NASA Project NNG06GH48G

Permafrost Dynamics within the Northern Eurasia Region and Related Impacts on Surface and Sub-Surface Hydrology

Final Report to NASA

October, 2010

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Project Goals:

The overarching goal of our research is to obtain a deeper understanding of the temporal (interannual and decadal to century time scales) and spatial (north to south and west to east) variability and trends in the active layer characteristics and permafrost temperatures in the 20th century and their impact on hydrology within the Northern Eurasia region, and to develop more reliable predictive capabilities for the projection of these changes into the 21st century. Permafrost has received much attention recently because surface temperatures are rising in most permafrost areas of the earth, bringing permafrost to the edge of widespread thawing and degradation. The thawing of permafrost that is already occurring at the southern limits of the permafrost zone can generate dramatic changes in ecosystems and in infrastructure performance. Observational data will be used in conjunction with a two-tiered modeling approach to simulate present, past and future permafrost conditions in the Northern Eurasia permafrost region. The observational data will consist of subsurface and surface data, together with relevant atmospheric and remote sensing data, for the entire Northern Eurasia permafrost domain. These data will be incorporated into a Geographical Information System (GIS) for spatially distributed permafrost models and for interpretation, synthesis and integration of model results. Two tiers of model simulations will include (1) simulations for specific sites with maximum available information for calibration and validation, (2) spatially distributed simulations for the entire Northern Eurasia permafrost region using the improved GIPL model developed at the Permafrost Lab, University of Alaska Fairbanks and described by Sazonova and Romanovsky (2003). Simulations will be both retrospective (spanning the 20th century) and prognostic (spanning the 21st century). Synthesis and integration activities will be achieved through the utilization of soil and atmospheric data from a wide range of sources in Northern Eurasia and by comparisons of present (measured) and simulated characteristics of the active layer and permafrost dynamics within the Northern Eurasia permafrost region. It also includes testing the hypothesis that recent and future climate warming will produce nonlinear responses in permafrost, thickening of the active layer over much of the Arctic, and permafrost degradation in areas in which the active layer fails to refreeze completely after summer thaw. Mapping of the latter areas will be possible from the simulations for the entire Northern Eurasia permafrost domain. The results of this calculations and mapping will be used then to test a possible relationship between permafrost degradation and Siberian rivers runoff. This research is in response to the Northern Eurasia Earth Science Partnership Initiative (NEESPI). It principally addresses the NEESPI science questions regarding the local and hemispheric effects of climate changes to permafrost.

Summary for each project component:

1. Data acquisition

a. Landscape characteristics

The landscape characteristics were collected in the form of electronic maps. This data set consists of maps of various soil characteristics for all of Russia. Vegetation cover characteristics were also obtained for the entire former USSR territory. The maps are available as ESRI Shapefiles and they are accompanied by databases of soil profiles and related characteristics (Stolbovoi and Savin, 2002). The soil classification Shapefile was generalized from the standard 1:2,500,000 soil map of Russia (Fridland, 1988). Several different soil classifications are presented as well as detailed soil characteristics. Additionally, the dataset contains two databases of detailed soil characteristics from 234 measured soil profiles.

The database also contains information on carbon content and pools as well as potential methane production (Stolbovoi, 2001). The soil drainage classification in combination with bulk density and carbon density provide the unique information, which could be used for hydrological modeling and also for soil thermal properties determination.

b. Meteorological data

Meteorological data such as monthly and daily air temperature and precipitation, every 10 days (decade) snow depth and density were obtained from the Russian State Weather Service meteorological stations (Figure 1) that are located within the areas of permafrost distribution and seasonal freezing. All obtained data span time interval from the beginning of measurements at each station up to December 2004 or up to the year when the station was closed.

Figure 1. *Permafrost and ground ice distribution within Northern Eurasia and location of the weather stations from which data will be used for analysis and computation.*

c. Active layer and permafrost temperature data

During the second year of the project, most of the available data from the Russian meteorological stations on monthly ground temperatures in the upper 3.6 m were obtained (Figure 2). We also collected data from a number of specialized permafrost observatories in East Siberia (Tiksi, Yakutsk, Chaboda) and in West Siberia (Igarka) with daily time resolution. Long-term permafrost temperature measurements in deeper boreholes from the European North of Russia, West and East Siberia, and Transbaikal region (Figure 3) were also obtained. We established a good working relationship with 12 scientific institutions in Russia, Kazakhstan, and Mongolia and signed an official Memorandum of Agreement with all of these institutions.

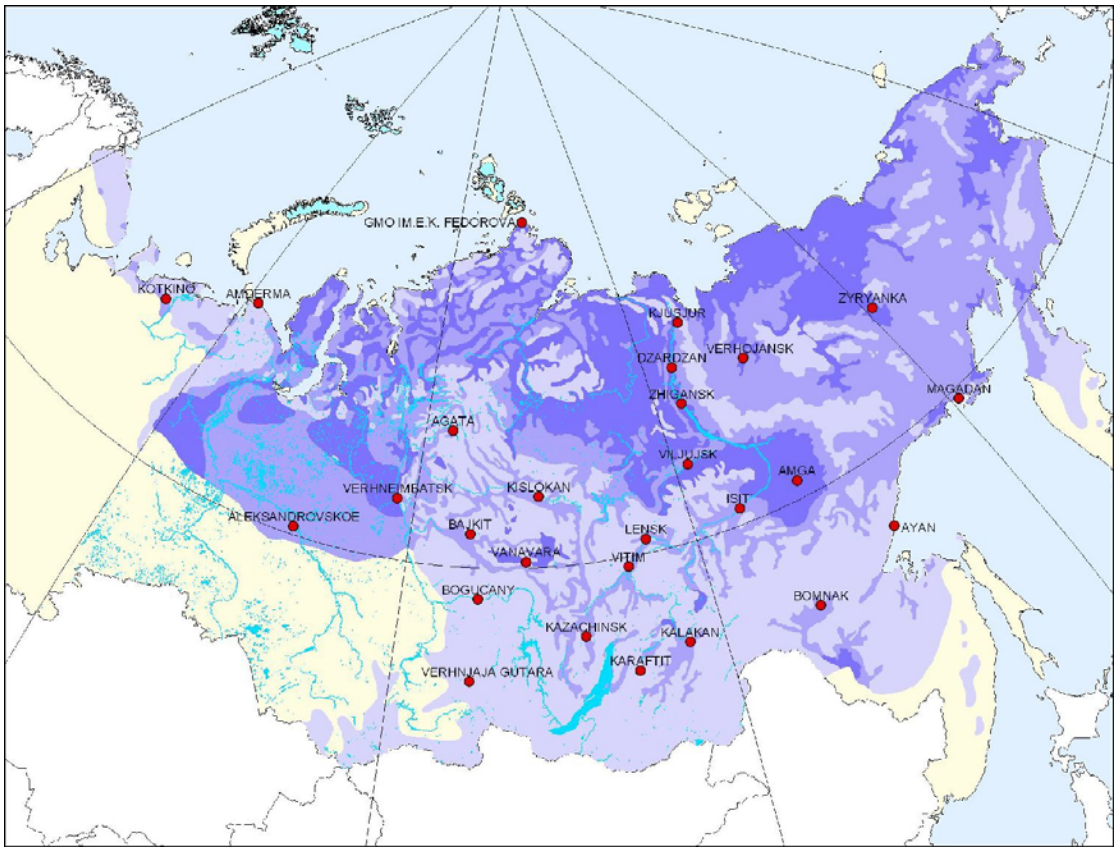

Figure 2*. Location of the weather stations, from which data were used for analysis and model calibration during the second year of the project*

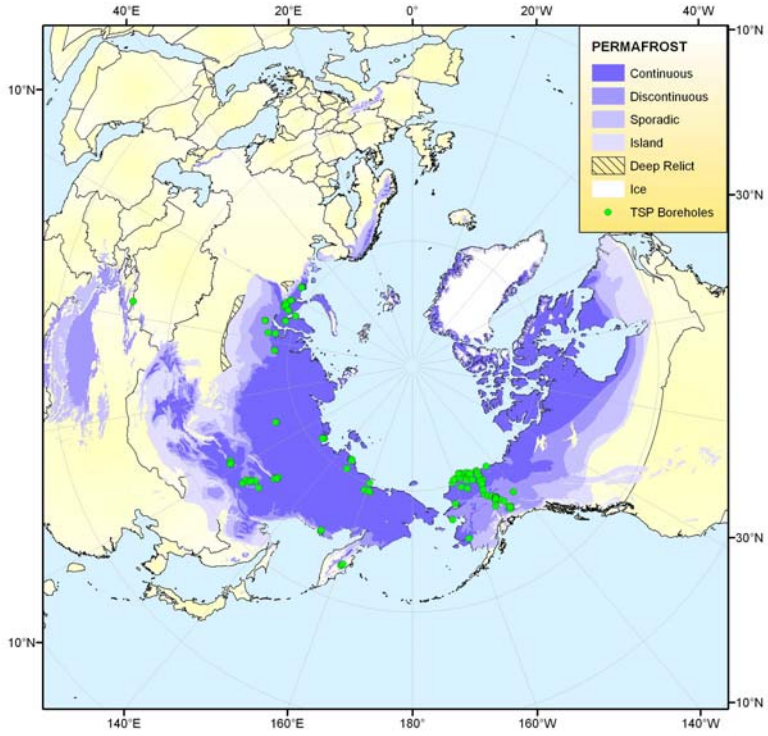

Figure 3. *Location of the active and newly equipped boreholes in Russia, Kazakhstan and Alaska*

d. GIS

The Northern Eurasian GIS already contains different thematic maps described above. The maps are in a vector format stored as ESRI Shapefile spatial data format. The Shapefiles are most easily imported into ESRI's ArcView, but most other GIS packages can import ESRI Shapefiles. Databases are stored as .dbf files. These can be imported into most spreadsheets and databases, and some GIS packages, including ArcInfo. The Northern Eurasian GIS also contains data on permafrost distribution, temperature and ice content for the whole permafrost area as well as data on active layer thickness for the central part of the region Lena River Basin, which was chosen as an area of special investigation.

2. *Remote sensing*

Surface Temperature

Surface temperature is a critical parameter to measure for understanding biological, hydrological and climatological systems, and their interactions. Arctic and sub-Arctic regions merit a particular attention in this respect since they are very sensitive to climate change. In these regions, permafrost is subject to thaw which affects its stability. The rate

at which permafrost evolves can be determined by studying its thermal regime, which is dependent on surface temperature. Given that the Eurasian North covers a large area, and is remote and relatively unpopulated, the costs associated with the operation and maintenance of ground-based permafrost monitoring stations can be prohibitive. Satellite remote sensing sensors operating at thermal infrared wavelengths can provide air-ground interface temperature measurements, also termed “skin” temperatures, over large areas and in sub-daily temporal resolution. However, to date, few studies have assessed the potential of land surface temperature (LST) measurements obtained from satellite platforms for mapping and monitoring the thermal regime of permafrost terrain (Goïta and Royer, 1997; Han et al. 2004; Traoré et al. 1997; Fily et al. 2003; Comiso, 2003). In addition, Hachem et al. (2009) have examined the potential of LST provided by the MODIS (Moderate Resolution Imaging Spectroradiometer) aboard NASA’s Terra and Aqua satellites for permafrost studies at high latitudes. MODIS LST data were found to be well correlated with near-surface air temperature measurements (2-3 m above ground) from several ground-based stations in herbaceous and shrub tundra environments, located in the continuous permafrost zone of northern Quebec and Alaska ($R^2 > 0.81$; $4.41 < RMSE < 6.89$; $-3.58 <$ mean bias < 5.92). Due to extensive periods of cloudiness in high-latitude regions (more than 50% of cloudy days in every year), monthly and 8-day LST composites are used here. Mean annual near-surface temperatures as well as freezing and thawing indices can be calculated over large areas. A large area covering from UK (Greenwich meridian 0°) to Bering-Strait (180°E) and from the North Pole (90°N) to South of Mongolia (40°N), is mapped (Figure 4). Maps produced for several years of MODIS data acquisitions are also presented below.

Figure 4*. Study area.*

Data and Methods

To map such a large area, the MODIS/TERRA LAND SURFACE TEMPERATURE /EMISSIVITY MONTHLY L3 GLOBAL 0.05DEG CMG V005 and the MODIS/TERRA LAND SURFACE TEMPERATURE/EMISSIVITY 8-DAY L3 GLOBAL 0.05DEG CMG V005 were downloaded and processed. As these products provide a global coverage, a window corresponding to the colored area of Figure 4 was extracted. Terra satellite data were used because it has a more complete record than the Aqua satellite, since 2000 instead of 2002.

Then, the monthly product was used to calculate the mean annual surface temperature for each year from 2001 to 2007. Unfortunately, we experienced some trouble to open few monthly products from 2005 and 2006 which prevented us from producing annual maps for these years. When the Land Processes Distributed Active Archive Center (LPDAAC) will correct errors on the problematic products we will be able to complete the 7 years records as planned. Therefore, in this report only mean annual surface temperature maps for 2001, 2002, 2003, 2004, and 2007 are presented (Figure 5).

The freezing and thawing indices have been calculated using the 8-days product. Freezing index is the sum of temperatures cumulated below 0°C (Figure 6). Thawing index is the sum of temperatures cumulated above 0°C (Figure 7). They are measured with the degree-days units. It is usually the average of all days with temperature below or above 0°C over a year, but here, the 8-day composite gives smoother information in particular during the shoulder seasons, which can last more than a week. It does not provide the extreme values compared to the daily product.

