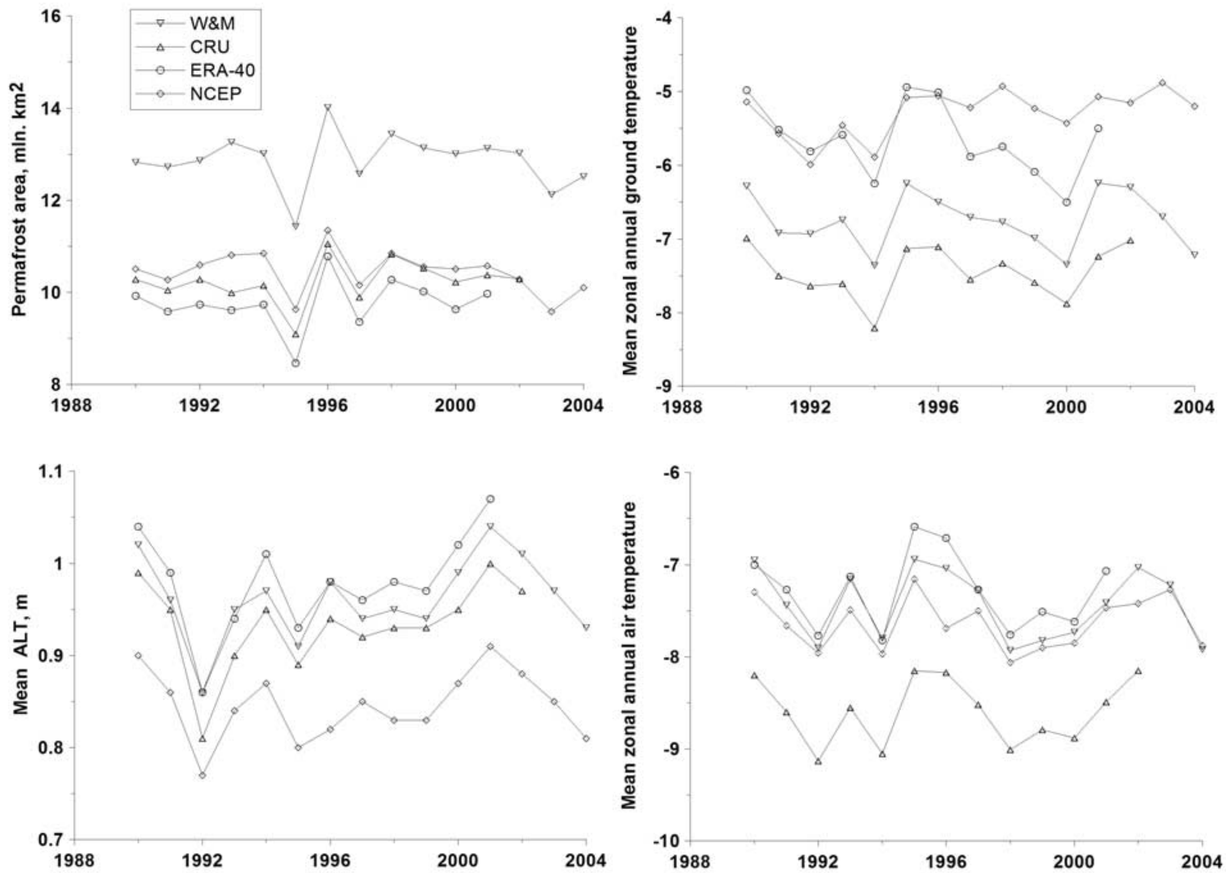

Figure 7. Comparison of broad-scale characteristics of Russian permafrost obtained with different climatic forcing data sets.

permafrost layers. Evaluation of the near-surface permafrost area through climatic data was based on the surface frost index [*Nelson and Outcalt*, 1987]. All calculations were made using 25 by 25 km equal-area EASE grid nodes, and mean zonal ALT was obtained by averaging the calculated ensemble-mean depth of thawing at all nodes where the surface frost index predicts the presence of near-surface permafrost.

