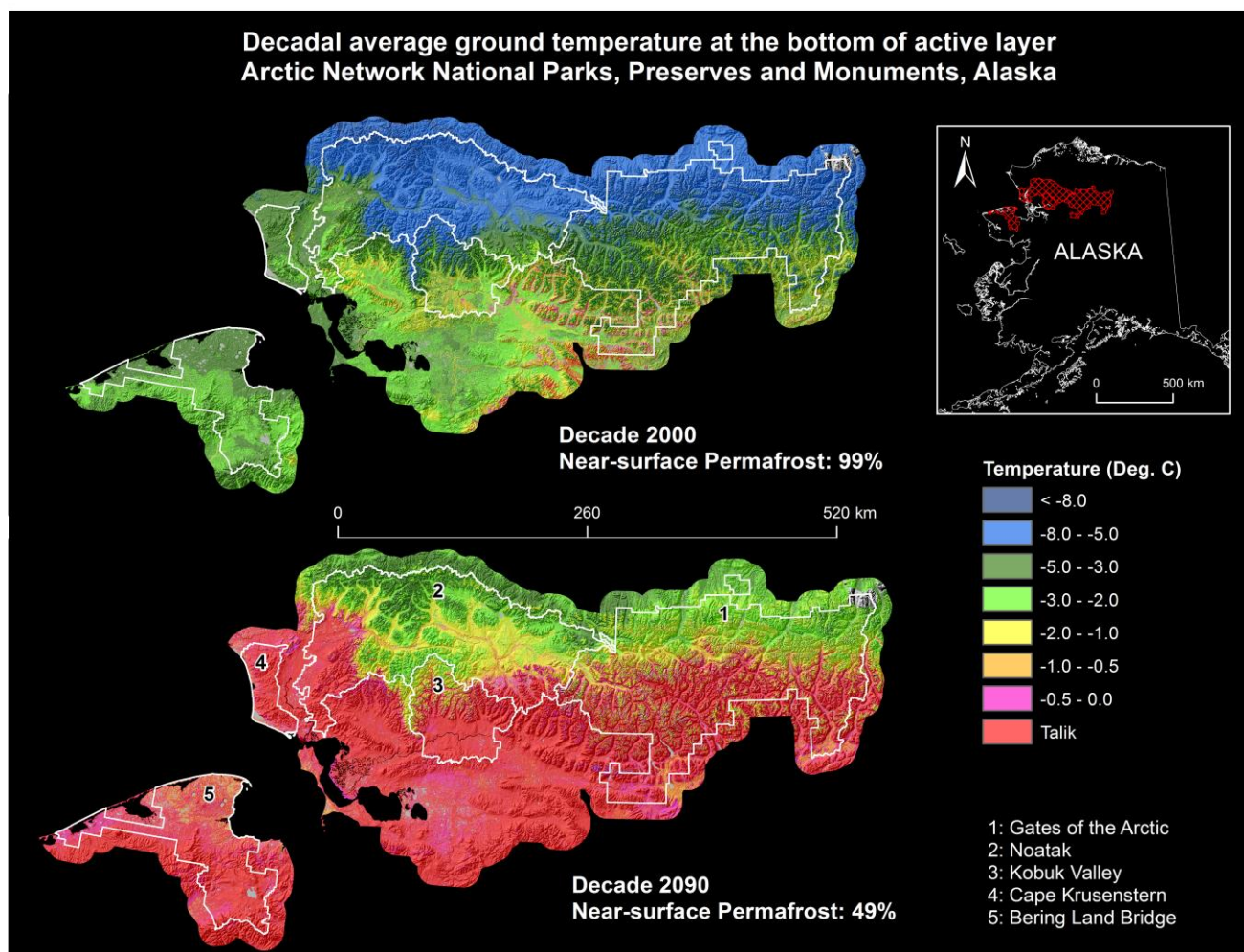




High-Resolution Permafrost Modeling in the Arctic Network National Parks, Preserves and Monuments

Natural Resource Report NPS/ARCN/NRR—2016/1366



ON THE COVER

Permafrost maps of the Arctic Network National Parks, Preserves and Monuments, Alaska, in the decade 2000 and 2090. The negative temperature values at the bottom of active layer indicate presence of near-surface permafrost. Temperature above 0 °C at the bottom of active layer indicates presence of talik, shown in red. The map is draped over a hillshade model shown in grayscale. The hillshade model is apparent in places where water landcover class is masked out. Image courtesy of NPS.

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Natural Resource Report NPS/ARC/NRR—2016/1366

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Executive Summary

We used the GIPL 1.0 model to produce near-surface permafrost maps for the Arctic Network for different time-periods. We used CRU (1950-1959 and 2000-2009) and projected 5-GCM composite (2051-2060, and 2091-2100) decadal climate forcing, ecotype and soil landscape (Jorgenson et al 2009) maps of Arctic Network to model the presence or absence of near-surface permafrost, ground temperature at the bottom of seasonal freeze-thaw layer, and thickness of seasonal freeze-thaw layer within Arctic Network. Permafrost is considered ‘near-surface’ when present immediately below the seasonal freeze-thaw layer for the purpose of this report. We produced maps of permafrost distribution, permafrost surface temperature, and seasonal freeze-thaw layer thickness at a pixel spacing of 28.5 m. This is a great improvement over the existing permafrost maps of Arctic Network. The model predicted near-surface permafrost underneath 99% of Arctic Network during 2000s, declining to 91% by 2050s and 49% by 2090s. Thus near-surface permafrost is predicted to be degrading in half of the Arctic Network toward the end of the century. The northern half of Noatak National Preserve and Gates of the Arctic National Park and Preserve are predicted to have ‘stable’ near-surface permafrost even by 2090s.

The output permafrost maps show the impact of changing climate on near-surface permafrost temperature and its distribution. We hope these permafrost maps help park managers understand the current status of near-surface permafrost within Arctic Network and how it may evolve in the future with changing climate, and to identify vulnerable sites and landscape units at higher risk of permafrost thawing, with concurrent changes to wildlife habitats and ecosystem function. We hope these maps will help decision makers in better planning of monitoring programs and management of park resources.

Acknowledgments

We would like to offer our sincere thanks to Dr. David K Swanson for his valuable advice, support and overall management of this project. His enthusiasm for the project and willingness to give time generously has been very much appreciated. Also, we would like to thank Pam Sousanes for help in accessing National Park Service climate data.