Downloading of daily LST data at the 1 km resolution for the Lena River Basin tiles are in process. The full area is composed of 10 tiles. Four tiles are already ready to be used. The final maps will be calculated using the model of Hachem et al. (in preparation). Analysis of the maps will be done using hydrography and topography, which are the main factors influencing climate after the latitudinal repartition. Topography is more obvious on Figure 7 where the Ural and Caucasian mountains have thawing indices lower than in their vicinity. Also, the ratio between Thawing index and Freezing index can give information on the continentality of climate.

Conclusion

The mean monthly and annual surface temperatures, as well as freezing and thawing indices derived from the MODIS LST products are an interesting and important alternative to conventional ground-based measurements which are limited spatially. Preliminary maps have been produced and are currently available in ARC/GIS for comparison and possible future data assimilation in the spatially-distributed permafrost model.

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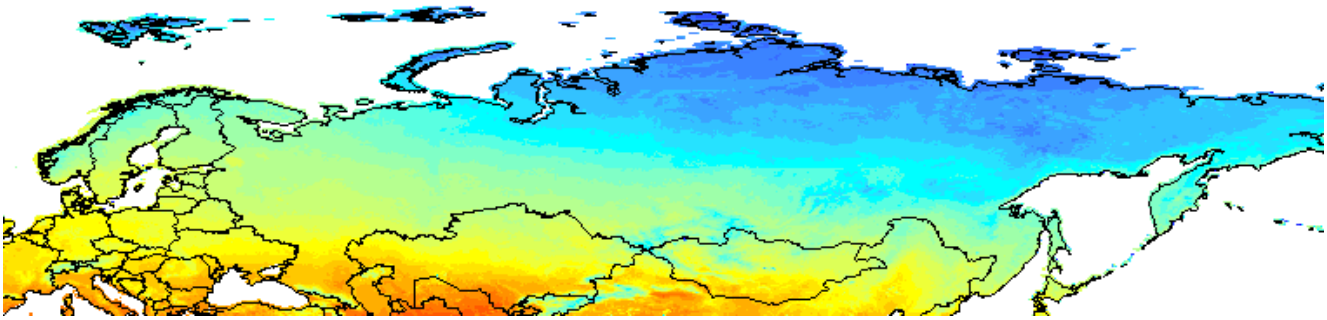

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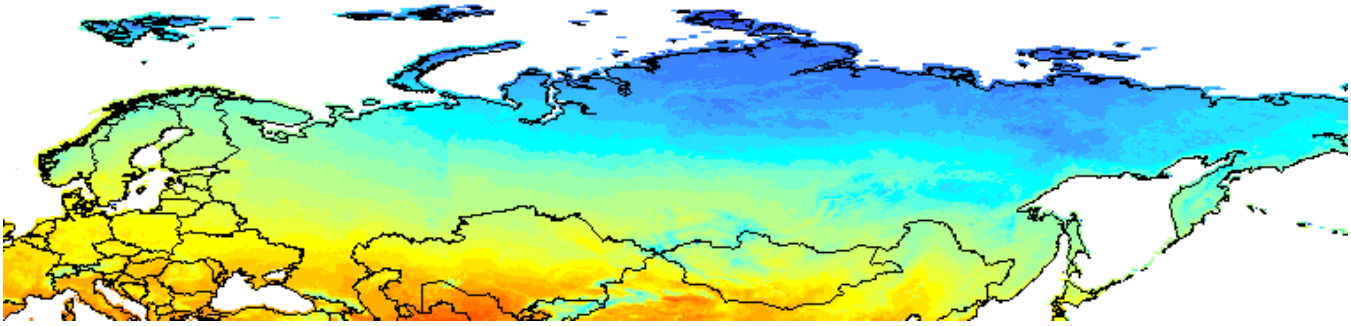

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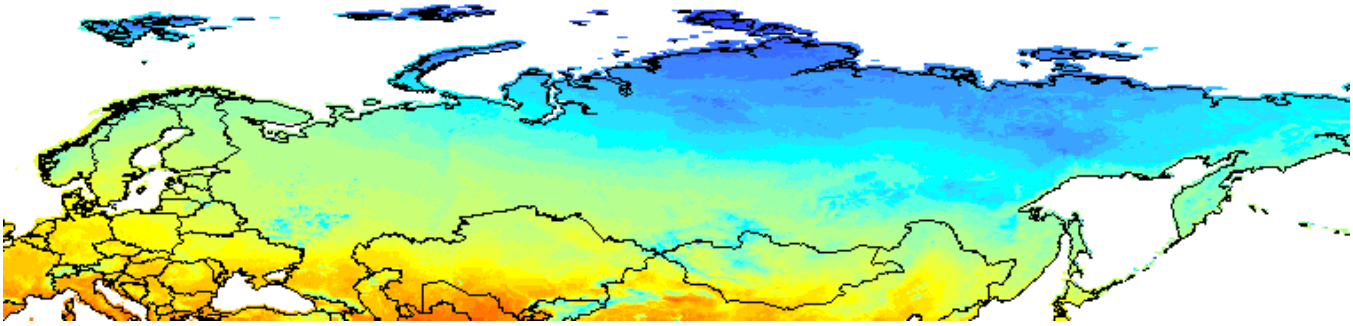

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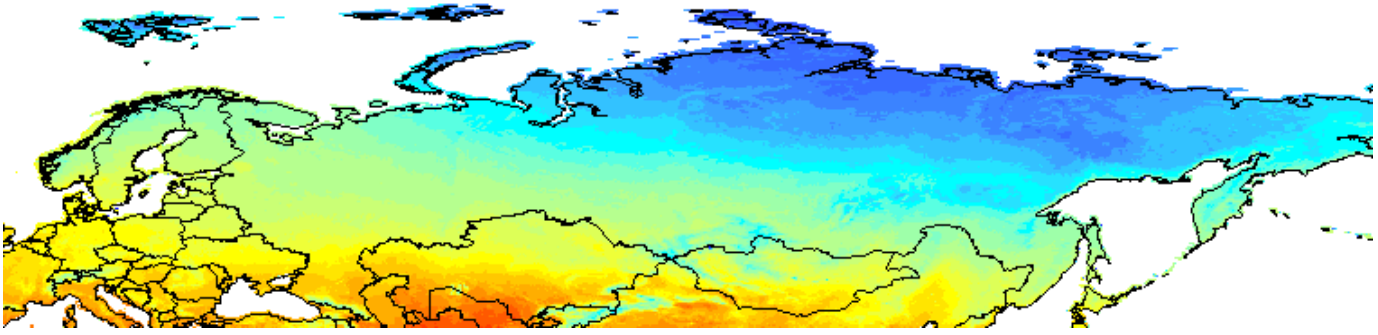

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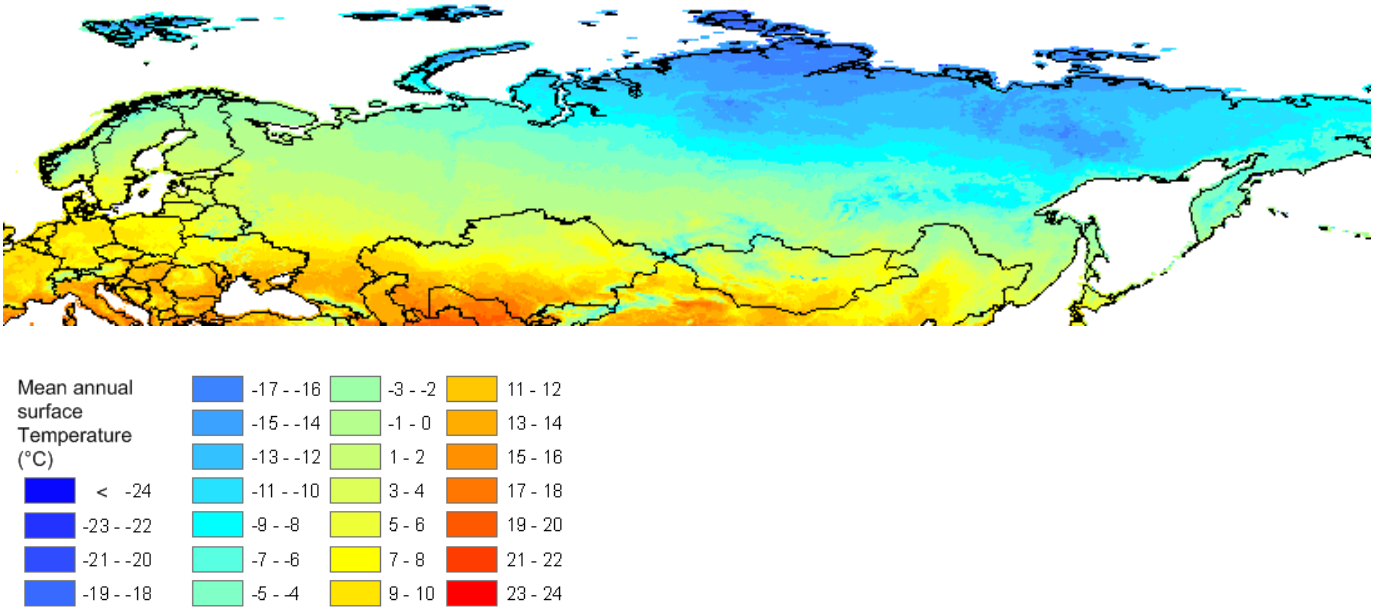

Figure 5. *Mean annual surface temperature in degree Celsius for 2001, 2002, 2003, 2004, and 2007.*

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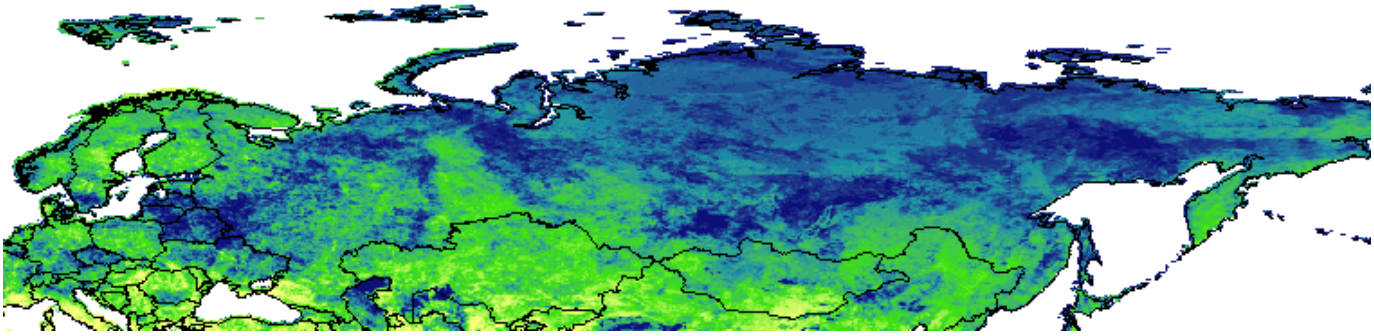
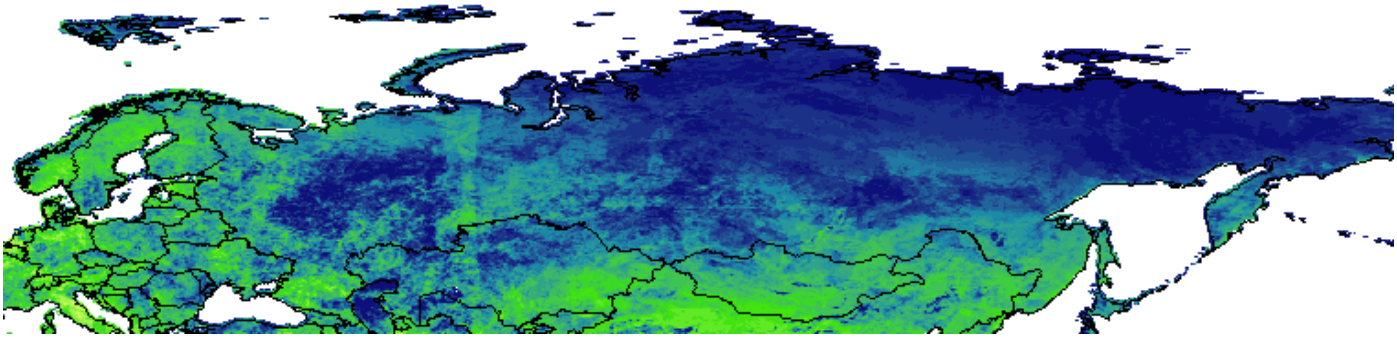