[30] The four sets of gridded climatic data provided noticeably different estimates of broad-scale permafrost characteristics. Results indicate that there is no direct correspondence between zonal MAAT or ALT and the area of near-surface permafrost. Forced by ERA-40, the permafrost model yields higher values of zonal ALT and ground temperature, and lower estimates of permafrost extent, as a reflection of generally higher zonal air temperatures. The coldest air temperatures are associated with the CRU data set, which leads to lower mean zonal annual ground temperature and the most extensive permafrost area. However, CRU provides relatively high ALT values. Although the NCEP fields utilize median air temperature, their application in conjunction with the permafrost model results in the highest mean annual ground temperatures, and the lowest values of ALT. The W&M fields yield midrange values of ALT and mean annual ground temperature, while providing the largest estimates of permafrost area. Differences in north-south gradients and spatial patterns of temperature fields produced by the various data sets have significant effects on the broad-scale permafrost characteristics.

4. Climatic Coherence

[31] Changes in climate and permafrost in the northern regions are not uniform over space and time. They exhibit pronounced spatial and interannual variability, although permafrost-related observations are sparse and data are available only for limited time periods. Systematic permafrost observations were organized in the mid-1990s under the Circumpolar Active Layer Monitoring (CALM) project [*Brown et al.*, 2000; *Nelson et al.*, 2004]. The locations of 12 Russian CALM sites with more than five years of observations are indicated by flags in Figures 2 and 3. Because all Russian CALM sites are located in close proximity to the Arctic Ocean coast, the observational data do not encompass the complete range of climatic, soil, vegetation, and topographic conditions in the permafrost region. This situation dictates that conventional interpolation routines are not suitable for broad-scale generalization of permafrost parameters in this region. In the context of global climate change, data derived from an unevenly distributed network of observational sites could lead to biased conclusions about the geographic aspects of perma-

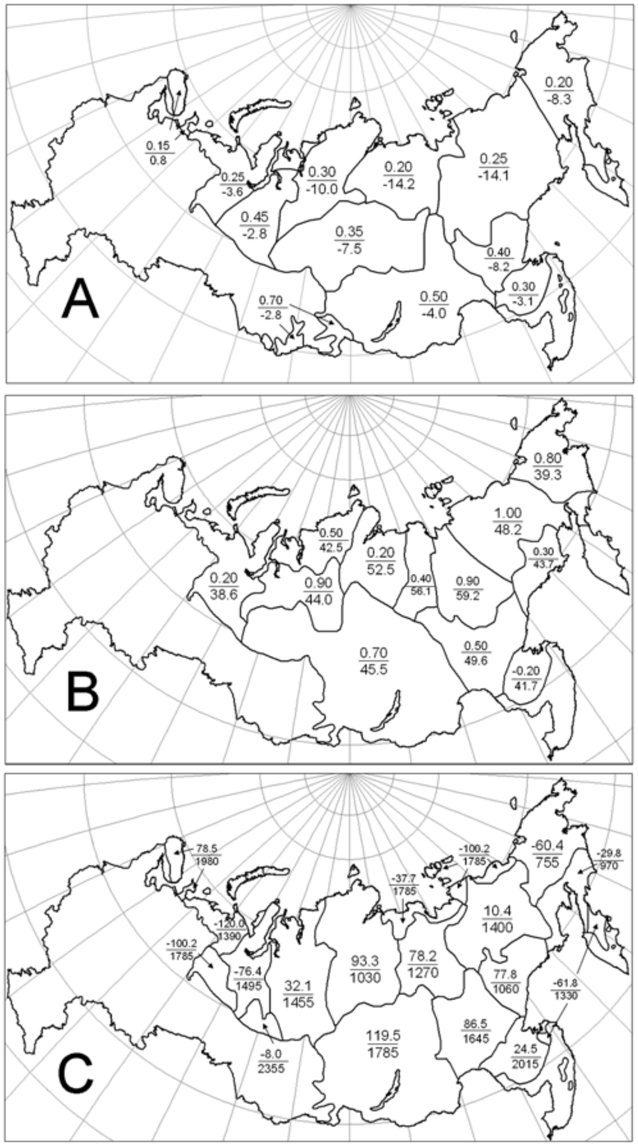

Figure 8. Regionalization with respect to coherence of temperature changes in the 1970–2002 period, based on data from weather stations. (a) Mean annual air temperature; (b) annual temperature amplitude; (c) degree days of thawing. Numerical inserts: numerators represent trends of MAAT and ATA (°C/decade) and DDT (°C days/decade) and denominators represent mean regional values.

frost dynamics. In the geographic context, optimal results are achieved when generalizations are based on spatially coherent climatic and permafrost data. We hypothesized that regularities in the interannual dynamic of near-surface permafrost parameters, such as ALT, are governed primarily by the spatial coherence of climatic characteristics. Our analysis is focused on the coherence of temperature changes.