List of Acronyms

ALT	Active-layer thickness
CRU	Climatic Research Unit, University of East Anglia (UK)
ARCN	National Park Service, Arctic Inventory and Monitoring Network
GCM	Global climate models
MAAT	Mean annual air temperature
MAGST	Mean annual ground surface temperature
MAGT	Mean annual ground temperature at the bottom of seasonal freeze-thaw layer
MDGT	Mean decadal ground temperature at the bottom of seasonal freeze-thaw layer
NPS	National Park Service
SFLT	Seasonally-frozen-layer thickness
SNAP	Scenario Network for Alaska & Arctic Planning

1. Introduction

Permafrost is defined as “ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years, for natural climatic reasons” (van Everdingen 1998). Permafrost and permafrost-affected regions underlie about 22% of the exposed land in the Northern hemisphere (Brown et al. 1997) and about 80% of Alaska (Jorgenson et al. 2008). Permafrost terrain consists of an “active layer” at the surface that thaws in summer and freezes again in winter (Muller 1947). The active layer is critical to the ecology and hydrology of permafrost terrain, as it provides a rooting zone for plants and acts as a seasonal aquifer for near-surface ground water (Burn 1998). Its thickness is highly variable and can be anywhere from a few decimeters to several meters, depending on the local microclimatic condition, topography, local hydrology, thickness of surface organic layer, vegetation type, and winter snow condition. Similarly, the form and texture of ground ice within permafrost also varies greatly. Ground ice forms include thin lenses of ice, layered ice, reticulated vein ice, and ice wedges as big as 2-4 m long and 3-5 m deep (French and Shur 2010, Kanevskiy et al. 2011).

Permafrost is pervasive in Alaska’s National Parks, Preserves, and Monuments. Nearly 40 million acres of Alaska’s National Park Service (NPS) units lie within the zone of continuous or discontinuous permafrost. This area constitutes over 70% of Alaska’s NPS land and nearly half of all the NPS administered land in the US. Much of this permafrost is vulnerable to major changes due to climatic warming because 1) it has temperatures within a few degrees of thawing, such that relatively minor warming could destabilize it entirely, and/or 2) it contains ice-rich material near the surface that could thaw with climatic warming, leading to major reconfiguration of the landscape through the development of thermokarst—an irregular topography resulting from melting of excess ground ice. Thawing permafrost has many consequences, such as drainage of thermokarst lakes, creation of new thaw ponds, soil erosion, thaw slumps, increased sediment loads and siltation of streams and lakes, release of greenhouse gasses, and changes in soil wetness and nutrient cycling. Thawing permafrost is the second most important disturbance to boreal forests after wildfires (Jorgenson and Osterkamp 2005). Because of its indispensable role in maintaining northern ecosystems’ health and vitality, permafrost is identified as one of the “vital signs” of ecosystem monitoring in Alaska’s National Parks (MacCluskie and Oakley 2005, Lawler et al. 2009).

Permafrost is difficult to observe and map directly because of its subsurface presence. Temperature measurements are required to evaluate the health of permafrost. Existing knowledge on the distribution and temperature of permafrost in NPS units is very limited due to the paucity of borehole observations and temperature monitoring sites. However, given sufficient environmental data, the current distribution and temperature of near-surface permafrost can be reliably predicted. By using projected climate data and scenarios, the same models used to predict current distribution of permafrost can predict the future distribution of permafrost.

We used a permafrost model called "GIPL 1.0" for this study (GIPL: Geophysical Institute Permafrost Laboratory of the University of Alaska Fairbanks). This model assesses the effect of changing climate on permafrost. Using the GIPL 1.0 model, *Marchenko et al.* (2008) mapped

permafrost distribution for the State of Alaska at kilometer scale. The GIPL 1.0 model gives a good representation of the coupling between permafrost and the atmosphere. It shows an accuracy of $\pm 0.2 - 0.4^{\circ}\text{C}$ for the mean annual ground temperature and $\pm 0.1 - 0.3$ m for the active-layer thickness calculations when applied to long-term (decadal and longer time scale) averages (Sazonova and Romanovsky 2003). As a part of its inventory and monitoring program, NPS has obtained vegetation, soil, and temperature data for all the NPS units that are suitable as inputs for the GIPL model (Stevens et al., 2001; Clark and Duffy, 2006; Stumpf, 2007; Jorgenson et al., 2008, 2009). These data were used previously to map permafrost in Denali National Park and Preserve and Wrangell-St. Elias National Park and Preserve (Panda et al. 2014a, b)

The goal of this project was to facilitate cooperation between NPS and GIPL to obtain improved and higher-resolution maps for NPS lands of permafrost distribution, temperature, and active-layer thickness under various climate scenarios, including present conditions, the recent past (e.g., 1950, prior to recently observed warming), and the future. The NPS environmental data (soil landscape and ecotype maps) along with past and projected climate forcing from global climate datasets are used to create 28.5 m-resolution maps of near-surface permafrost distribution, permafrost temperature, and active-layer thickness, for the recent past (1950s), the present (2000s), and the future (2050s and 2090s). Permafrost is considered ‘near-surface’ when present immediately below the seasonal freeze-thaw layer for the purpose of this report. Field observation of permafrost presence/absence, summer thaw depth, and ground temperature records from NPS climate stations are used to assess the overall accuracy of the modeled permafrost maps.

2. Arctic Network Parks, Preserves and Monuments (ARCN)

The Arctic Network consists of following Parks, Preserves, and Monuments: Gates of the Arctic National Park and Preserve (GAAR), Noatak National Preserve (NOAT), Kobuk Valley National Park (KOVA), Bering Land Bridge National Preserve (BELA), and Cape Krusenstern National Monument (CAKR). Our study area also includes the Selawik Wildlife National Refuge and covers about 40 million acres (Fig. 1).

Permafrost distribution can be classified as continuous (>90% of land area underlain by permafrost), discontinuous (90% – 50%), sporadic (50% – 10%), or isolated (<10%) (Ferrians 1965). In ARCN permafrost distribution is considered continuous (Jorgenson et al., 2008a). In most of the Arctic Network the average annual air temperature is colder than -3 °C according to Climatic Research Unit (CRU) climate dataset (Fig. 2). The average annual ground temperatures just below the –seasonal freeze-thaw layer are usually 0 to 5 °C warmer than the average annual air temperature. Hence, permafrost is present everywhere on the landscape where average annual air temperature is below -5 °C except under deep water bodies that do not freeze to the bottom during winter (Jorgenson et al., 2008a; Swanson, 2016). Permafrost generally occupies progressively less of the land area at higher Mean Annual Air Temperature (MAAT), becoming nearly absent where MAAT is above 0 °C (Jorgenson et al., 2008a). Due to disturbance or climate warming permafrost becomes unstable and it thaws. Thawing of permafrost results in development of thermokarst; about 13.5% of the continuous permafrost has thermokarst features (Jorgenson et al. 2008b).