Fi 2001 – 2002



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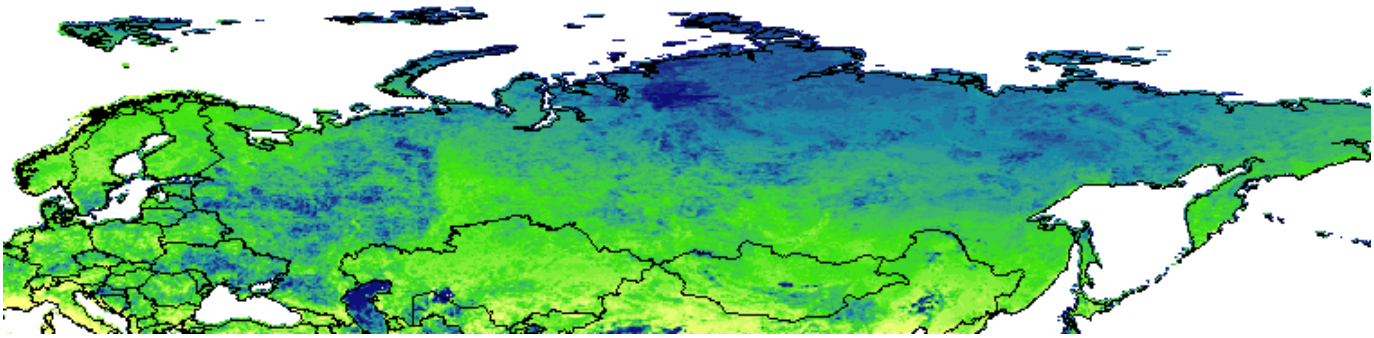
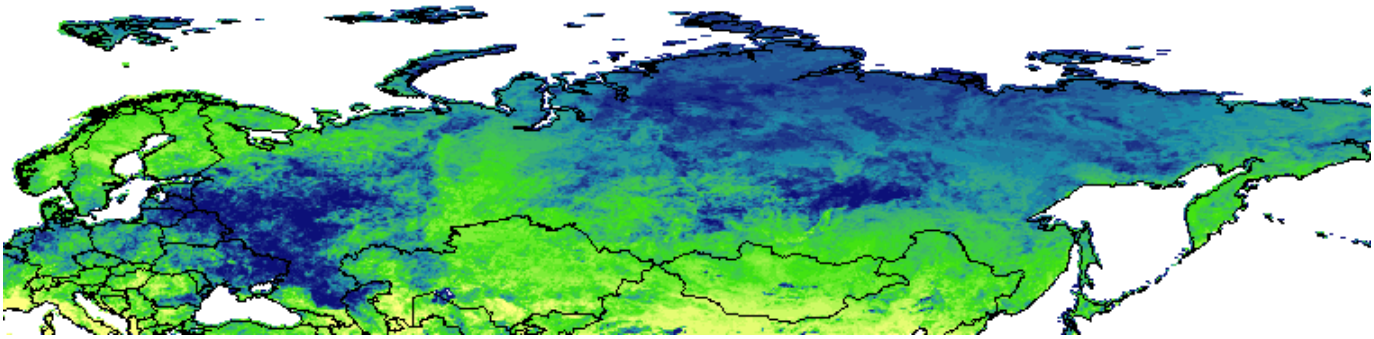
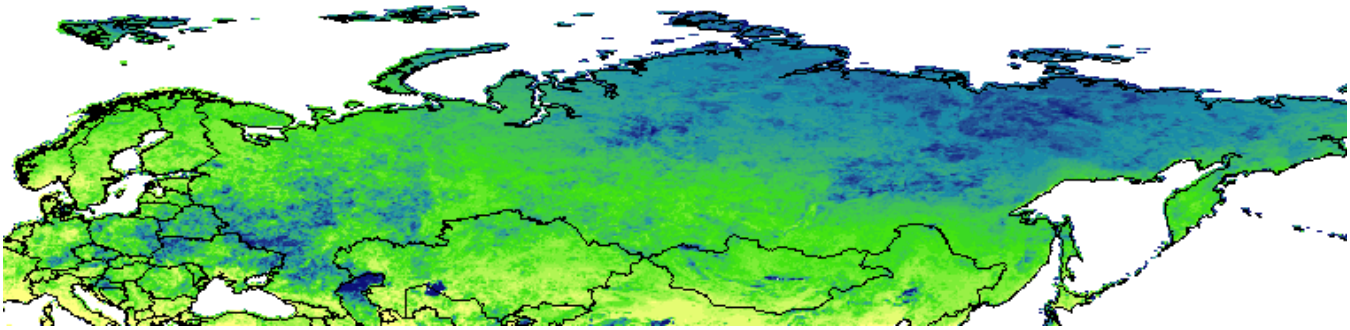


Fi 2003 – 2004



Fi 2004 – 2005



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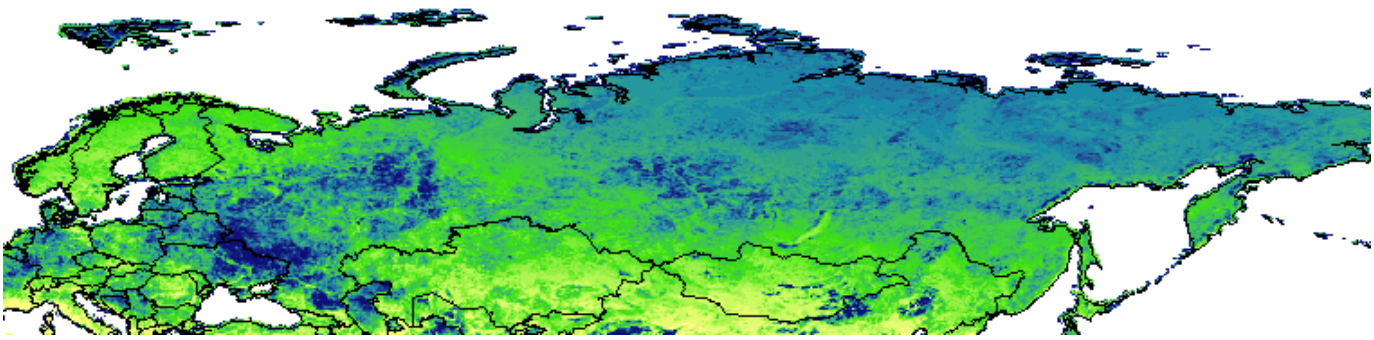

Fi 2006 – 2007

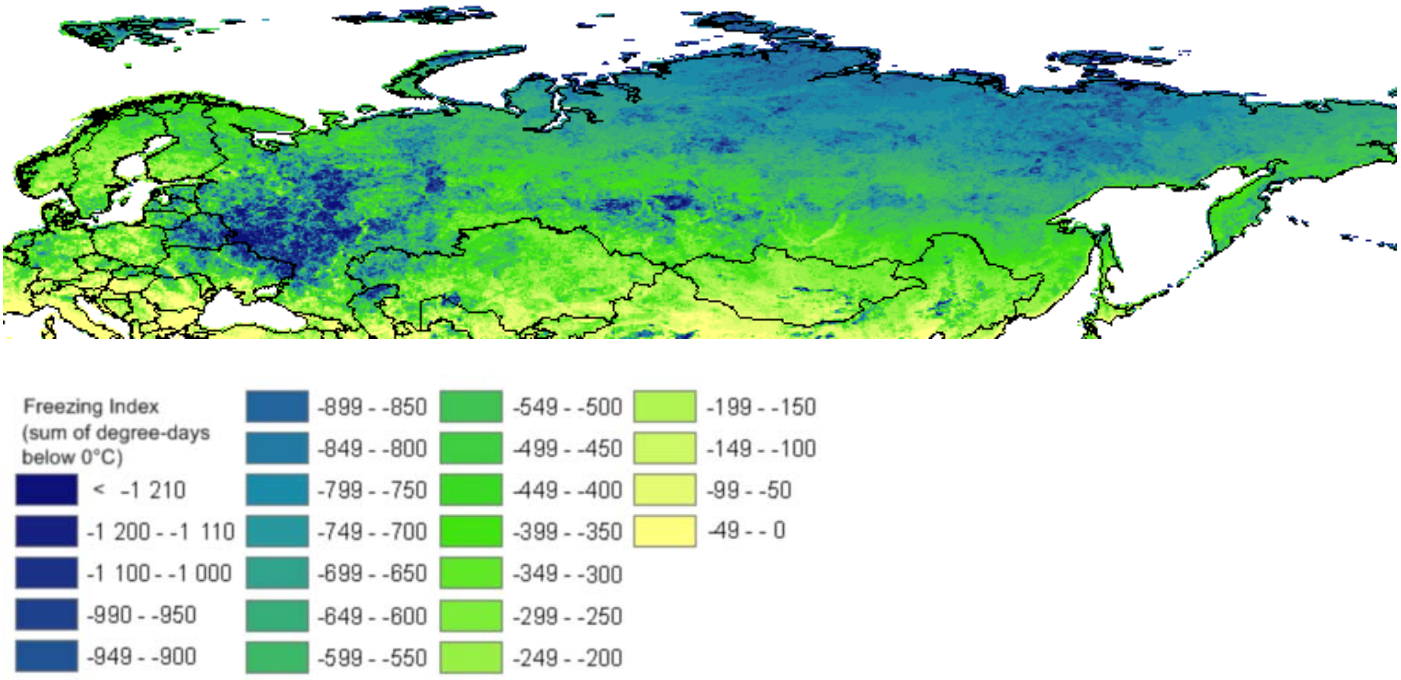

***Figure 6**. Freezing Index for winters 2000-2001 to 2006-2007.*

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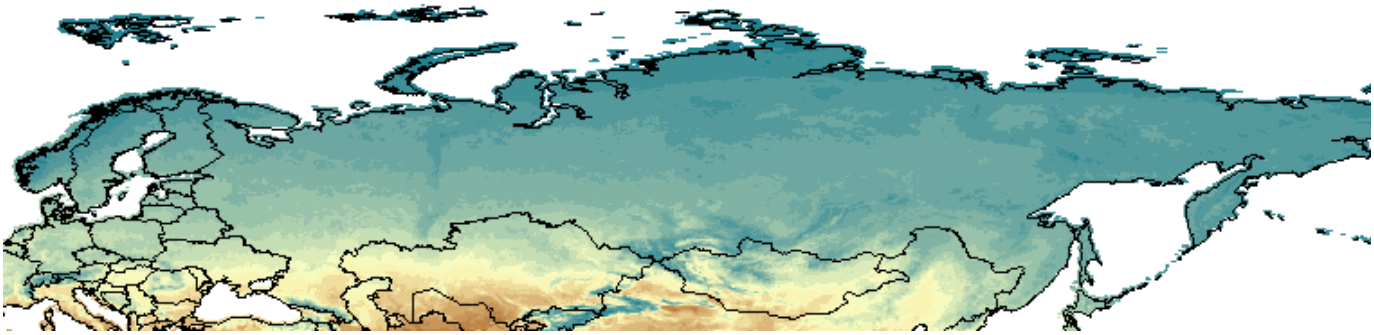

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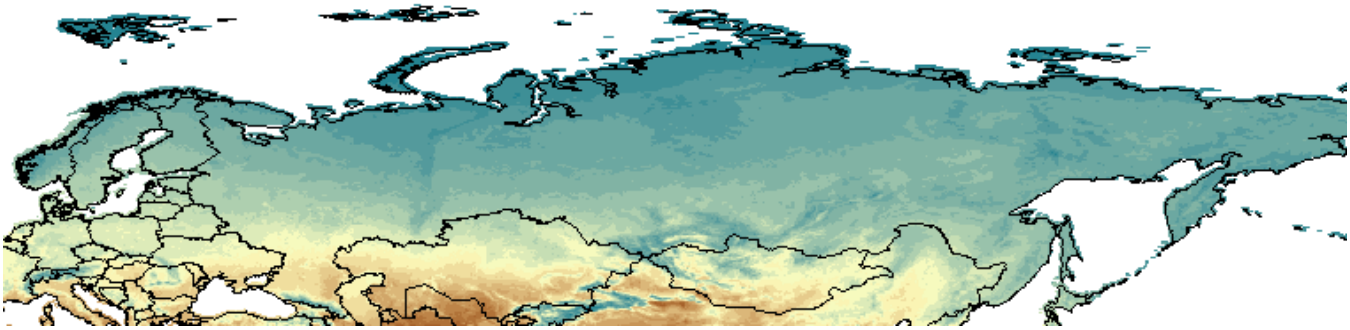

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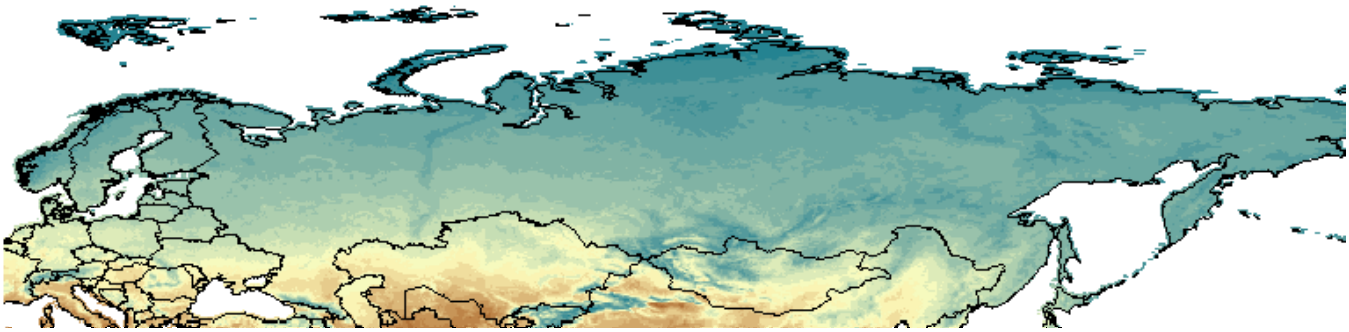