[32] Regions with coherent changes were delineated on the basis of the spatial correlation between each of the three temperature characteristics. We calculated correlation coefficients between the time series of MAAT, ATA, and DDT for the 1970–2002 period at different paired locations, using data from the four gridded sets and from weather stations. Stations or grid nodes with paired correlation coefficients above 0.8 were combined into "regions with coherent changes." Coherence patterns of each temperature characteristic supplement the conventional "rate of change-based" climatic regionalization, and are of particular importance for analysis of records from sparse observational networks with short records. The procedure can also be utilized for effective planning of observational networks.

[33] Patterns of the spatial correlation functions calculated using different data sets were close to each other, indicating that these data reproduce the interannual variability much better than the mean climatology. Figures 8a–8c show coherence patterns with respect to changes of MAAT, ATA, and DDT, calculated using 1970–2002 data from 156 weather stations located on permafrost. An important metric in such regionalization is the homogeneity parameter H,

which characterizes the spatial correlation function in each region. H is defined by:

$$H = n^{-1}\Sigma(r_{i,j}), \quad (4)$$

where n is the number of different pairs of stations within one region, and $r_{i,j}$ is the correlation coefficient between stations i and j in the region ($i \neq j$). Regions in Figures 8a–8c have H > 0.80, indicating high coherence of intra-regional changes in climatic parameters.

5. Discussion

[34] The geographic noncoherence of changes in MAAT, ATA, and DDT over the Russian permafrost region has important implications for planning permafrost observation networks, predictive mapping, and modeling. Each of the three parameters possesses a unique and complex spatial pattern of temporal change and variability (Figure 8). To date, selection of locations for Russian CALM sites has been driven, to a significant extent, by logistical constraints. Many stations in the network were preexisting field facilities. With a few exceptions, observations are conducted in close proximity to the Arctic coast and do not characterize the variety of climatic conditions over the whole permafrost region. With respect to broad-scale interannual and interdecadal variability of climatic parameters, current permafrost observations are undersampled. The relationship between climate and near-surface permafrost is affected by a complex interplay between surface and subsurface conditions. Broad-scale geographic assessment of surface and subsurface parameters is required to achieve a more comprehensive evaluation of the adequacy of permafrost observation networks.

[35] The complexity of the MAAT, ATA, and DDT patterns indicates that conventional statistical upscaling/downscaling techniques, which are frequently used in climatology to provide transitions between different geographical scales and to extrapolate results from selected locations to larger territories, are not applicable to the near-surface permafrost observations currently available for the Russian territory. These results stress the need for combining available observations with comprehensive modeling to provide realistic characterization of permafrost conditions over large spatial domains. Such work may require expansion of observations into areas underrepresented by currently operational permafrost observation networks. Coherence patterns (Figure 8) that represent characteristic variability and changes in mean annual and seasonal air temperature may serve as a guide for establishing future sites for monitoring permafrost-climate interactions.

6. Summary and Conclusions

[36] We examined spatial and temporal variations of air temperature using four gridded data sets and compared them with observations from Russian weather stations. Analysis was focused on mean annual air temperature (MAAT), annual temperature amplitude (ATA), and degree days of thawing (DDT), all of which are important parameters for permafrost modeling. Averaged over the 1990–2000 period MAAT, ATA, and DDT data depart from each other and from the weather-station observations (Figures 1–3). Although data biases and errors may have resulted from transformation of the native grids in the four data sets to a common 25 km by 25 km grid, regridding is often used when data from different sources are combined or compared with each other. Although it is beyond the scope of this paper to analyze the effects this practice may have on data quality, we have replicated the conventional regridding technique and focused on the effects that differences in the resulting forcing data sets have on broad-scale, model-based evaluation of permafrost parameters. In the case of the four gridded data sets examined in this paper, the 0.5–1.0°C difference in zonal mean MAAT led to 10%–20% uncertainty in the estimates of zonal permafrost areas (Figure 7). This degree of uncertainty is comparable with changes in the permafrost regions projected for the mid-21st century [*Symon*, 2005] and is much higher than the uncertainty associated with the temperature observations. For example, *Zhang et al.* [1996] and *Frauenfeld et al.* [2006] found that the relative error of the DDT estimated using daily and monthly air temperature is generally within 5% for most high-latitude land areas, and also works well in many midlatitude regions. Our rough estimate, based on the semiempirical N-factor permafrost model [*Klene et al.*, 2001], indicated that 5% uncertainty in DDT values produces less than 3% uncertainty in the model-based evaluation of ALT.