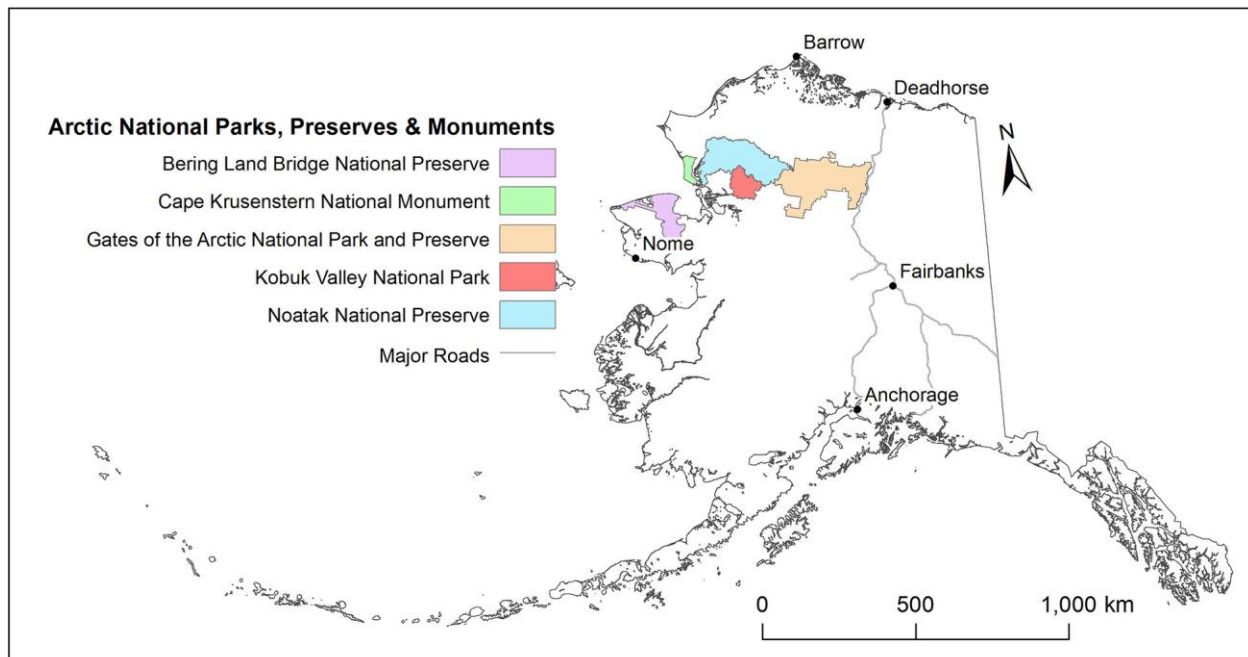


Figure 1. Location of NPS units in the Arctic Network.

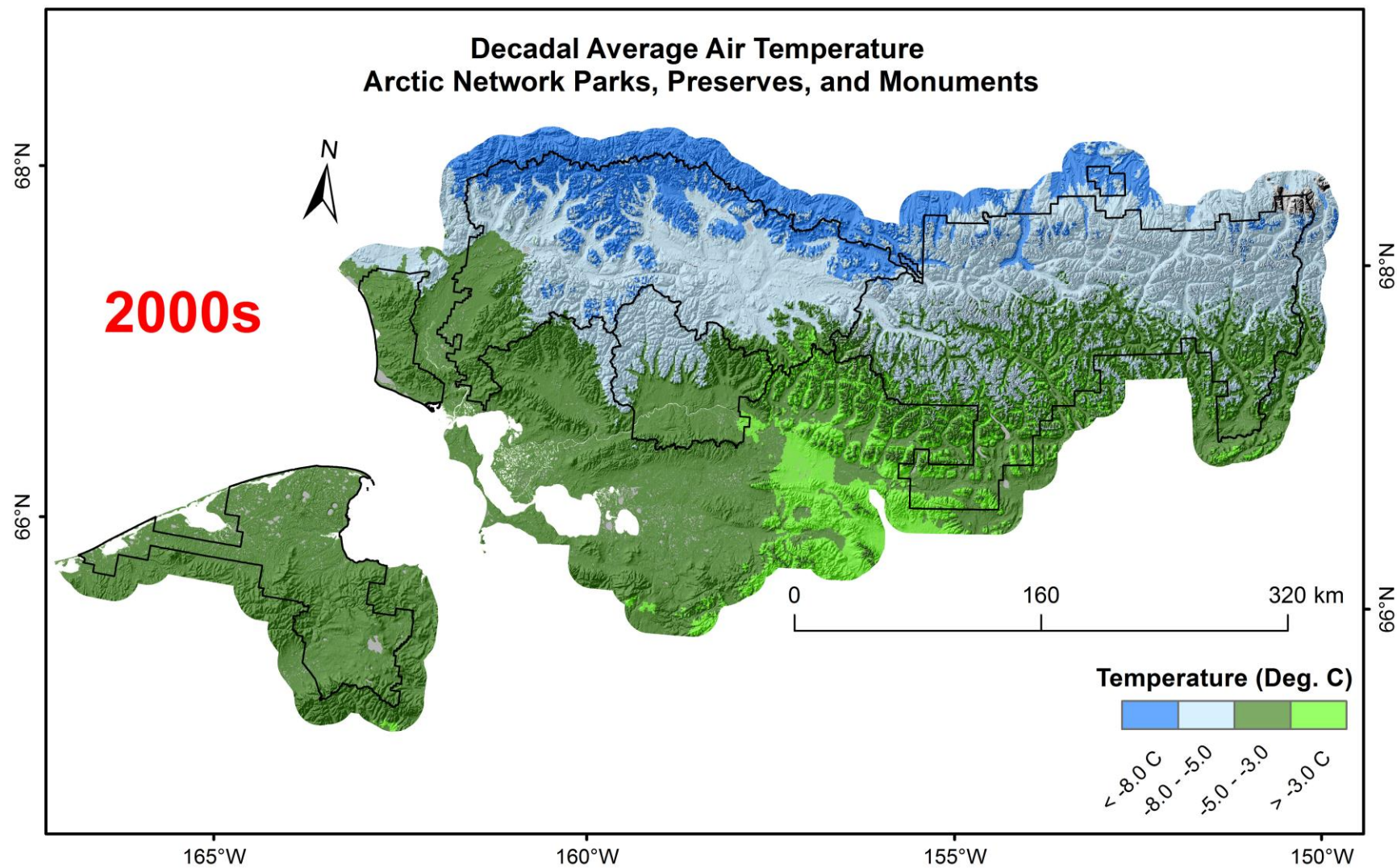


Figure 2. Average decadal (2000-09) air temperature in ARCN. The air temperature data is from the CRU dataset.

3. GIPL 1.0 Model

GIPL 1.0 is a quasi-transitional, spatially distributed, equilibrium model for calculating the mean annual temperature at the ground surface and bottom of seasonal freeze-thaw layer, and thickness of seasonal freeze-thaw layer. In the absence of permafrost the seasonal freeze-thaw layer is called “seasonally-frozen layer” (the top layer of the ground that freezes in winter and thaws back in summer and does not have permafrost underneath). The model accounts for the effects of snow cover, surface vegetation, soil moisture, and soil thermal properties (Fig. B1). Refer to Appendix B for detailed description of this model.