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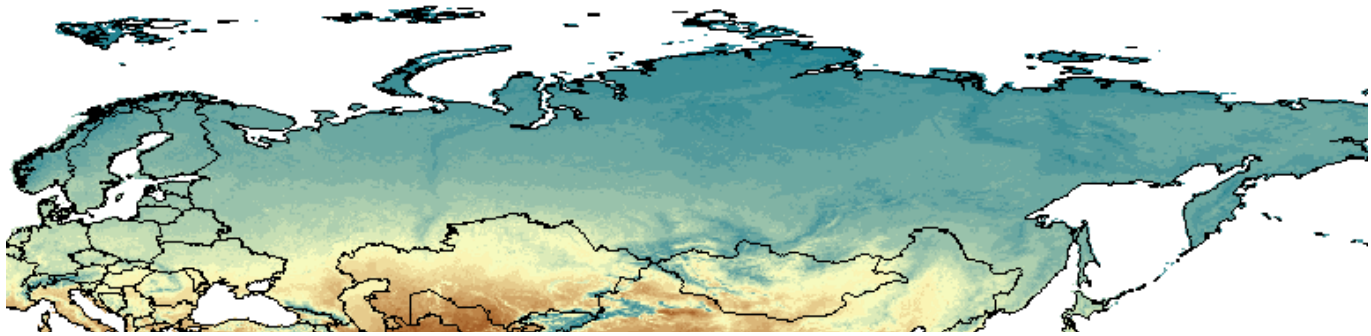

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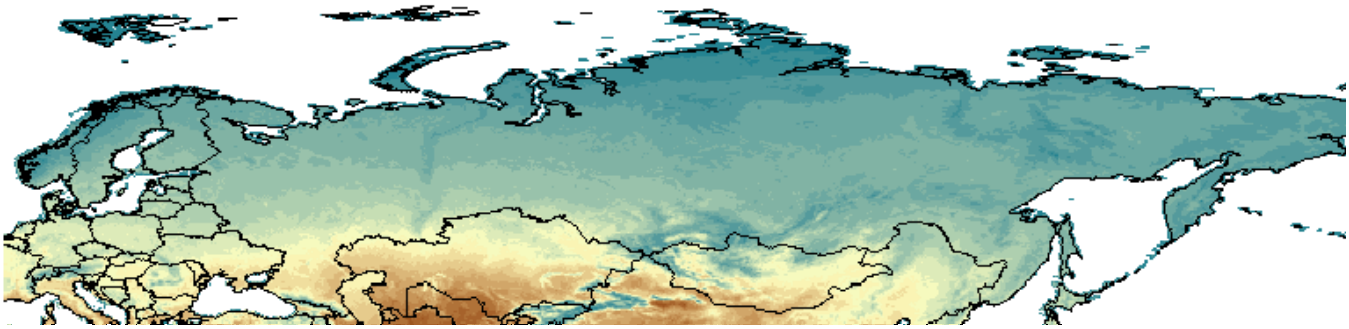

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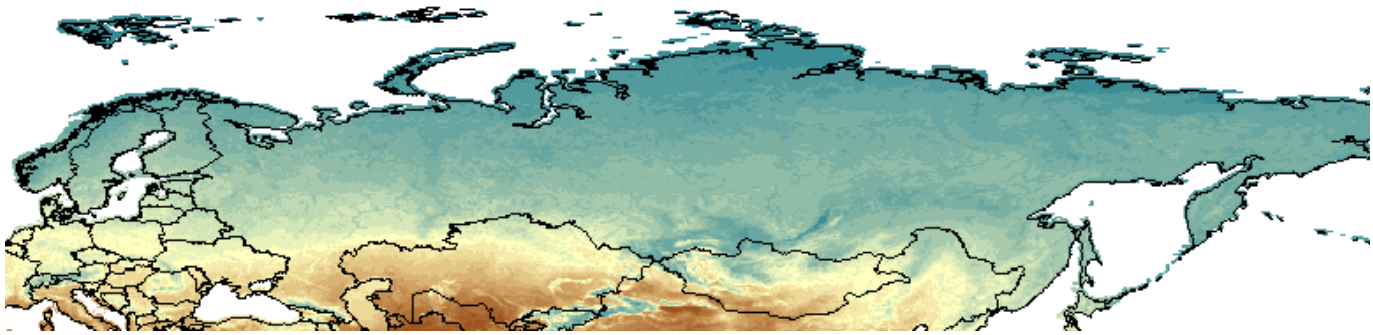

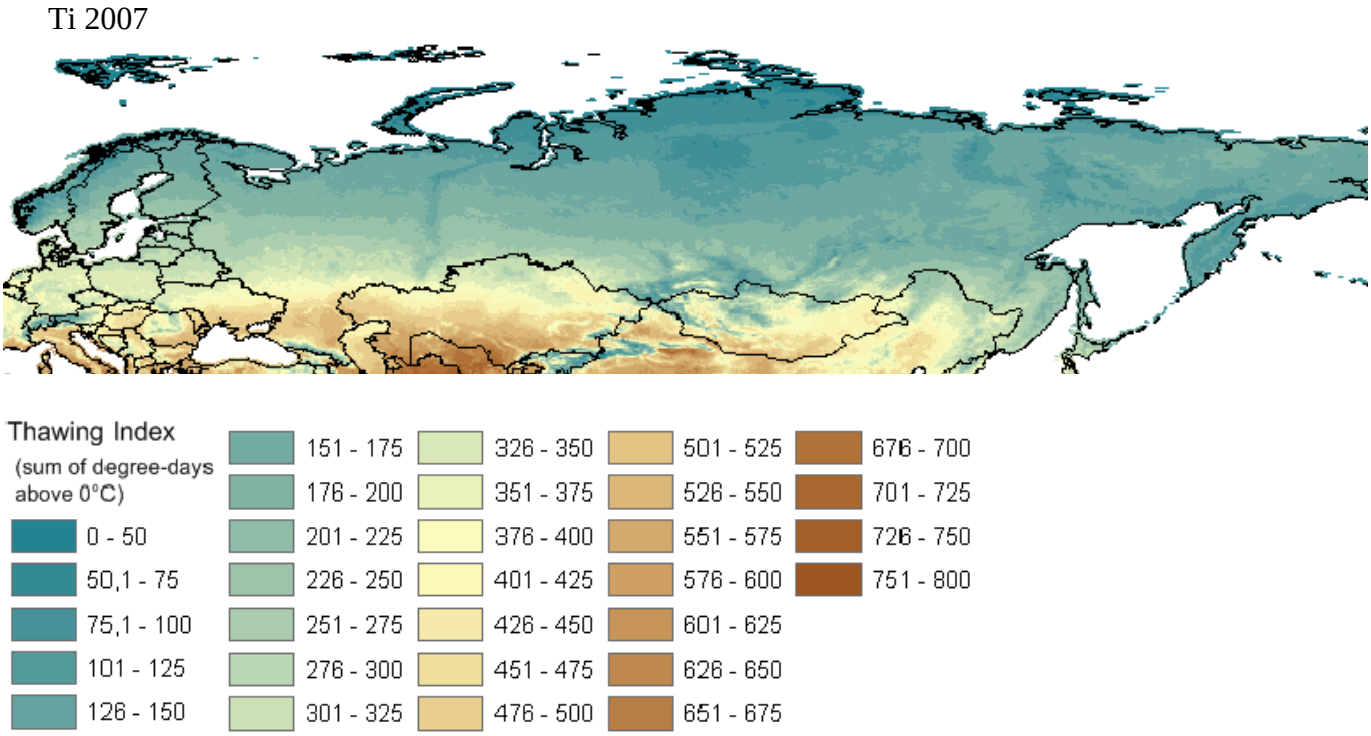

Figure 7*. Thawing index for summers 2001 to 2007.*

Snow water equivalent

Snow water equivalent or snow thickness and density are required to calculate permafrost temperature dynamics and active layer depth. During the second year of the project, we started our activities to derive these data from the available remote sensing products. Figure 8 illustrates a possibility to derive Snow Water Equivalent from the SMMR SMM/I SWE maps. Maps for November 1978 and for May 2007 are shown.

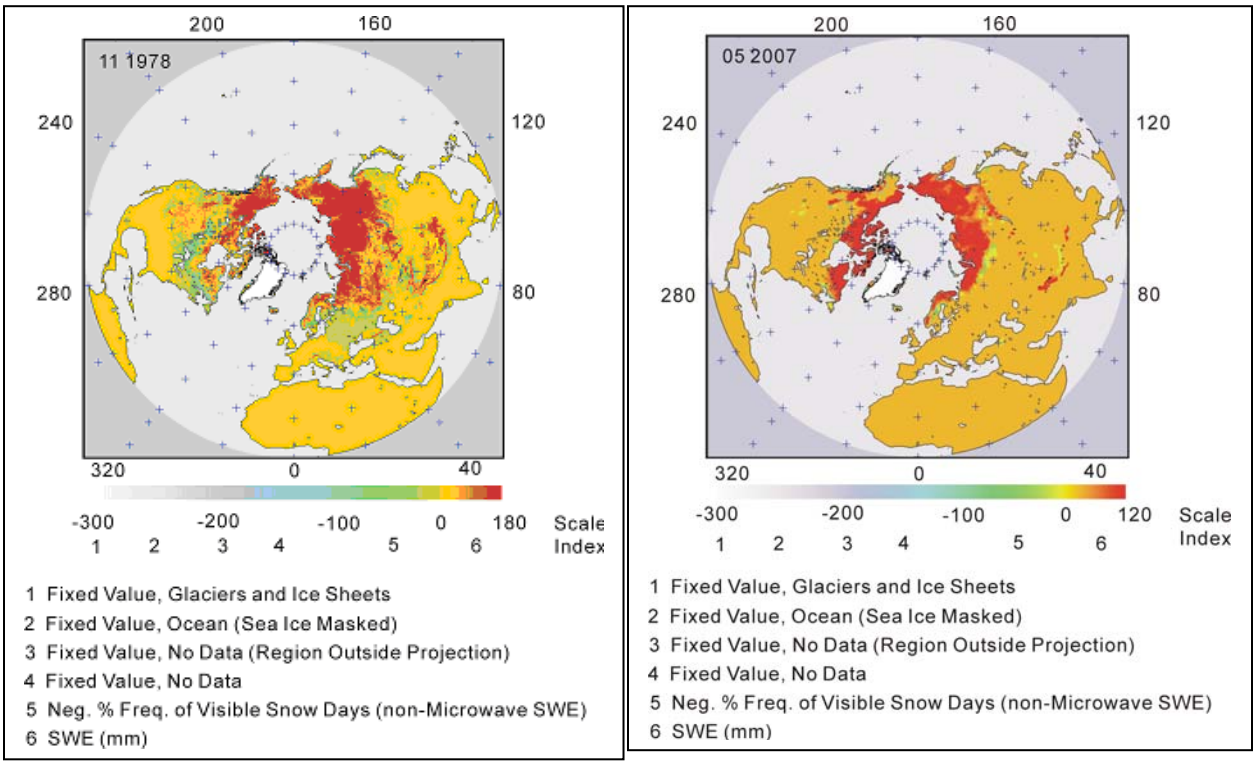

Figure 8*. Snow water equivalent products for November 1978 (left) and May 2007 (right).*

Here is a short report of our findings so far. Satellite-based Passive Microwave (PM)-derived estimates of Snow Water Equivalent (SWE), i.e. snow mass, rely on the absorption/emission and emissivity contrasts and polarization of snow and a substratum, converted to brightness temperatures per microwave channels (Armstrong and Brodzik, 2001; Koenig and Forster, 2004; Langlois and Barber, 2007). Contributors to error stem from:

1) Local-to-regional physical heterogeneity of snow (and substratum) structure and chemistry (metamorphism of snow during the snow season),
2) Influence of vegetation cover (type, density and their variability),
3) Convolution of radiances at the sensor from ground sources at scales smaller than the sensor instantaneous field of view (raw resolution),
4) Degradation of sensor in orbit during satellite life time,
5) Algorithm assumptions of constant snow density, grain size, wetness (dry), and atmosphere adjustment (radiances at sensor) (Turk et al., 1998; Armstrong and Brodzik, 2001; Pitter and Nolin, 2002; Koenig and Forster, 2004; Foster et al., 2005; Langlois and Barber, 2007; Armstrong et al., 2007; Savoie et al., 2007).

Errors show seasonally variability; underestimates in October and overestimates in May for Tundra and Taiga terrain for example (Foster et al., 2005). Four SWE algorithms were tested using in-situ measured SWE (end-of-winter, 1993 through 1996) distributed

in the Kuparuk River Watershed, North Slope of Alaska (Koenig and Forster, 2004). Regional average percent errors were variable for each algorithm in each comparison year, ranging from -50% (underestimate) to +64% (overestimate). Comparison of near-concurrent satellite PM-derived SWE with in-site measurements on a pixel to point-location basis showed errors from about 3% to 300% with mean error percentage from 44% to 193% depending on the algorithm.

GRACE Hydrologic Mass Balance Secular Trends and Variations of the Lena RiverBasin, Siberia, from March 2002 through December 2006

GRACE data analysis was not specifically proposed in our project. However, the potential of GRACE data to help in permafrost hydrology studies prompted us to start looking at the various GRACE products with intend to develop a reasonable hypothesis to explain GRACE spatial and temporary anomalies and to explore the possibility of using these data in our permafrost hydrology analysis.