[37] Observations and modeling indicate that ongoing climate change involves pronounced warming in the high latitudes and disproportional increases in seasonal temperatures [*Folland and Karl*, 2001]. General circulation models predict markedly higher rates of warming in winter than in summer, implying a gradual decrease in annual air temperature amplitude. The interplay between changes in MAAT and ATA has important implications for predictive permafrost modeling because the depth of seasonal thawing is highly sensitive to changes in these parameters. The projected decrease in ATA may compensate for the effects of an increase of MAAT on active layer thickness. However, results from this study indicate that changes in ATA over the 1970–2002 period were generally irregular. Averaged over the entire permafrost region, the overall trend is small, positive, and statistically insignificant. A slight, insignificant decrease in annual air temperature amplitude was found only at the southeastern margins of permafrost. The frequency distribution of annual ATA values over the decade is close to normal, and centered on zero (Figure 4b), while frequency distributions of MAAT (Figure 4a) and DDT (Figure 4c) values are skewed positively.

[38] In the context of predictive permafrost modeling, currently existing uncertainties are associated with both conceptual differences between computational algorithms and forcing data, particularly in characterizing baseline and projected climatic conditions. In this study we used a relatively simple equilibrium model and found that it can accurately estimate long-term mean ALT and its standard deviation at point locations if all required forcing data are supplied (Figure 6). The major problem of undersampling arises when estimates of permafrost dynamics supplied from an inadequate number of field locations are generalized and extrapolated over a larger territory with noncoherent, complex, and patterned variations in MAAT, ATA, and DDT.

The range of uncertainties in model-based characterization of broad-scale permafrost dynamics may be narrowed if more accurate and consistent gridded climatic data sets become available.

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References

Anisimov, O. A., and B. Fitzharris (2001), Polar regions (Arctic and Antarctic), in *Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by O. F. C. J. McCarthy et al., pp. 801–841, Cambridge Univ. Press, Cambridge, U. K.

Anisimov, O. A., N. I. Shiklomanov, and F. E. Nelson (1997), Global warming and active-layer thickness: Results from transient general circulation models, *Global Planet. Change*, *15*, 61–77.

Anisimov, O. A., S. A. Lavrov, and S. A. Reneva (2005a), Emission of methane from the Russian frozen wetlands under the conditions of the changing climate, in *Problems of Ecological Modeling and Monitoring of Ecosystems*, edited by Y. Izrael, pp. 124–142, Hydrometeoizdat, St. Petersburg, Russia.

Anisimov, O. A., S. A. Lavrov, and S. A. Reneva (2005b), Modelling the emission of greenhouse gases from the Arctic wetlands under the conditions of the global warming, in *Climatic and Environmental Changes*, edited by G. V. Menzhulin, pp. 21–39, Hydrometeoizdat, St. Petersburg, Russia.

Armstrong, R. L., and M. J. Brodzik (1995), An Earth-gridded SSM/I data set for cryospheric studies and global change monitoring, *Adv. Space Res.*, *16*(10), 155–163.

Betts, A. K., J. H. Ball, and P. Viterbo (2003), Evaluation of the ERA-40 surface water budget and surface air temperature for the Mackenzie River basin, *J. Hydrometeorol.*, *4*, 1194–1211.

Brown, J., K. M. Hinkel, and F. E. Nelson (2000), The Circumpolar Active Layer Monitoring (CALM) program: Research designs and initial results, *Polar Geogr.*, *24*, 163–258.

Burn, C. R., and F. E. Nelson (2006), Comment on "A projection of severe near-surface permafrost degradation during the 21st century" by David M. Lawrence and Andrew G. Slater, *Geophys. Res. Lett.*, *33*, L21503, doi:10.1029/2006GL027077.