3.1. GIPL 1.0 Model Input

3.1.1. *Climate Data*

We used historical (1901–2009) monthly average air temperature (°C) and total precipitation (mm) data, CRU TS 3.1 from the University of East Anglia (UK) Climatic Research Unit, downscaled to 771 m by Scenario Network for Alaska & Arctic Planning (SNAP) for past climate forcing (SNAP 2012). Projected (2001–2100) monthly average air temperature (°C) and total precipitation (mm) data are available from Fourth Assessment Report (AR4) Global Climate Models (GCM) for a range of possible emission scenarios. Walsh et al. (2008) identified 5 out of a set of 15 global models used in the Coupled Model Intercomparison Project (CMIP) as best performer for Alaska and Greenland. Those 5 AR4 GCMs are:

- cccma_cgcm31: Canadian Centre for Climate Modeling and Analysis, Coupled General Circulation Model version 3.1 – t47, Canada
- mpi_echam5: Max Planck Institute for Meteorology, European Centre Hamburg Model 5, Germany
- gfdl_cm21: Geophysical Fluid Dynamics Laboratory, Coupled Model 2.1, United States
- ukmo_hadcm3: UK Met Office – Hadley Centre, Coupled Model version 3.0, United Kingdom
- miroc3_2_medres: Center for Climate System Research, Model for Interdisciplinary Research on Climate 3.2 (medres), Japan

SNAP averaged the monthly average air temperature and total precipitation projections from the above 5 models for 3 possible emission scenarios (B1: low, A1B: moderate, and A2: high) and created a composite climate dataset for Alaska downscaled to 771 m (SNAP 2012). We used this 5-GCM composite climate dataset for A1B emission scenario as the future climate forcing for the GIPL 1.0 model runs.

3.1.2. *Ecotype Data*

Jorgenson et al. (2009) mapped 44 different ecotypes in Arctic Network using Landsat Enhanced Thematic Mapper (ETM+) multi-spectral imagery of 2002. They emphasized primarily geomorphology and vegetation structure in developing the ecotype classes and used an easy to

understand nomenclature for ecotypes that describe ecological characteristics (climate, physiography, soil chemistry, moisture, vegetation, structure, and dominant species). We masked out 7 ecotypes related to fresh water, coastal water, snow, shadow and human modified classes and used the remaining ecotypes as model input.

Surface organic layer thickness and its thermal diffusivity are the two essential ecotype parameters required for ground temperature modeling. Since thermal diffusivity measurements of surface organic layer were not available, for the Arctic Network ecotypes, we prescribed thermal diffusivity values based on ecotype and our modeling experience in other parts of Alaska. The following ecotype properties are used as the model input (Table A1):

- Thawed thermal diffusivity (m^2/s)
- Frozen thermal diffusivity (m^2/s)
- Surface organic layer thickness (m)

3.1.3. Soil Data

Jorgenson et al. (2009) identified 24 different soil landscapes in ARCN. They developed soil landscapes to characterize and map broader relationships among soil type, physiography, and vegetation. The soil landscapes are named based on physiography, soil texture, and dominant vegetation structure. We prescribed the following thermal properties to each soil landscape as the model input (Yershov 1984; Table A2):

- Thawed heat capacity ($\text{J}/\text{m}^3\text{K}$)
- Frozen heat capacity ($\text{J}/\text{m}^3\text{K}$)
- Thawed thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)
- Frozen thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)
- Volumetric water content (Fraction of 1)

3.1.4. Snow Data

Snow cover plays an important role in the heat exchange processes between the land surface and the atmosphere. The insulating effect of the snow cover is calculated using approximate formulas derived by Lachenbruch (1959) and Romanovsky (1987) which incorporate ground properties, vegetation cover, and their respective effect on heat turnovers through the snow. Heat turnovers are defined as the quantity of incident heat (during the heating period), or out-going heat (during the cooling period) throughout the medium over a given time interval (usually half year increments). The model takes into account only conductive heat transfer through different mediums.

Sturm et al. (1995) has identified five seasonal snow classes in Alaska. Each snow class is defined by a unique ensemble of textural and stratigraphic characteristics including the sequence of snow layers, their thickness, density, and the crystal morphology and grain characteristics within each layer. We

linked the dominant vegetation in each ecotype with one of the five seasonal snow classes identified by Sturm et al. (1995). This resulted in fifteen snow classes for ARCN. The following snow properties for each snow class are used as the model input (Table A3):

- Density of fresh snow (kg/m^3)
- Maximum density of snow (kg/m^3)

3.2. GIPL 1.0 Model Output

The GIPL 1.0 permafrost model calculates the following permafrost characteristics:

- Mean annual ground surface temperature (MAGST, $^{\circ}\text{C}$).
- Mean annual ground temperature (MAGT, $^{\circ}\text{C}$) at the bottom of seasonal freeze-thaw layer.
- Thickness (m) of seasonal freeze-thaw layer.

4. Preparation of Input Data for Modeling

We prepared the input data for the model runs in a GIS environment using the program ArcMap 10.2 (www.esri.com/software/arcgis/arcgis-for-desktop).

4.1. Mask

We masked out the water, permanent snow, shadow, and human modified classes within ARCN as GIPL 1.0 model calculates temperature on and below the land surface only. We generated the Snow-Ice-Water mask by using the following procedure:

- Generated an ARCN boundary shape file (ARCN-Boundary.shp) from the ARCN land cover map developed by Jorgenson et al. (2009). We used this boundary shape file to subset climate input data layers — air temperature and precipitation.
- Reclassified the ‘Fresh water’, ‘Coastal water’, ‘Snow’, ‘Shadow/Indeterminate’, ‘Human modified’ ecotype classes identified in the land cover map as ‘nodata’.
- This reclassified land cover raster layer was used to mask out ‘Fresh water’, ‘Coastal water’, ‘Snow’, ‘Shadow/Indeterminate’, ‘Human modified’ pixels from the air temperature and precipitation input data layers.

4.2. Climate Forcing

The monthly average air temperature and monthly total precipitation data, from CRU TS 3.1 and 5-GCM composite, are available at 771m and 800 m cell size, respectively, for the entire state of Alaska (SNAP 2012). We used the following procedure to prepare the input climate data for model runs:

- Created decadal average air temperature and precipitation raster layers for every month for the time periods of interest i.e., 1950-1959, 2000-2009, 2051-2060, and 2091-2100.
- Created ARCN subsets of the decadal average air temperature and precipitation data from the previous step by using the ‘ARCN-Boundary.shp’ shape file.
- Resampled the ARCN decadal average air temperature and precipitation data from the previous step to the resolution of ARCN landcover map i.e., 28.5 m.
- Masked out the ‘Fresh water’, ‘Coastal water’, ‘Snow’, ‘Shadow/Indeterminate’, ‘Human modified’ from the resampled decadal average air temperature and precipitation data by using ‘ARCN-Mask.tif’ layer.
- Used CRU climate forcing for the modeling time periods 1950-1959 and 2000-2009, and 5-GCM climate forcing for the modeling time periods 2051-2060, and 2091-2100.
- Converted the raster air temperature and precipitation data layers from the previous step to ASCII format as GIPL 1.0 model requires input data to be in ASCII format.

4.3. Ecotype Map

We used the reclassified landcover map from Section 4.1 as Ecotype model input. We fixed the sequence of class values by assigning a continuous sequence of numbers '1-37' and converted the resulting raster (.tif) landcover map to ASCII format.

4.4. Soil Landscape Map

Jorgenson et al. (2009) identified soil landscapes associated with each ecotype for ARCN. We used the ecotype map derived from the ARCN landcover map as model input (Table A2).

4.5. Snow Map

We mapped the seasonal snow classes for Alaska identified by Sturm et al. (1995) to the ecotype classes identified by Jorgenson et al. (2009). Our approach resulted in 15 snow classes for ARCN, each with a unique set of fresh snow density and maximum snow density.