Observations of the globally distributed hydrologic mass balance (water equivalent thickness change relative to the geoid) from the GRACE mission offer to provide a greater understanding of the processes controlling redistribution of water mass (groundwater storage, discharge, snow water equivalent and glacier mass balance) under ongoing effects of climate warming. The GRACE dual satellite configuration senses gravity field changes which can be processed as mass changes, relative to the geoid (the GRACE GG02S model, in the ITRF 2005) on a global basis, after removal of atmospheric mass change and effects from GIA. A preliminary study of the GRACE hydrologic mass balance on Arctic river systems and the Arctic Ocean (freshwater exchanges) has begun. For the Lena River basin of Eastern Siberia, the GRACE monthly secular trend shows an area-average water equivalent volume gain of 43.74 ± 9.49 km3/yr, from August 2002 through December 2006. Analysis of inter-basin secular trends shows spatial non-uniformity; overall higher positive trends in the southern parts relative to the northern parts (Figure 9). Near-annular periodic variability is stronger in the middle part of the Lena River basin than in either southern or northern parts. Overall, monthly variance increases over the basin from south-to-north. Likely, the trends and variations observed in the regional-average mass balance are due to spatial variations of multiple sources of mass changes. Continued investigations, by comparison to in-situ observations and spatially distributed assimilation model of other satellite-derived physical parameters are warranted.

GRACE by itself cannot resolve the source or sources of mass change, or the magnitude of any one particular mass component of the total mass change (Wahr et al., 2004). For this task, other spatially distributed observations (in-situ or assimilation model) of the changes in river discharge, groundwater storage, soil water, snowfield water equivalent (glacier mass balance where appropriate), and permafrost (including water content of the active layer) are needed to derive the mass change of each component and the total hydrologic mass change at the months during the ongoing GRACE mission. In this case, to resolve the changes in permafrost and the active layer, observations of the other contributing factors to the GRACE observations of the hydrologic mass balance will be needed, to reduce the GRACE signal. The residual, after reduction by the other possible

sources of hydrologic mass balance, will be an estimate of the spatially distributed permafrost (ice-rich) and active layer (water content) changes on the Lena River basin.

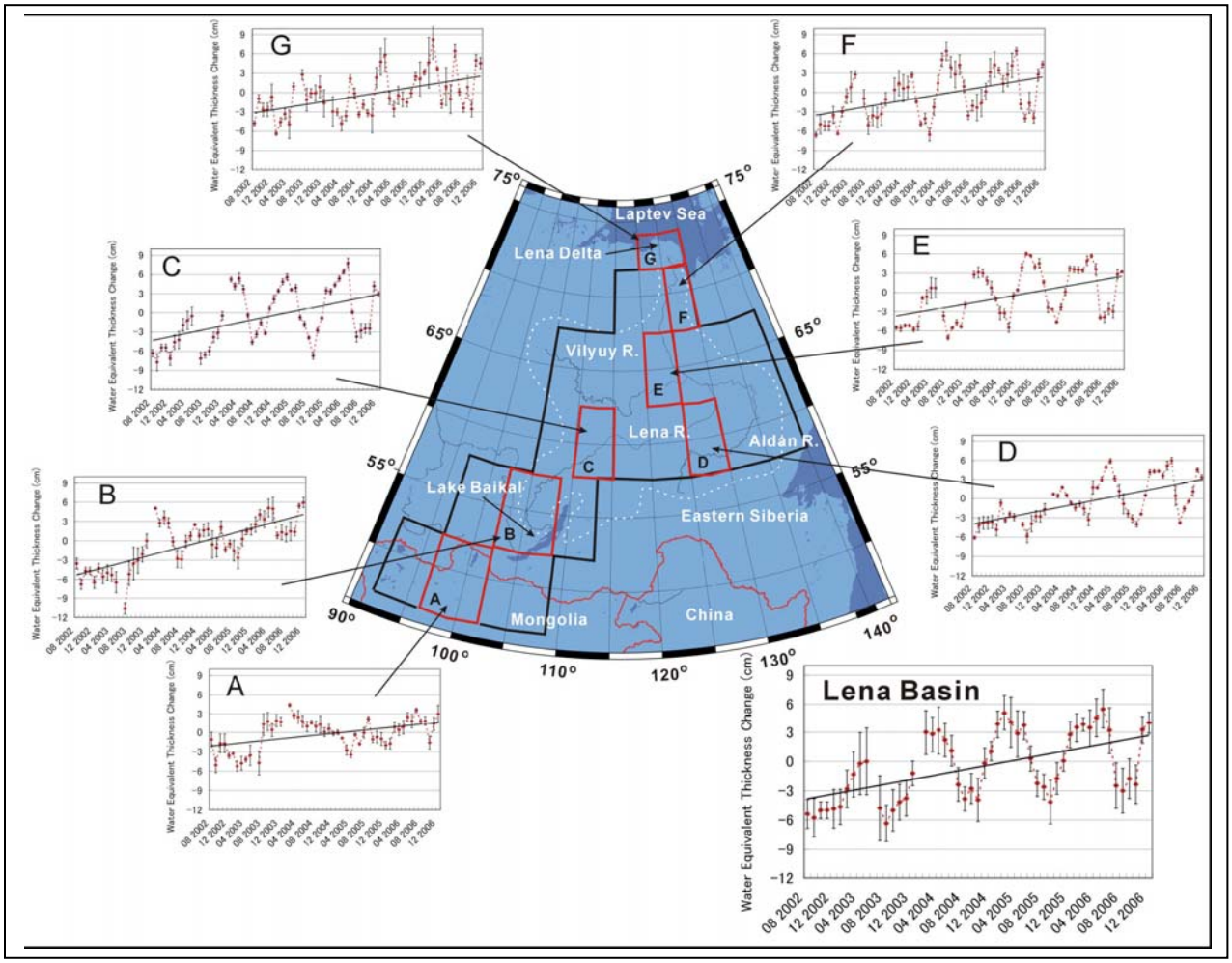

Figure 9. *Lena River Basin (dashed white line) and enclosing geographic region, Eastern Siberia. A total of 21 sub-regions (5-by-5 degrees in area) enclose the Lena basin. An additional four sub-regions on the southwest for testing GRACE observations of the hydrologic mass balance (monthly water equivalent thickness change) are shown. Select sub-region monthly mean time-series and least-squares regression secular trends are shown in the plots. The total Lena River basin monthly mean time-series and secular trend plot is also shown.*

Groups of investigators have been evaluating the usage of GRACE mass balance estimates for studies of Arctic river basin discharge (including the Lena), from March 2003 through November 2005, and Arctic snow water equivalent changes (including the Ob River basin, which is west of the Lena River basin), from April 2002 through May 2004 (Syed et al., 2007; Frappart et al., 2006). Other groups have investigations ongoing in their analysis of GRACE data (D. Chambers, pers. comm., 2008). Some discrepancies in the earlier published analyses have been noted and are largely due to corrections for processing errors in the earlier release datasets, in particular Release 1 and Release 2.

With the continued progress of the GRACE mission to a 10-year time span, there is anticipation that resolution of physical variations of the global hydrologic mass balance will become better understood.

3. *Modeling*

Two levels of permafrost modeling are implemented in our research, a "permafrost temperature reanalysis" and a spatially distributed physically based permafrost model. The first level of modeling is the "permafrost temperature reanalysis" approach (Romanovsky *et al.*, 2002). At this level, a sophisticated numerical model (Tipenko and Romanovsky, 2001; Sergueev *et al*., 2003), which takes into account the temperature-dependent latent heat effects, is used to reproduce active layer and permafrost temperature field dynamics at the chosen sites. The input data are prescribed specifically for each site and include detailed description of soil thermal properties and moisture for each distinct layer, surface vegetation, snow cover depth and density, and air temperature. In this modeling approach variations in air temperature and snow cover thickness and properties are the driving forces of permafrost temperature dynamics.

The second level of permafrost modeling involves the application of a spatially distributed physically based model that was recently developed in the University of Alaska Fairbanks (UAF) Geophysical Institute Permafrost Lab (GIPL; Sazonova and Romanovsky, 2003). The model was calibrated using available data for air temperature, snow depth and density, vegetation, soil properties, and soil temperatures obtained in this project (see section "Data Acquisition"). The retrospective run of the model provides information for better calibration of the model and will be used for a second level of quality control.

Calibration, Reconstruction of past temperature regimes, Improving the existing GIPL model

We continue to develop our spatially distributed permafrost models GIPL 1.1 and GIPL2.0. GIPL2.0 is a GIS-based permafrost and active layer dynamics model with very high vertical resolution and based on a sophisticated one-dimensional permafrost model that describes the active layer and permafrost thermal state and dynamics with very high accuracy. The model is driven by prescribed upper boundary conditions (air temperature, snow, vegetation, etc) derived from observations or from the decoupled runs of global or regional climate models. This stand-alone, spatially distributed, GIPL2.0 permafrost model satisfactory predicts permafrost temperature distribution in Siberia (Figures 10 and 11). The difference between calculated and measured permafrost temperatures, by UAF observation group, is typically less than 1-1.5 K (Figures 10 and 11). Data on soil temperature at the depth interval between 0.2 and 3.2 meters form 5 additional Siberian meteorological stations were used in this calibration. The previous version (GIPL1.1) of this model was applied to the entire Northern Eurasia permafrost domain (Figure 12A). Comparison between calculated distribution of permafrost temperatures using this model (Figure 12A) and the IPA permafrost map (Figure 12B) shows a very good agreement.

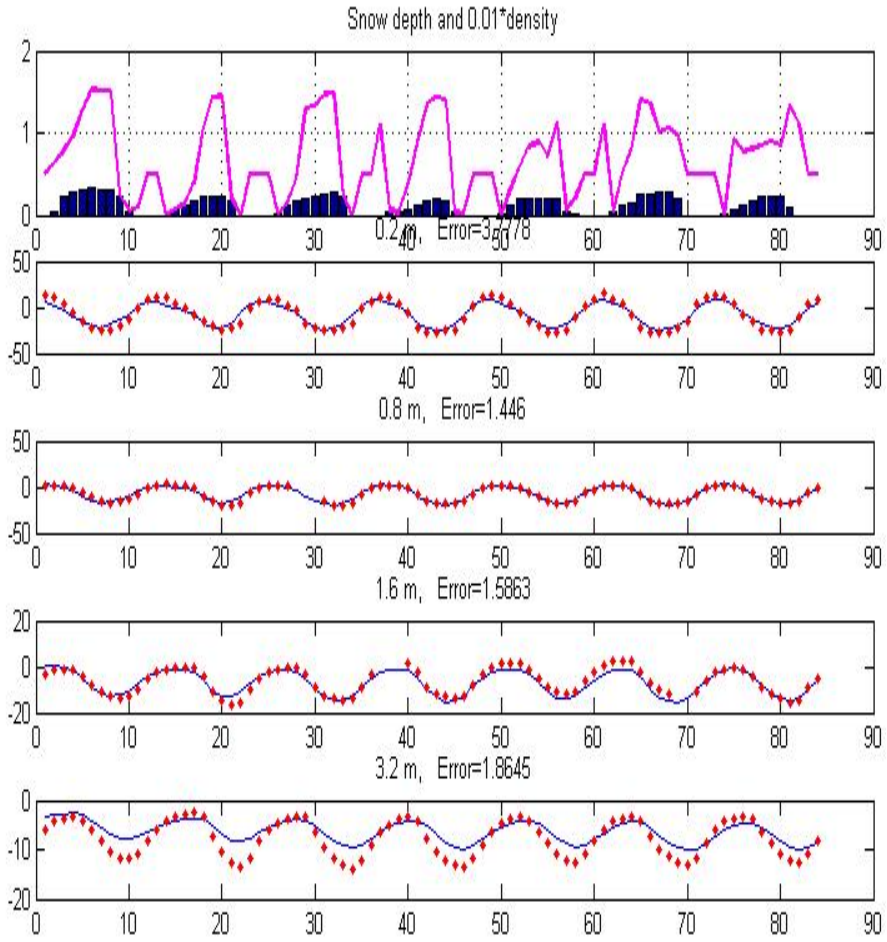

Figure 10 *. Comparison of soil temperatures at several depths simulated (blue) with GIPL2.0 model and measured (red) at the Verkhoyansk, Siberia station during the* 08.1977-08.1984 *time period.*

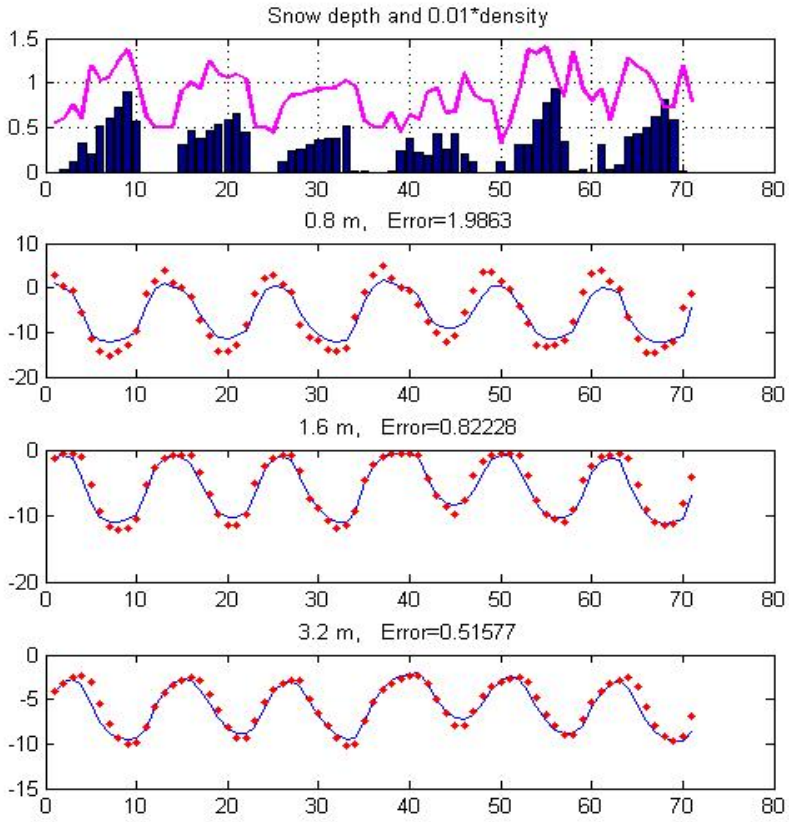

Figure 11. *Comparison of soil temperatures at several depths simulated (blue) with GIPL2.0 model and measured (red) at the Kyusyur, Siberia station during the* 08.1977-08.1983 *time period.*