Callaghan, T. V., et al. (2004), Climate change and UV-B impacts on Arctic tundra and polar desert ecosystems, *Ambio*, *33*, 386–392.

Chapin, F. S., III, et al. (2004), Resilience and vulnerability of northern regions to social and environmental change, *Ambio*, *33*, 342–347.

Christensen, J. H., and P. Kuhry (2000), High-resolution regional climate model validation and permafrost simulation for the East European Russian Arctic, *J. Geophys. Res.*, *105*, 29,647–29,658.

Christensen, T. R., T. Johansson, H. J. Åkerman, M. Mastepanov, N. Malmer, T. Friborg, P. Crill, and B. H. Svensson (2004), Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, *Geophys. Res. Lett.*, *31*, L04501, doi:10.1029/2003GL018680.

Climatic Research Unit (2007), Data available from CRU, http://www.cru.uea.ac.uk/cru/data/, Univ. of East Anglia, Norwich, U. K.

Cressman, G. P. (1959), An operational objective analysis system, *Mon. Weather Rev.*, *87*, 367–374.

European Centre for Medium-Range Weather Forecasts (2002), *Proceedings of the ERA-40 Project Report Series 3: Workshop on Re-Analysis*, Reading, U. K.

Fekete, B. M., C. J. Vörösmarty, J. O. Roads, and C. J. Willmott (2004), Uncertainties in precipitation and their impacts on runoff estimates, *J. Clim.*, *17*, 294–304.

Folland, C. K., and T. R. Karl (2001), Observed climate variability and change, in *Climate Change 2001: The Scientific Basis Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Y. D. J. T. Houghton et al., pp. 99–181, Cambridge Univ. Press, Cambridge, U. K.

Forbes, B. C., and O. I. Sumina (1999), Comparative ordination of low Arctic vegetation recovering from disturbance: Reconciling two contrasting approaches for field data collection, *Arct. Antarct. Alp. Res.*, *31*, 389–399.

Frauenfeld, O. W., T. Zhang, R. G. Barry, and D. Gilichinsky (2004), Interdecadal changes in seasonal freeze and thaw depths in Russia, *J. Geophys. Res.*, *109*, D05101, doi:10.1029/2003JD004245.

Frauenfeld, O. W., T. Zhang, and J. L. McCreight (2006), Northern Hemisphere freezing/thawing index variations over the 20th century, *Int. J. Climatol.*, *27*, 47–63.

Friborg, T., H. Soegaard, T. R. Christensen, C. R. Lloyd, and N. S. Panikov (2003), Siberian wetlands: Where a sink is a source, *Geophys. Res. Lett.*, *30*(21), 2129, doi:10.1029/2003GL017797.

Garagulia, L. S., and E. D. Ershov (2000), *Geocryological Hazards*, *Nat. Hazards Russ. Ser.*, vol. 1, edited by V. I. Osipov and S. K. Shoigu, 316 pp., Kruk, Moscow.

Hinkel, K. M., and F. E. Nelson (2003), Spatial and temporal patterns of active layer thickness at Circumpolar Active Layer Monitoring (CALM) sites in northern Alaska, 1975–2000, *J. Geophys. Res.*, *108*(D2), 8168, doi:10.1029/2001JD000927.

Il'ichev, V. A., V. V. Vladimirov, A. V. Sadovskyi, A. V. Zamaraev, V. I. Grebenetc, and M. Kutvickaia (2003), *Perspectives of the Development of the Modern Northern Settlements*, 152 pp., Russ. Acad. of Archit. Sci., Moscow.

Jorgenson, M. T., C. H. Racine, J. C. Walters, and T. E. Osterkamp (2001), Permafrost degradation and ecological changes associated with a warming climate in central Alaska, *Clim. Change*, *48*, 551–579.

Kallberg, P., A. Simmons, S. Uppala, and M. Fuentes (2007), *ERA-40 Project Report Series*, vol. 17, Eur. Cent. for Med. Range Weather Forecasts, Reading, U. K. (Available at http://www.ecmwf.int/publications/library/do/references/list/192.)