5. Results

The modeling effort resulted in high-resolution maps for Arctic network of near-surface permafrost temperature, active-layer thickness and talik distribution for the decades 1950-1959, 2000-2009, 2051-2060, and 2091-2100.

5.1. CRU Climate Forcing (1950-1959 and 2000-2009)

The modeling results using CRU climate forcing can be compared to understand the past permafrost distribution and changes to its characteristics between 1950s and 2000s (Table 1). The CRU (1950-1959) decadal average air temperature within ARCN ranged from -12.0°C to -3.0°C and the mean was -7.0°C . The CRU (1950-1959) decadal average annual precipitation ranged from 246 to 892 mm and the mean was 455 mm. The modeled (1950-59) permafrost temperature within ARCN ranged from -10.1 to -0.5°C and the mean permafrost temperature was $-5.5 \pm 1.7^{\circ}\text{C}$ (Figs. 3 and 4). The modeled (1950-59) active-layer thickness ranged from 0.16 to 3.44 m and the mean was 0.62 ± 0.2 m (Figs. 4). The model mapped 100% of the ARCN area as underlain by near-surface permafrost during the 1950s. The CRU (2000-2009) decadal average air temperature for ARCN was 1.8°C warmer than that of 1950-1959 (Table 1). Consequently, the modeled (2000-2009) decadal average permafrost surface temperature was 1.5°C warmer than that of 1950-1959. The model mapped 99% of the ARCN total area as underlain by near-surface permafrost during the decade of 2000s, not a significant loss of near-surface permafrost in the 50 year span (Figs. 5 and 6). However, the percentage of most vulnerable permafrost (i.e., permafrost within a degree of thawing) increased from 0.03% of ARCN total area in 1950s to 3.8% in 2000s.

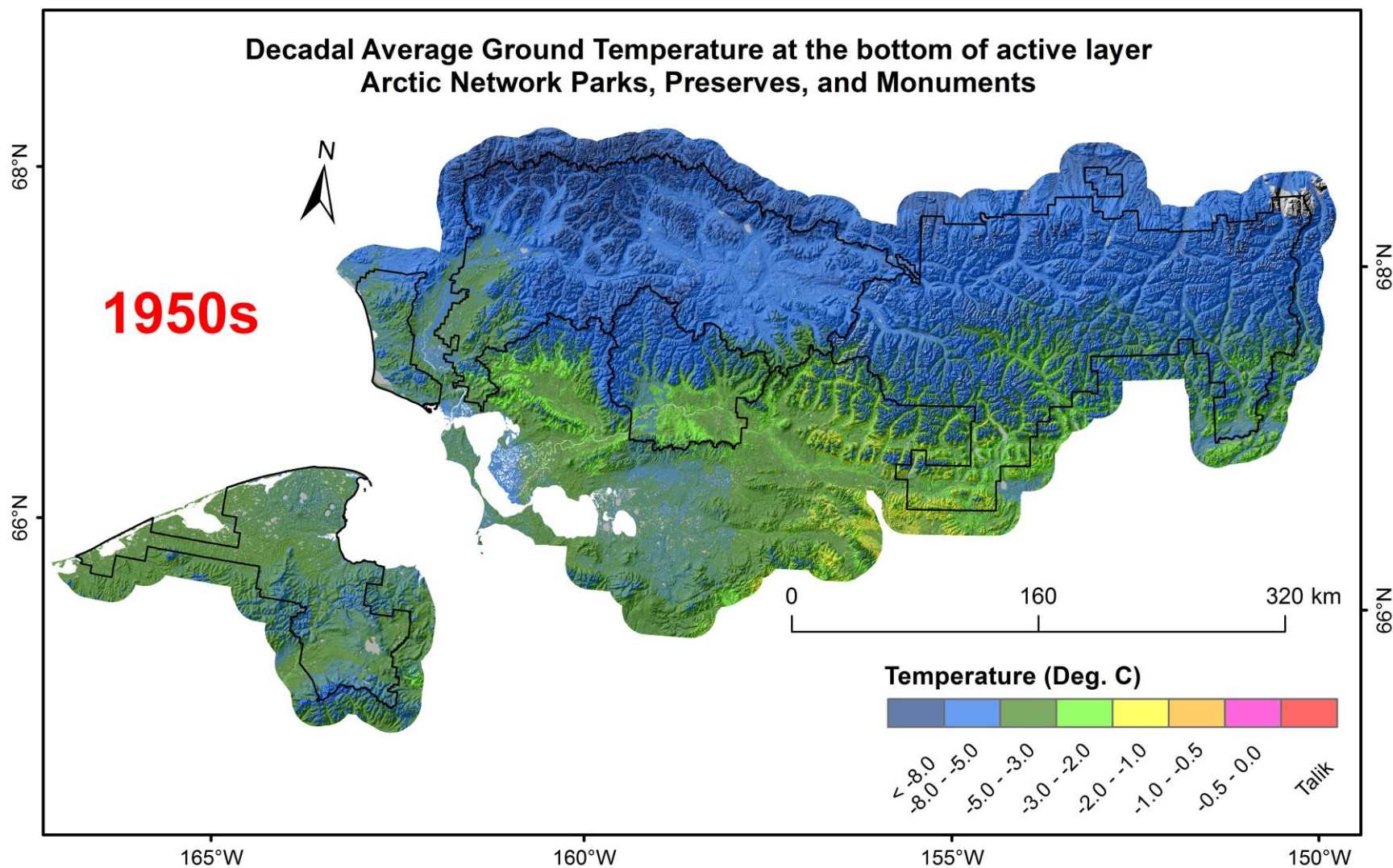


Figure 3. Permafrost map (as per 1950-1959 CRU climate forcing) of Arctic Network, Alaska. The negative temperature values indicate presence of near-surface permafrost. The red color identifies areas with Talik—unfrozen ground above permafrost. The map is draped over a hillshade model for 3D perspective. The hillshade model is apparent in places where water landcover class is masked out.