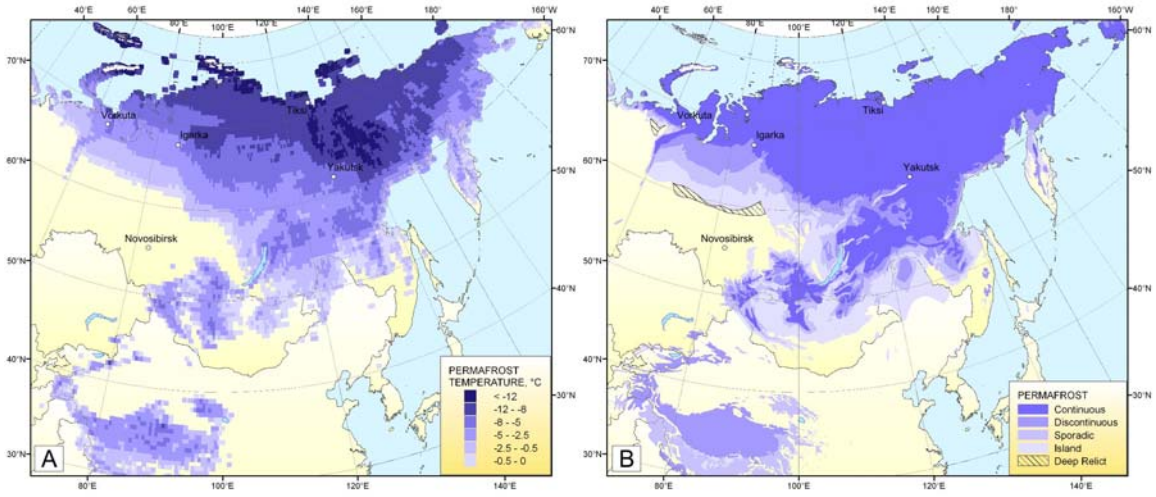

Figure 12. *Calculated using the GIPL1.1 mean annual permafrost temperature spatial distribution within the entire northern Eurasia permafrost domain (A) in comparison with the IPA permafrost map (Brown et al., 1997) (B).*

d. Future temperature regime forecast

We developed a new version (GIPL1.1) of the spatially distributed permafrost model and implemented it for the entire Northern Eurasia permafrost domain for the 1900-2100 time interval (Figure 13). Parameterization and input climatic data for this model were developed in close cooperation with other modeling groups in UAF and NCAR. At the moment, the same groups are working together to establish input data for the GIPL2.0 for the entire circumpolar domain.

Figure 13 shows a projection in permafrost temperatures for the Eurasian permafrost domain. In this example we used the GIPL1.1 permafrost model. Two time intervals were considered; the first represents the present-day conditions (Figure 13 A), and the second reflects changes in permafrost that may occur by the end of the 21st century (Figure 13 B). For the present-day climatic conditions the CRU2 data set with 0.5° x 0.5° latitude/longitude resolution (New et al., 2002) was used. The future climate scenario was derived from the MIT 2D climate model output for the 21st century (Sokolov and Stone, 1998).

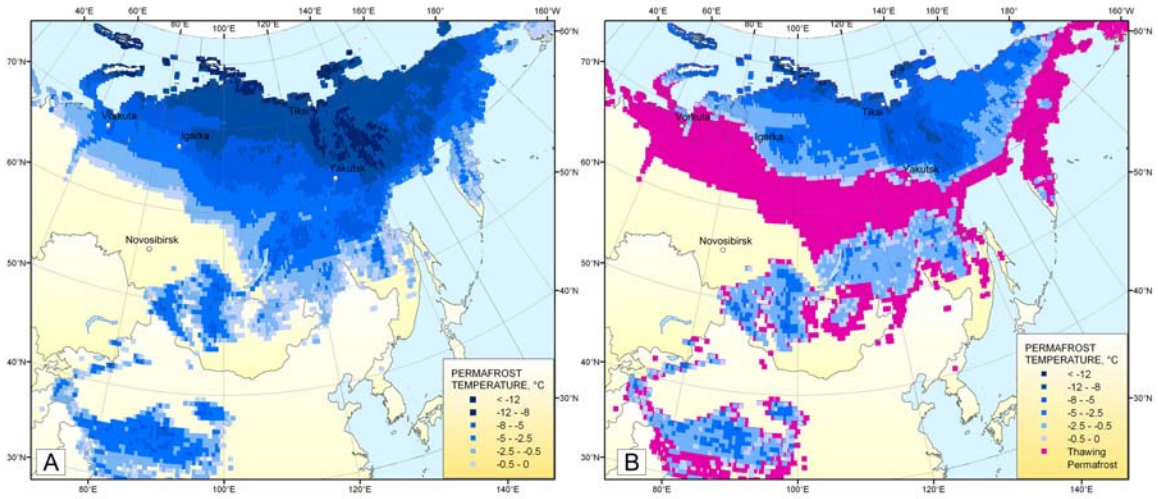

Figure 13. *Modeled north Eurasian permafrost temperatures (mean annual temperature at the permafrost surface) averaged over 1980-2000 (A) and 2080-2100 (B) time interval.*

e. Using remote sensing products in permafrost modeling

The monthly satellite-derived land surface temperature (LST) and snow water equivalent (SWE) climatologies from 1978 through 2005 (see **Section 2**) also were used to perform permafrost temperature and active layer thickness simulations (Figure 14). Global SWE data are gridded to the Northern and Southern 25 km Equal-Area Scalable Earth Grids (EASE-Grids). Global snow water equivalent is derived from Scanning Multichannel Microwave Radiometer (SMMR) and selected Special Sensor Microwave/Imagers (SSM/I) (Armstrong & Brodzik, 2001). Using these boundary conditions the distribution

and temperatures of permafrost (Figure 15A) and active layer thickness (Figure 15B) for the entire Northern Eurasia permafrost domain were simulated.

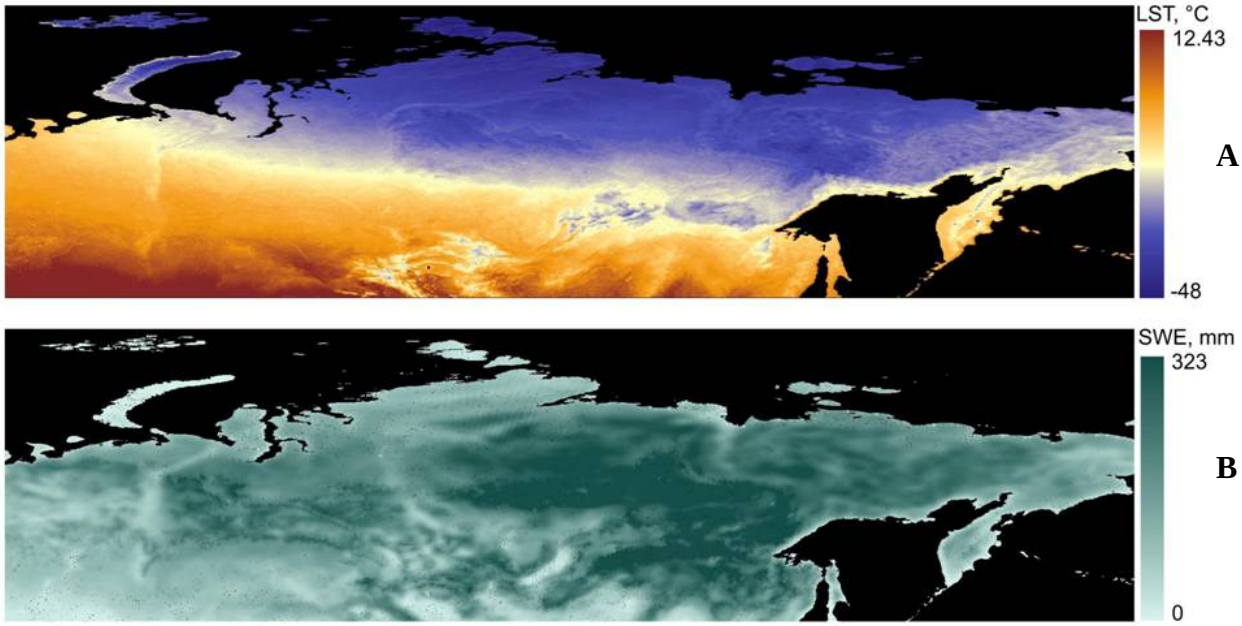

***Figure 14**. Five by five kilometers spatial resolution of MODIS Land Surface Temperature (A) and SSM/I snow water equivalent (B) averaged for 2001-2007.*

The results of permafrost modeling using as a forcing for GIPL-1.2 model MODIS LST and SSM/I SWE show a satisfactory result and agreement between calculated distribution of permafrost temperatures and the distribution of permafrost derived from the International Permafrost Association (IPA) permafrost map. One paper was presented at the EGU 2009 General Assembly as a result of this work (Marchenko et al., 2009).

f. Using Regional Climate Models (RCM) outputs in permafrost modeling

Another important element of this project was our collaborative work on CARBO-North project that aims at quantifying the carbon budget in Northern Russia across temporal and spatial scales. Activities address rates of ecosystem change, effects on the carbon budget (radiative forcing), and global climate and policy implications (Kyoto). Department of Physical Geography and Quaternary Geology, Stockholm University invited Co-PI Sergei Marchenko to visit Stockholm University for tree weeks to initiate join research on spatial and temporal permafrost dynamics modeling under the different climate scenarios. With collaborators P. Kuhry (Stockholm University), J. Christensen and M. Stendel (Danish Meteorological Institute), and A. Rinke (Alfred Wegener Institute, Germany) we conducted analysis of climate variability in Northeast European Russia and initiated permafrost modeling efforts using HIRHAM5 high-resolution outputs as a climate forcing.

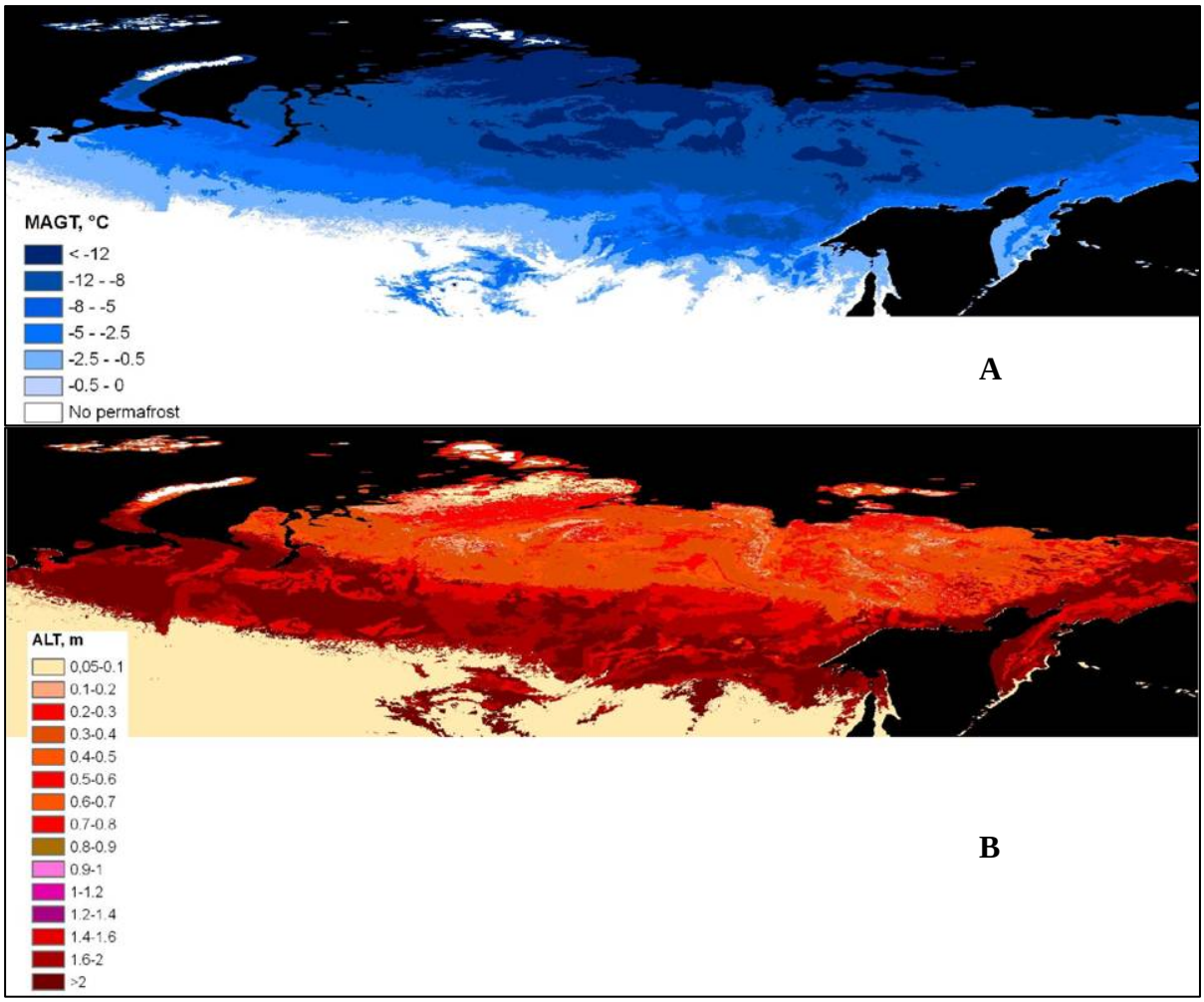

***Figure 15**. The GIPL-1.2 modeled permafrost distribution, mean annual ground temperature at the permafrost table (A), and active layer thickness (B) using as a forcing MODIS LST and SSM/I SWE*

During the past 128 years (since 1881), the annual surface air temperature in Northern Eurasia has increased by 1.5°C and in the winter season by 3°C. Nearby to the north in the Arctic Ocean, the late summer sea ice extent decreased by 40% exposing a source of water vapor for the dry arctic atmosphere in early cold season months. As a result of these processes in the cold season maximum snow depth and snow water equivalent (SWE) have increased over most of Russia (Bulygina et al., 2009).