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Kane, D. L., L. D. Hinzman, C. S. Benson, and G. E. Liston (1991), Snow hydrology of a headwater Arctic basin: Physical measurements and process studies, *Water Resour. Res.*, *27*, 1099–1109.

Kane, D. L., L. D. Hinzman, M.-K. Woo, and K. R. Everett (1992), Arctic hydrology and climate change, in *Arctic Ecosystems in a Changing Climate: An Ecophysiological Pespective*, edited by F. S. Chapin III et al., pp. 35–57, Academic, San Diego, Calif.

Kaplan, J. O., et al. (2003), Climate change and Arctic ecosystems: 2. Modeling, paleodata-model comparisons, and future projections, *J. Geophys. Res.*, *108*(D19), 8171, doi:10.1029/2002JD002559.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*, 247–267.

Klene, A. E., F. E. Nelson, and N. I. Shiklomanov (2001), The *n*-factor as a tool in geocryological mapping: Seasonal thaw in the Kuparuk River basin, Alaska, *Phys. Geogr.*, *22*, 449–466.

Kudryavtsev, V. A., L. S. Garagulya, K. A. Kondrat'yeva, and V. G. Melamed (1974), *Fundamentals of Frost Forecasting in Geological Engineering Investigations* (in Russian), Nauka, Moscow. (English translation, U. S. Army Cold Regions Research and Engineering Laboratory Draft Translation 606, Hanover, N. H. 1977.)

Lawrence, D. M., and A. G. Slater (2005), A projection of severe near-surface permafrost degradation during the 21st century, *Geophys. Res. Lett.*, *32*, L24401, doi:10.1029/2005GL025080.

Malevsky-Malevich, S. P., E. K. Molkentin, E. D. Nadyozhina, and O. B. Shklyarevich (2001), Numerical simulation of permafrost parameters distribution in Russia, *Cold Reg. Sci. Technol.*, *32*, 1–11.

Matsuura, K., and C. J. Willmott (2005a), Arctic Land-Surface Air Temperature: 1930–2004 Gridded Monthly Time Series, Version 1.03, http://climate.geog.udel.edu/~climate/html_pages/Arctic4_files/README.arctic.t_ts4.html, Cent. for Clim. Res., Dep. of Geogr., Univ. of Del., Newark.

Matsuura, K., and C. J. Willmott (2005b), Arctic Land-Surface Air Temperature: 1930–2004 Gridded Monthly Time Series, Version 1.03, http://climate.geog.udel.edu/~climate/html_pages/Arctic4_files/README.arctic.p_ts4.html, Cent. for Clim. Res., Dep. of Geogr., Univ. of Del., Newark.

Mitchell, T. D., and P. D. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, *25*, 693–712.

Nelson, F. E., and S. I. Outcalt (1987), A computational method for prediction and regionalization of permafrost, *Arct. Alp. Res.*, *19*, 279–288.

Nelson, F. E., O. A. Anisimov, and N. I. Shiklomanov (2001), Subsidence risk from thawing permafrost, *Nature*, *410*, 889–890.

Nelson, F. E., O. A. Anisimov, and N. I. Shiklomanov (2002), Climate change and hazard zonation in the circum-arctic permafrost regions, *Nat. Hazards*, *26*, 203–225.