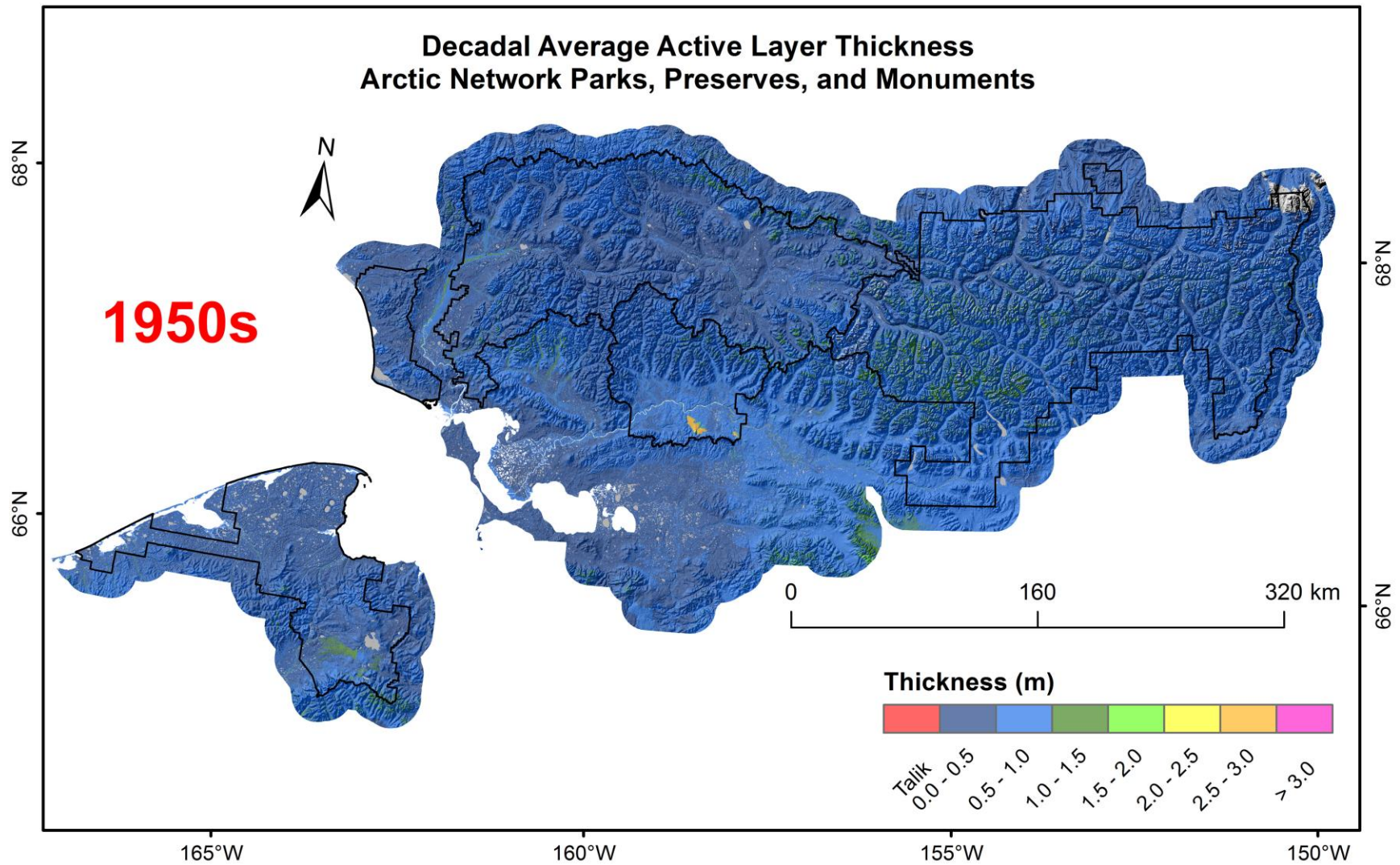


Figure 4. Active-layer thickness map (as per 1950-1959 CRU climate forcing) of Arctic Network, Alaska. The red color identifies areas with Talik—unfrozen ground above permafrost.

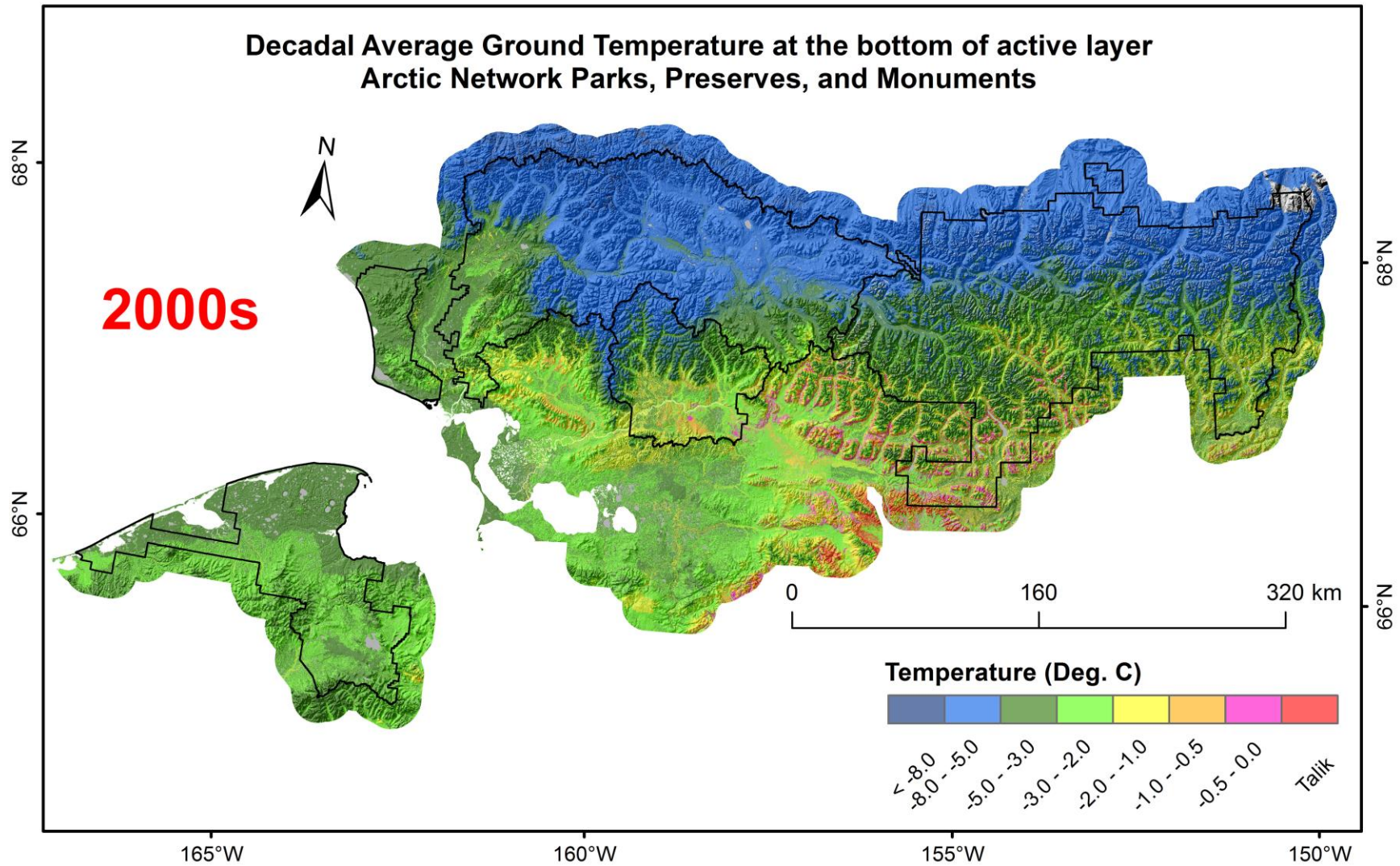


Figure 5. Permafrost map (as per 2000-2009 CRU climate forcing) of Arctic Network, Alaska. The negative temperature values indicate presence of near-surface permafrost. The red color identifies areas with Talik—unfrozen ground above permafrost.