Recent observations indicate a warming of permafrost in many northern regions with a resulting degradation of ice-rich and carbon-rich permafrost (Romanovsky et al., 2010). Permafrost temperature has increased by 1 to 2°C in northern Eurasia during the last 30 years. Warming in permafrost temperatures observed in the Russian North, west and east Siberia has resulted in the thawing of permafrost in natural, undisturbed conditions in areas close to the southern boundary of the permafrost zone.

Major climate changes in Polar Regions and a substantial reduction of the area of the Northern Hemisphere underlain by permafrost can be expected according to simulations

with global circulation models (GCMs). However, thawing of permafrost, in particular if it is ice-rich is subject to a time lag due to the large latent heat of fusion. State-of-the-art GCMs are unable to adequately model these processes because (a) even the most advanced subsurface schemes rarely treat depths below 5 m explicitly, (b) soil thawing and freezing processes cannot be dealt with directly due to the coarse resolution of present GCMs, and (c) due to the underestimation of orographic variance, simulated GCM precipitation is often underestimated and the proportion of rain and snow is incorrect.

One possibility to overcome resolution-related problems is to use regional climate models (RCMs). Such an RCM, HIRHAM, has until now been the only one used for the entire circumpolar domain, and its most recent version, HIRHAM5, has also been used in the high resolution study described here. Instead of the traditional degree-day frost index approach, we make use the regional model itself to create boundary conditions for our advanced permafrost model. This implies that the permafrost model can be run on the RCM grid, i.e. in a considerably higher resolution than in previous approaches.

Model hierarchy and downscaling

The driving GCM is ECHAM5/MPI-OM1 at T63 resolution (~1.8° by 1.8°). The RCM is HIRHAM5 with the physical parameterization of ECHAM5, so that HIRHAM5 can be thought of as a high resolution limited area version of ECHAM5. The boundary forcing from the global model is updated every six hours in a region 10 grid points wide with a relaxation of all prognostic variables.

Varying concentrations of well-mixed greenhouse gases, ozone and sulphate aerosol have been prescribed from observations prior to 2000 and following the SRES A1B scenario thereafter. In this scenario, the CO2 concentration in 2100 is near 700 ppm, and the globally averaged warming with respect to present-day climate is 3.5°C.

As the final step for regional permafrost modeling we have used the GIPL2 model, which is a spatially distributed, physically based numerical model for the calculation of active layer thickness ALT and soil temperature at of the entire soil column (500 m in depth) with daily resolution.

We present here the first results from new time-slice integrations for the 20th and 21st centuries with an unprecedented horizontal resolution of only 4 km, covering part of northeast European Russia (Figure 16). According to this specific climate scenario, projections of future changes in permafrost suggest that by the end of the 21st century, permafrost in the Russian North may be actively thawing at many locations of the Pechora River watershed. The detailed data on soil properties (mineral and organic, peat layers), ice content and initial temperature profiles for different ecosystems and soil types were available from the Seyda site, Pechora River watershed. The level 1 of the GIPL-2 transient permafrost model (see the beginning of **Section 3**) has been implemented to predict the rate of permafrost thawing using HIRHAM climate forcing. The modeling results show how different types of ecosystems affect the stability and thermal state of permafrost (Figure 17).

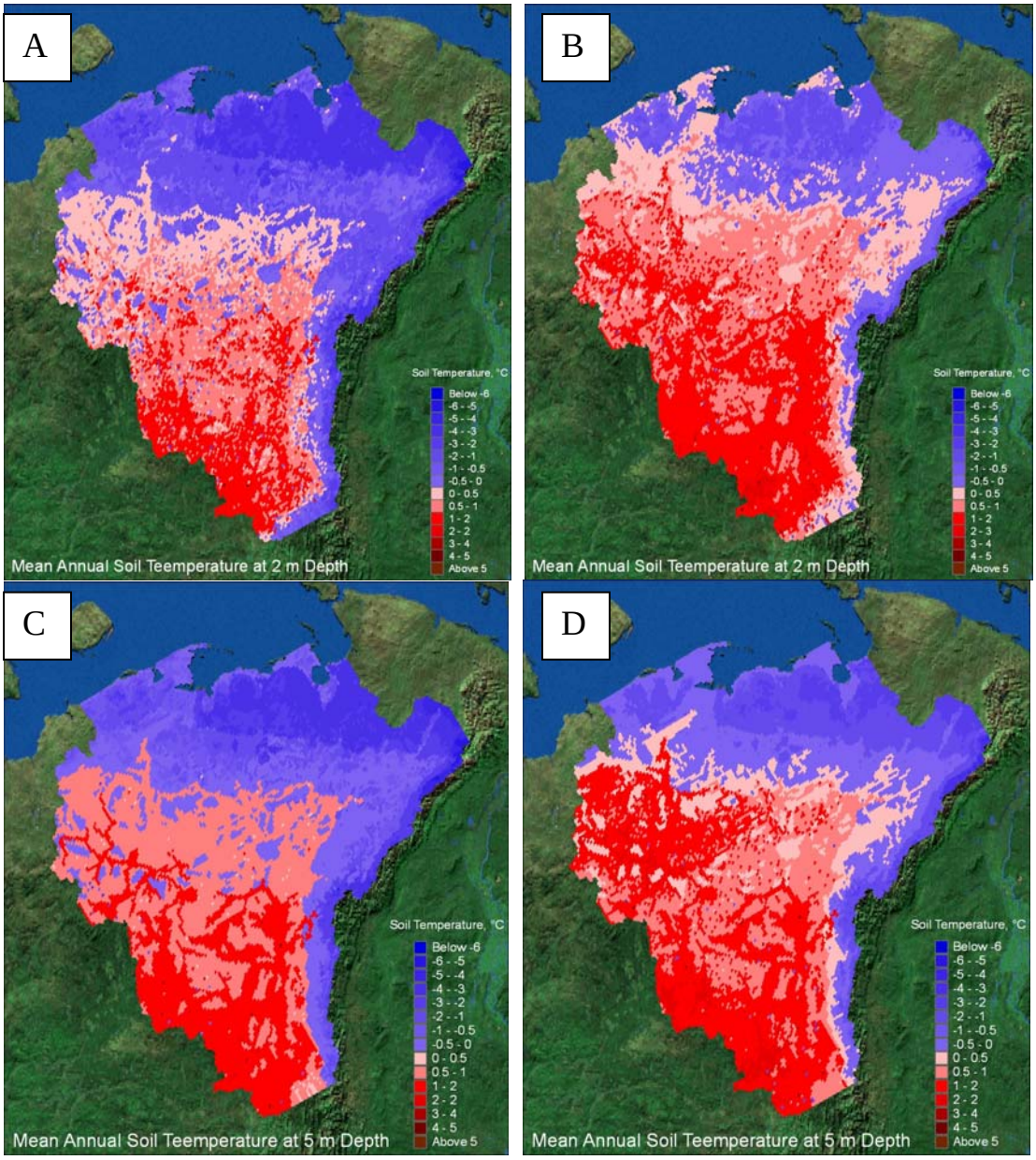

***Figure 16**. Modeled MAGT at 2 m and 5 m depth for 1980-99 (A, C) and for 2046-65 (B, D) derived from the GIPL-2 transient permafrost model run using the 4x4 km HIRHAM climate forcing.*

The resilience and vulnerability of permafrost to climate change depends on complex interactions among topography, water, soil, vegetation, and snow, which allow permafrost to persist at mean annual air temperatures (MAATs) as high as +2 °C and degrade at MAATs as low as –10 °C. To assess these interactions, we compiled existing data and tested effects of varying conditions on mean annual surface temperatures (MASTs) and 2 m deep temperatures (MADTs) through modeling. Organic layer and ice had the largest effect, with surface vegetation as moss. A 50% reduction in snow depth reduces MADT by 2 °C. Covarying vegetation structure, organic matter thickness, soil

moisture, and snow depth of terrestrial ecosystems, ranging from barren silt to white spruce forest to tussock shrub, affect MASTs by ~6 °C and MADTs by ~7 °C (Jorgenson et al., 2010).

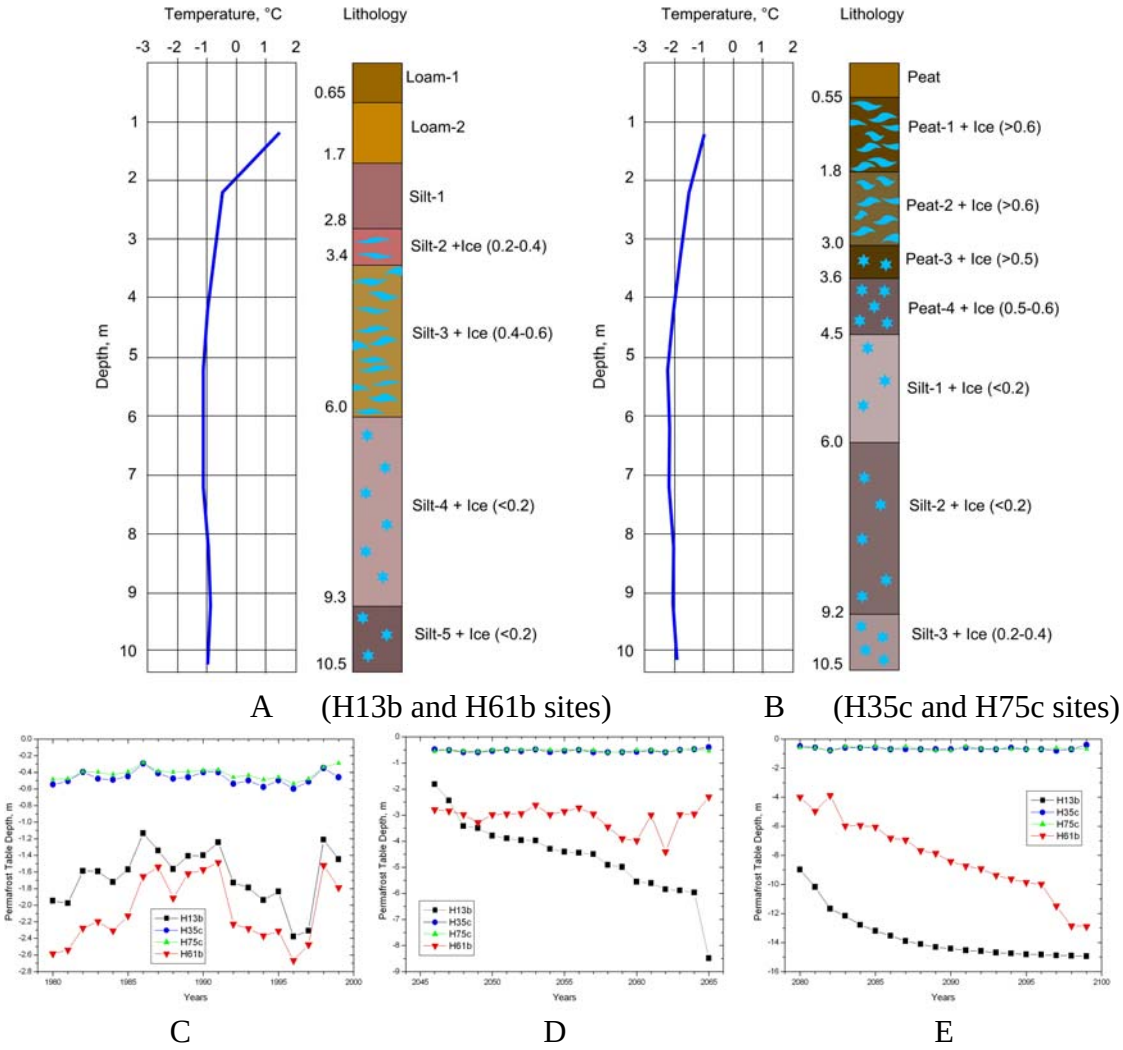

Figure 17*. Two different ecosystem and soil types (mineral and organic soil) and initial ground temperature distribution with depth (A, B) and simulated permafrost table depth dynamics (C, D, E) for 1980-99, 2046-65, and 208-99 time intervals derived from the GIPL-2 transient permafrost model run using the HIRHAM output for Seyda site. A – H13b and H61b boreholes. B – H35c and H75c boreholes.*

g. Special hydrogeological and permafrost research

As a result of this project we coupled the Permafrost Model (GIPL) and the pan-Arctic Water Balance Model (PWBM), developed at the University of Alaska Fairbanks and the University of New Hampshire, respectively. The coupled model simulates temperature dynamics, snow water equivalent, and soil ice/water stores, along with fluxes such as evaporation, evapotranspiration, and runoff at daily time steps on 25 km resolution EASY

grid (NSIDC, 1995). We also improved parameterization of the organic layer in order to include in the model the so-called thermal offset effect that plays an important role in proper modeling of permafrost dynamics (Figure 18).