Nelson, F. E., N. I. Shiklomanov, K. M. Hinkel, and H. H. Christiansen (2004), The Circumpolar Active Layer Monitoring (CALM) Workshop and the CALM II Program, *Polar Geogr.*, *28*, 253–266.
New, M., M. Hulme, and P. Jones (1999), Representing twentieth-century space-time climate variability. part I: Development of a 1961–90 mean monthly terrestrial climatology, *J. Clim.*, *12*, 829–856.
Oelke, C., T. Zhang, M. C. Serreze, and R. L. Armstrong (2003), Regional-scale modeling of soil freeze/thaw over the Arctic drainage basin, *J. Geophys. Res.*, *108*(D10), 4314, doi:10.1029/2002JD002722.
Rawlins, M. A., R. B. Lammers, S. Frolking, B. M. Fekete, and C. J. Vörösmarty (2003), Simulating pan-arctic runoff with a macro-scale terrestrial water balance model, *Hydrol. Process.*, *17*, 2521–2539.
Romanovsky, V. E., and T. E. Osterkamp (1995), Interannual variations of the thermal regime of the active layer and near-surface permafrost in northern Alaska, *Permafrost Periglacial Process.*, *6*, 313–335.
Sazonova, T. S., and V. E. Romanovsky (2003), A model for regional-scale estimation of temporal and spatial variability of active-layer thickness and mean annual ground temperatures, *Permafrost Periglacial Process.*, *14*, 125–140.
Serreze, M. C., and C. M. Hurst (2000), Representation of mean Arctic precipitation from NCEP-NCAR and ERA reanalysis, *J. Clim.*, *13*, 182–201.
Serreze, M. C., A. P. Barrett, and F. Lo (2005), Northern high-latitude precipitation as depicted by atmospheric reanalyses and satellite retrievals, *Mon. Weather Rev.*, *133*, 3407–3430.
Shepard, D. (1968), A two-dimensional interpolation function for irregularly-spaced data, in *Proceedings of the 1968 23rd ACM National Conference*, pp. 517–523, edited by R. B. Blue and A. M. Rosenberg, ACM Press, New York.
Shiklomanov, N. I., and F. E. Nelson (1999), Analytic representation of the active layer thickness field, Kuparuk River basin, Alaska, *Ecol. Modell.*, *123*, 105–125.
Sitch, S., et al. (2003), Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model, *Global Change Biol.*, *9*, 161–185.
Smerdon, J. E., and M. Stieglitz (2006), Simulating heat transport of harmonic temperature signals in the Earth's shallow subsurface: Lower-boundary sensitivities, *Geophys. Res. Lett.*, *33*, L14402, doi:10.1029/2006GL026816.
Symon, C. (2005), *Impacts of a Warming Arctic: Arctic Climate Impacts Assessment*, Cambridge Univ. Press, Cambridge, U. K.
Takata, K., and M. Kimoto (2000), A numerical study on the impact of soil freezing on the continental-scale seasonal cycle, *J. Meteorol. Soc. Jpn.*, *78*, 199–221.
Tilley, J. S., and A. H. Lynch (1998), On the applicability of current land surface schemes for Arctic tundra: An intercomparison study, *J. Geophys. Res.*, *103*, 29,051–29,063.
University Consortium for Atmospheric Research (2007), NCEP/NCAR Reanalysis, http://dss.ucar.edu/pub/reanalysis/, Boulder, Colo.
Vandenberghe, J., and M. K. Woo (2002), Modern and ancient periglacial river types, *Prog. Phys. Geogr.*, *26*, 479–506.
Walker, D. A., et al. (1998), A major Arctic soil pH boundary: Implications for energy and trace-gas fluxes, *Nature*, *394*, 469–472.
Willmott, C. J., and M. A. Rawlins (1999), Arctic Monthly Air Temperature: Land-Surface Station Climatology Archive, Version. 1.01, http://climate. geog.udel.edu/~climate/html_pages/ac_readme/README.temp.clim.html, Cent. for Clim. Res., Dep. of Geogr., Univ. of Del., Newark.
Willmott, C. J., C. M. Rowe, and W. D. Philpot (1985), Small-scale climate maps: A sensitivity analysis of some common assumptions associated with grid-point interpolation and contouring, *Am. Cartogr.*, *12*, 5–16.
Zhang, T., T. E. Osterkamp, and K. Stamnes (1996), Some characteristics of the climate in northern Alaska, U.S.A., *Arct. Alp. Res.*, *28*, 509–518.
Zhang, T., et al. (2005), Spatial and temporal variability in active layer thickness over the Russian Arctic drainage basin, *J. Geophys. Res.*, *110*, D16101, doi:10.1029/2004JD005642.
Zhang, Z., D. L. Kane, and L. D. Hinzman (2000), Development and application of a spatially-distributed Arctic hydrological and thermal process model (ARHYTHM), *Hydrol. Process.*, *14*, 1017–1036.
Zhuang, Q., V. E. Romanovsky, and A. D. McGuire (2001), Incorporation of a permafrost model into a large-scale ecosystem model: Evaluation of temporal and spatial scaling issues in simulating soil thermal dynamics, *J. Geophys. Res.*, *106*, 33,649–33,670.
Zhuang, Q., et al. (2003), Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th century: A modeling analysis of the influences of soil thermal dynamics, *Tellus, Ser. B*, *55*, 751–776.

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