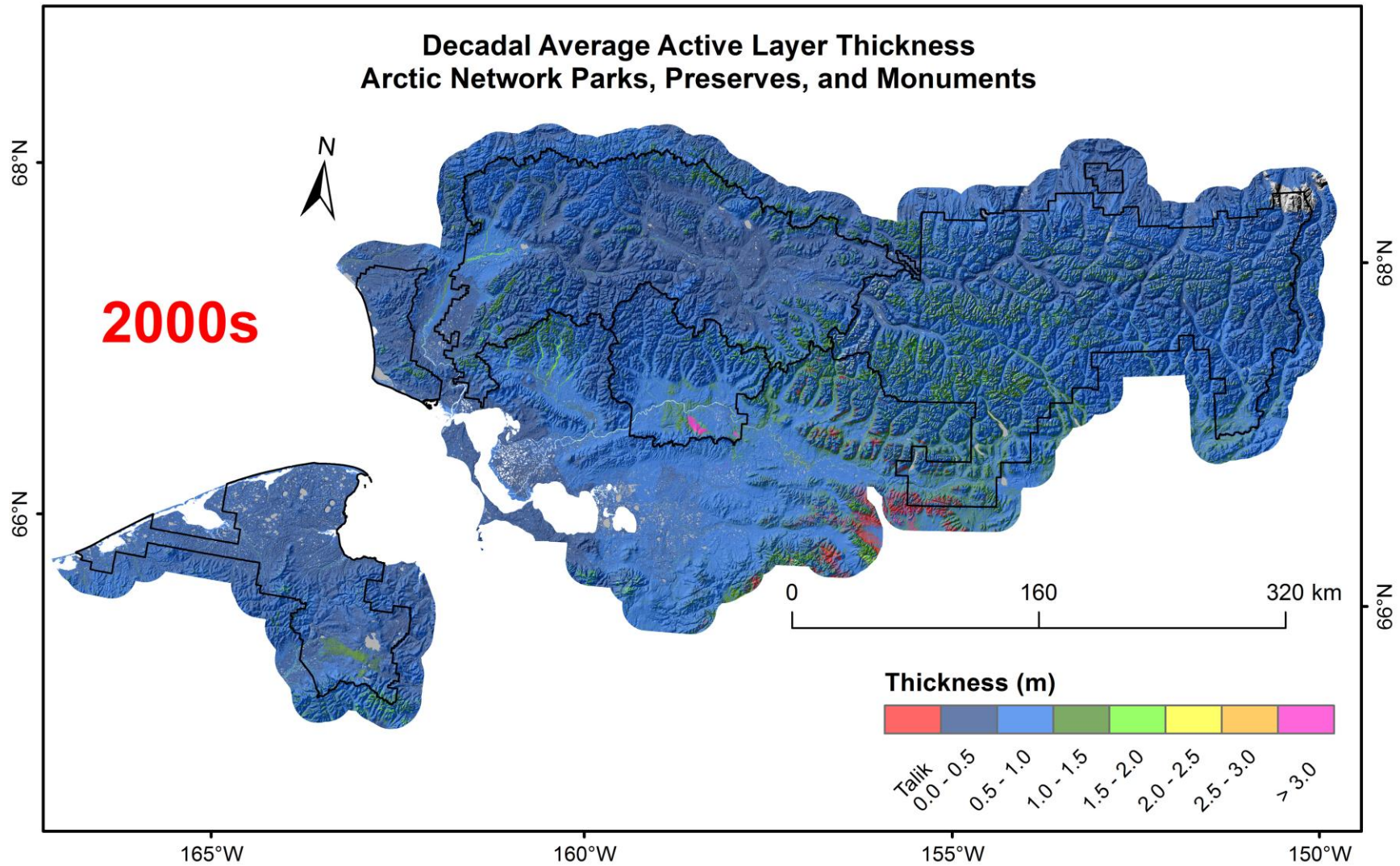


Figure 6. Active-layer thickness map (as per 2000-2009 CRU climate forcing) of Arctic Network, Alaska. The red color identifies areas with Talik—unfrozen ground above permafrost.

Table 1. Summary statistics of climate and modeled permafrost characteristics in the Arctic Network as per CRU climate forcing.

Characteristics	1950-1959	2000-2009
Climate characteristics		
Decadal air temperature range (°C)	-12.0 to -3.0	-10.0 to -1.0
Mean decadal air temperature (°C)	-7.0±2.0	-5.2±1.9
Decadal precipitation range (mm)	246 to 892	270 to 862
Mean decadal precipitation (mm)	455	472
Modeled permafrost characteristics		
Mean decadal permafrost temperature (°C)	-5.5±1.7	-4.0±1.8
Permafrost distribution (% of ARCN area)	100	99.3
Permafrost warmer than -1°C (% of ARCN area)	0.03	3.8
Decadal ALT range (m)	0.16 to 3.44	0.16 to 4.58
Mean decadal ALT (m)	0.62±0.2	0.67±0.26

5.2. 5-GCM Composite Climate Forcing (2051-2060, and 2091-2100)

The modeling results from 5-GCM composite climate forcing show future permafrost distribution and changes to its characteristics due to the projected climate warming (Table 2).

The 5-GCM composite decadal average (2051-60) air temperature is predicted to be 2.1 °C warmer and the total annual precipitation is 27 mm higher than the CRU decadal (2000-09) average air temperature and the total annual precipitation. Our model mapped 91% of ARCN total area as underlain by near-surface permafrost in the 2050s, of which 15.5% will be within 1 degree of thawing. The modeled decadal average permafrost temperature in the 2050s is - 2.6±1.6 °C (Figs. 7 and 8). According to the climate models, the Arctic climate will continue to warm and the 5-GCM composite suggests another 2.4°C increase in mean decadal air temperature by 2090s, i.e. a total of 4.5°C increase in the decadal average air temperature between 2000s and 2090s. This increase in air temperature is expected to cause further increase in ground temperature and loss of near-surface permafrost. Only half (49%) of ARCN total area is predicted to be underlain by near-surface permafrost by the end of the 21st century, mostly in the northern half of Noatak and Gates of Arctic National Park and Preserve (Figs. 9 and 10, Table 2). In the 2090s, permafrost in 16.6% of ARCN will be within 1 degree of thawing. The near-surface permafrost, i.e. permafrost immediately below the active layer, is predicted to be replaced by taliks in the southern half of the Arctic Network and most of Selawik National Wildlife Refuge toward the end of this century.