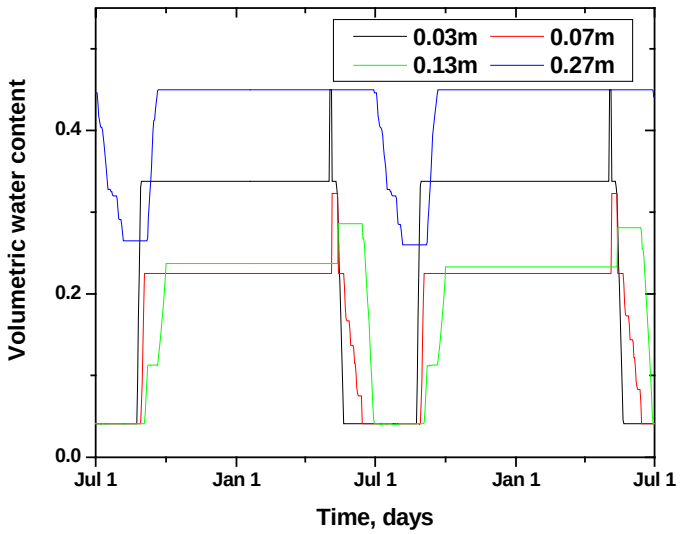

Figure 18. *Simulated water content dynamics for several soil layers at a certain grid point. Water content in the upper layers (moss/peat) decreases during summer due to evapotranspiration, and then increases due to a decrease in the evapotranspiration in the fall. Higher water content in the organic layer during fall and winter results in a larger thermal offset effect, and hence improves simulation of the permafrost dynamics under certain climate conditions.*

We analyzed sensitivity of the coupled model to changes in the soil properties, parameterization of the snow cover, and other parameters. Additionally, we investigated sensitivity of the model with respect to changes in the climate forcing. During the visit of Dr. Rawlins to the University of Alaska Fairbanks, we assembled 4 widely used climate drivers such as ERA40, NCEP-NCAR, CRU, and Willmott-Masuura. An examination of simulation results using 4 different climate inputs provides insights into our ability to model active layer dynamics at large scales and the challenges which must be overcome given limitations in model parameterizations and available climate forcing data (Figure 19). At a present stage of development, the simulated characteristics of climate are being compared to observed data to reveal biases in parameterization of hydraulic and thermal properties of ground material.

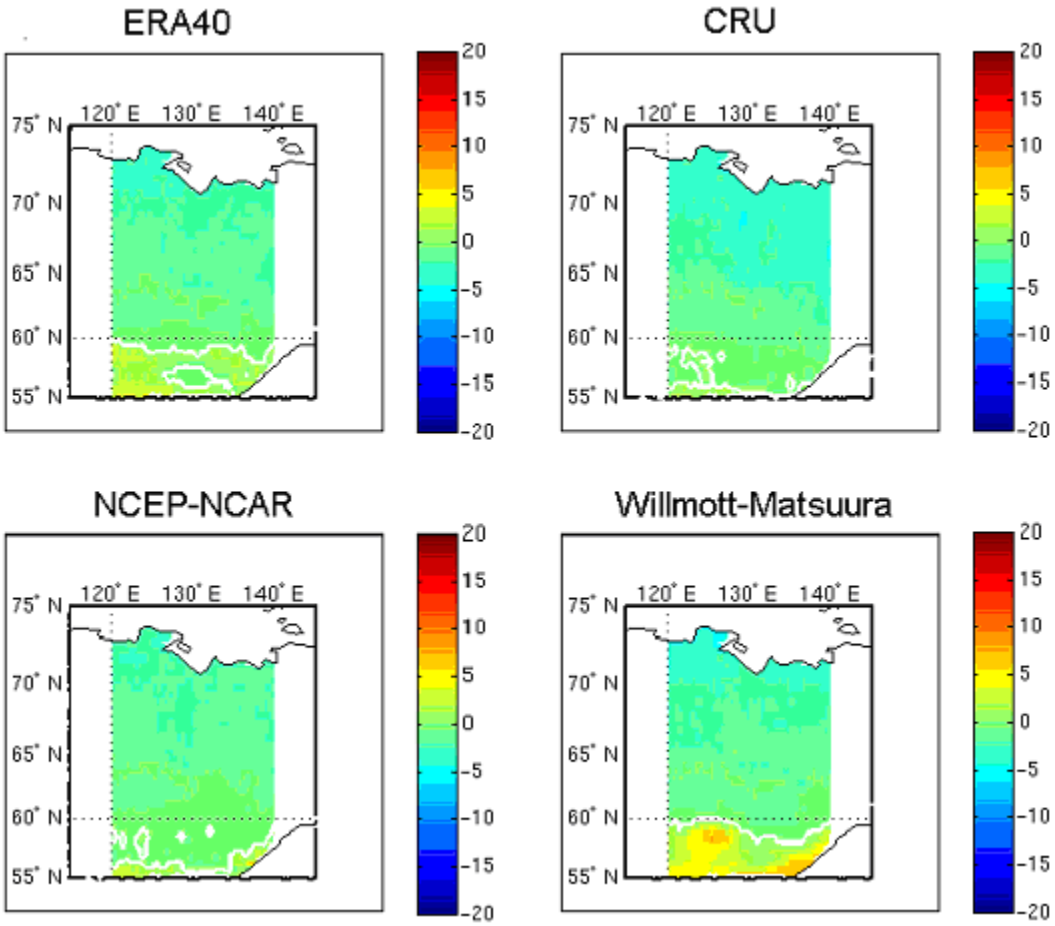

Figure 19. *Mean annual ground temperature at 1m depth in the Northern Eurasia Region computed using different climate forcings: ERA40, CRU, NCEP-NCAR, Willmott-Matsuura. The temperature is calculated for the climate conditions of 1980-1990 years. The thick white line is a 0 ^{o}C isotherm.*

Hydro-Thermo Dynamic Model (HTDM-1.0)

As a further development of the coupled hydrology and thermal model, our modeling group (Romanovsky & Marchenko) in collaboration with Drs. D. Wisser and S. Frolking (Water Systems Analysis Group of Institute for the Study of Earth, Oceans and Space, University of New Hampshire) developed a Hydro-Thermo Dynamic Model (HTDM-1.0). An initial stage of coupling the models took place during a two-week visit by Dr. S. Marchenko to Water Systems Analysis Group located at the University of New Hampshire at Durham, and Aug 6 - 22, 2009, Dr. D. Wisser return visit to the University of Alaska Fairbanks. During these visits, the first version of a coupled model was developed.

We assess the large-scale changes in permafrost formation in Northern regions using a coupled hydrological and thermodynamic model that simulates hydrological budgets as well as soil temperatures for the entire soil column taking into account hydraulic and thermal properties of different soil types and using global climate drivers. Predicted soil temperatures and soil moisture dynamics are validated against a large set of observations in Alaska and Northern Eurasia as well as active layer measurements from the Circumpolar Active Layer Monitoring (CALM) program representing a wide range of climate conditions, soil properties and landscape characteristics. We test the sensitivity of the model to parameters and input data, present maps of the future geography of peatlands and permafrost regions, and report results of simulations for a number of different climate drivers derived from climate model outputs for a set of IPCC scenarios.

We couple a macroscale hydrologic model WBMplus (Wisser et al., 2009) and one of the versions of the GIPL thermo dynamic (permafrost) model. The HTDM is a fully coupled soil water balance and heat transfer model that simulates the vertical water exchange between the land surface and the atmosphere, horizontal water transport along a prescribed river network, and soil temperature dynamics and the depth of seasonal freezing and thawing by solving 1D non-linear heat equation with phase change numerically. It is a physically-based spatially distributed transient model. Soil moisture predictions depend on soil hydraulic properties, climate drivers, and soil temperature.

In the soil model, the soil layers thicken with depth and span 100-meter thick soil column. Soil layers containing roots are associated with a root zone, whereas all other soil layers are attributed to the deep zone. The root zone gains water from infiltration and looses water via evapotranspiration and horizontal and vertical drainage, and a deep zone that gains water via root zone vertical drainage and loses water via a horizontal drainage. Seasonal changes and in soil water/ice content is computed explicitly by the GIPL model, which now incorporates soil moisture dynamics and hence temporal changes in thermal properties depending on volumetric water content. Using climate forcing from ECHAM5 for the 21st century we implemented HTDM to assess future dynamics of permafrost over the entire Northern Hemisphere permafrost domain (Figure 20).

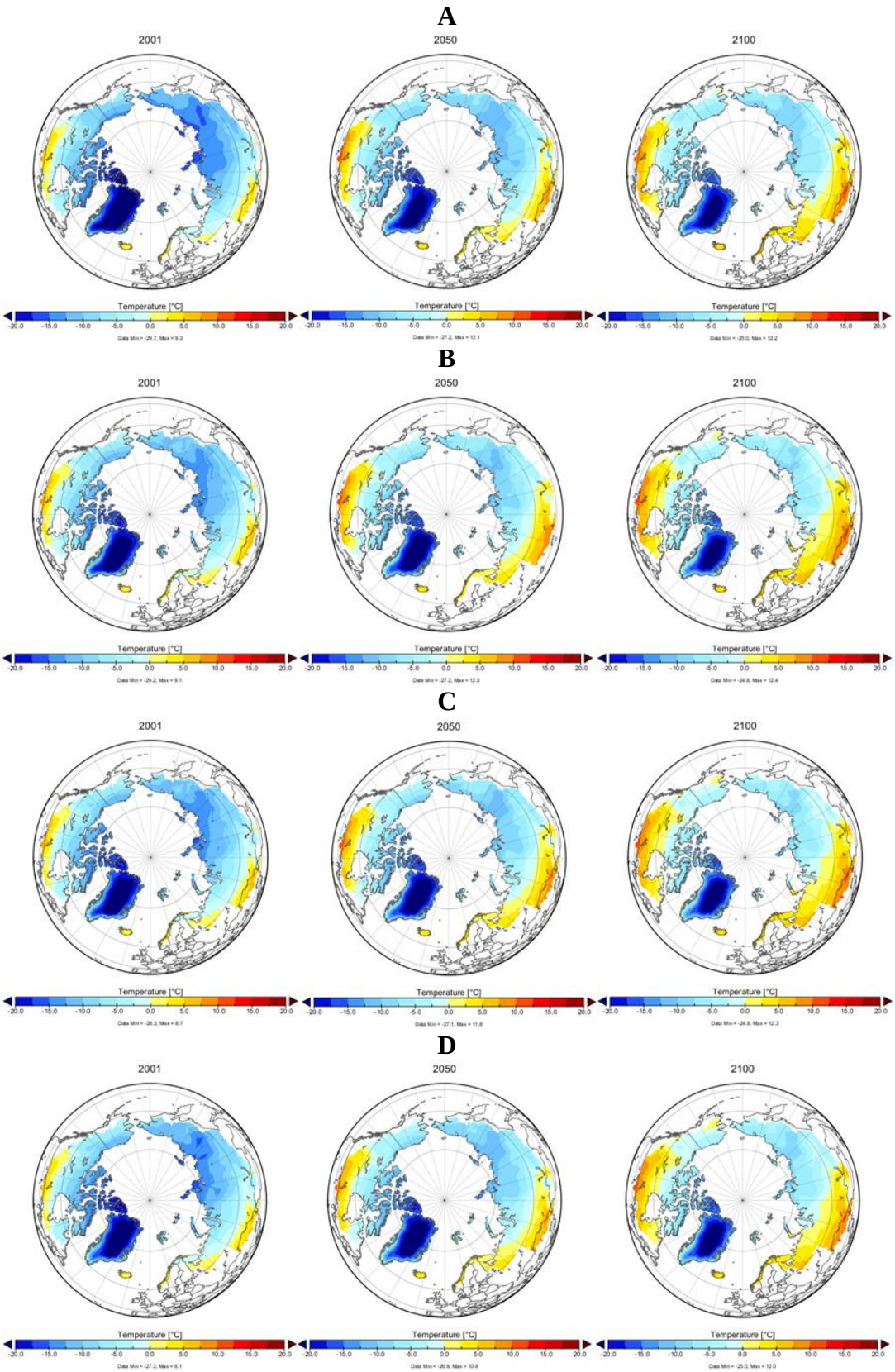
A
2001
2050
2100
Temperature [°C]
-20.0 -15.0 -10.0 -5.0 0.0 5.0 10.0 15.0 20.0
B
2001
2050
2100
Temperature [°C]
-20.0 -15.0 -10.0 -5.0 0.0 5.0 10.0 15.0 20.0
C
2001
2050
2100
Temperature [°C]
-20.0 -15.0 -10.0 -5.0 0.0 5.0 10.0 15.0 20.0
D
2001
2050
2100
Temperature [°C]
-20.0 -15.0 -10.0 -5.0 0.0 5.0 10.0 15.0 20.0

Figure 20*. Reconstructed for 2001 and projected mean annual soil temperatures at 0.5 m (B), 2 m (C), and 5 m (D) depths on, 2050 and 2100 according to spatially distributed permafrost model HTDM-1.0 using climate forcing from ECHAM5 (A) output for the 21st century*

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