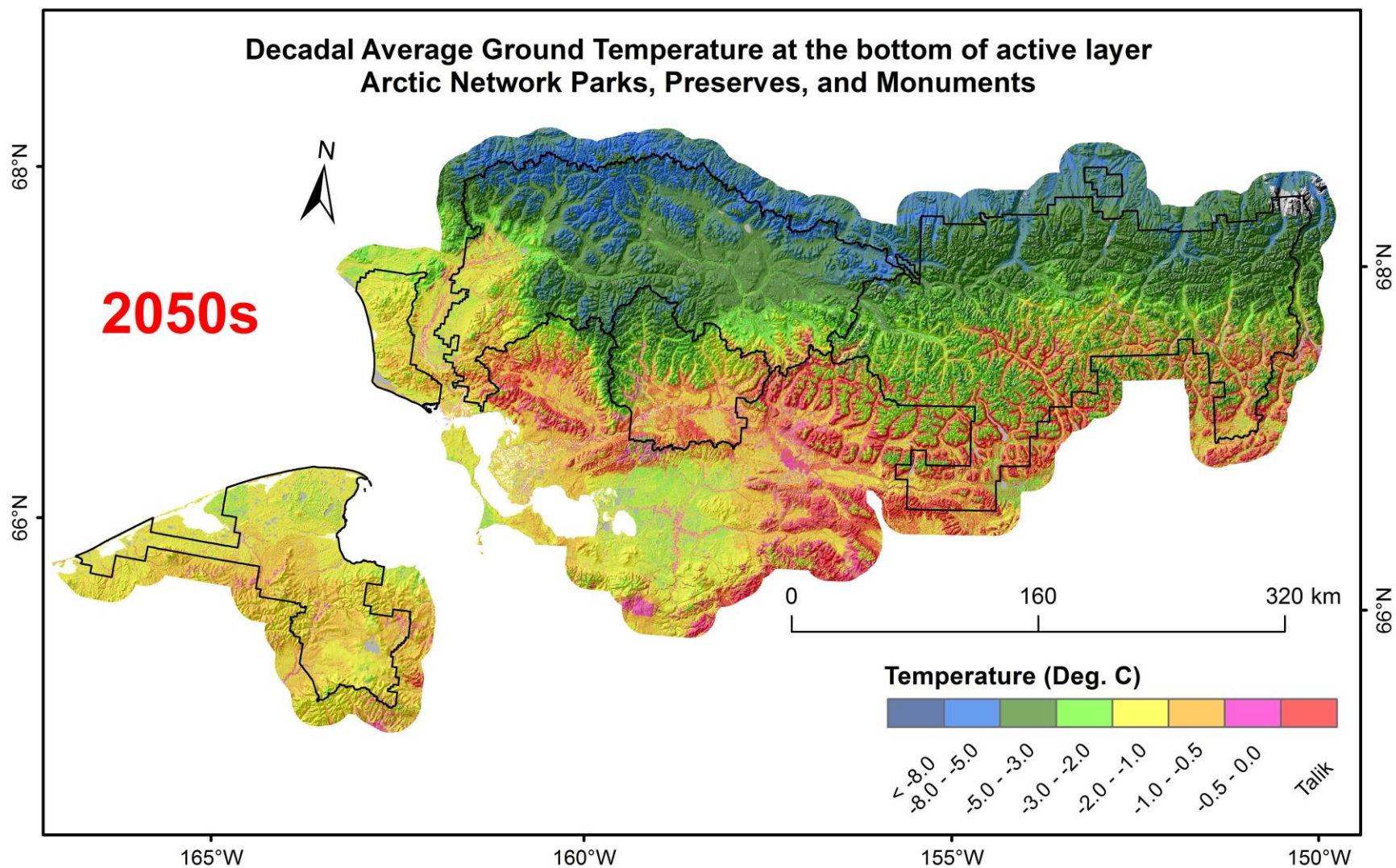


Figure 7. Permafrost map (as per 2051-2060 5-GCM climate forcing) of Arctic Network, Alaska. The negative temperature values indicate presence of near-surface permafrost. The red color identifies areas with Talik—unfrozen ground above permafrost.

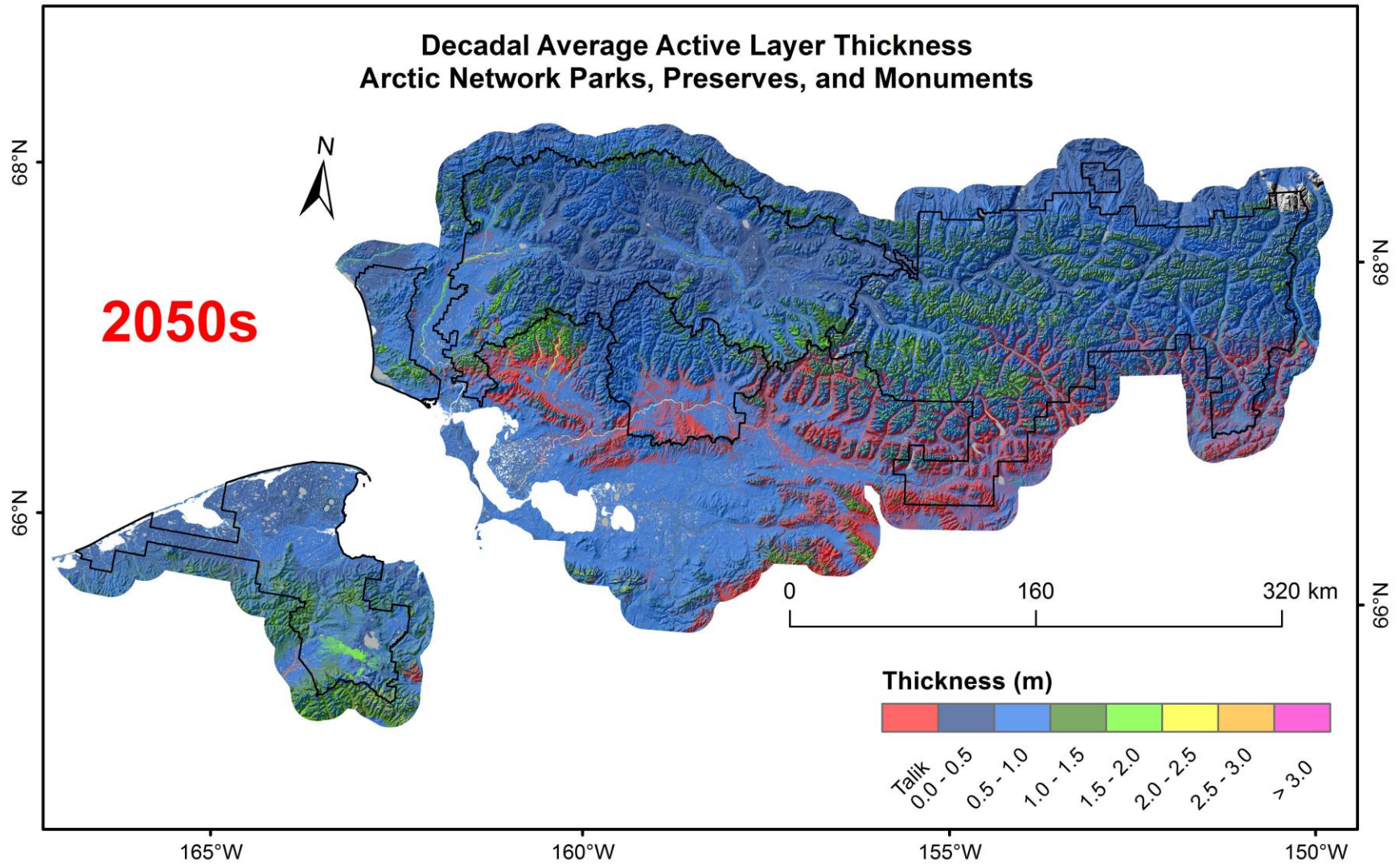


Figure 8. Active-layer thickness map (as per 2051-2060 5-GCM climate forcing) of Arctic Network, Alaska. The red color identifies areas with Talik—unfrozen ground above permafrost.

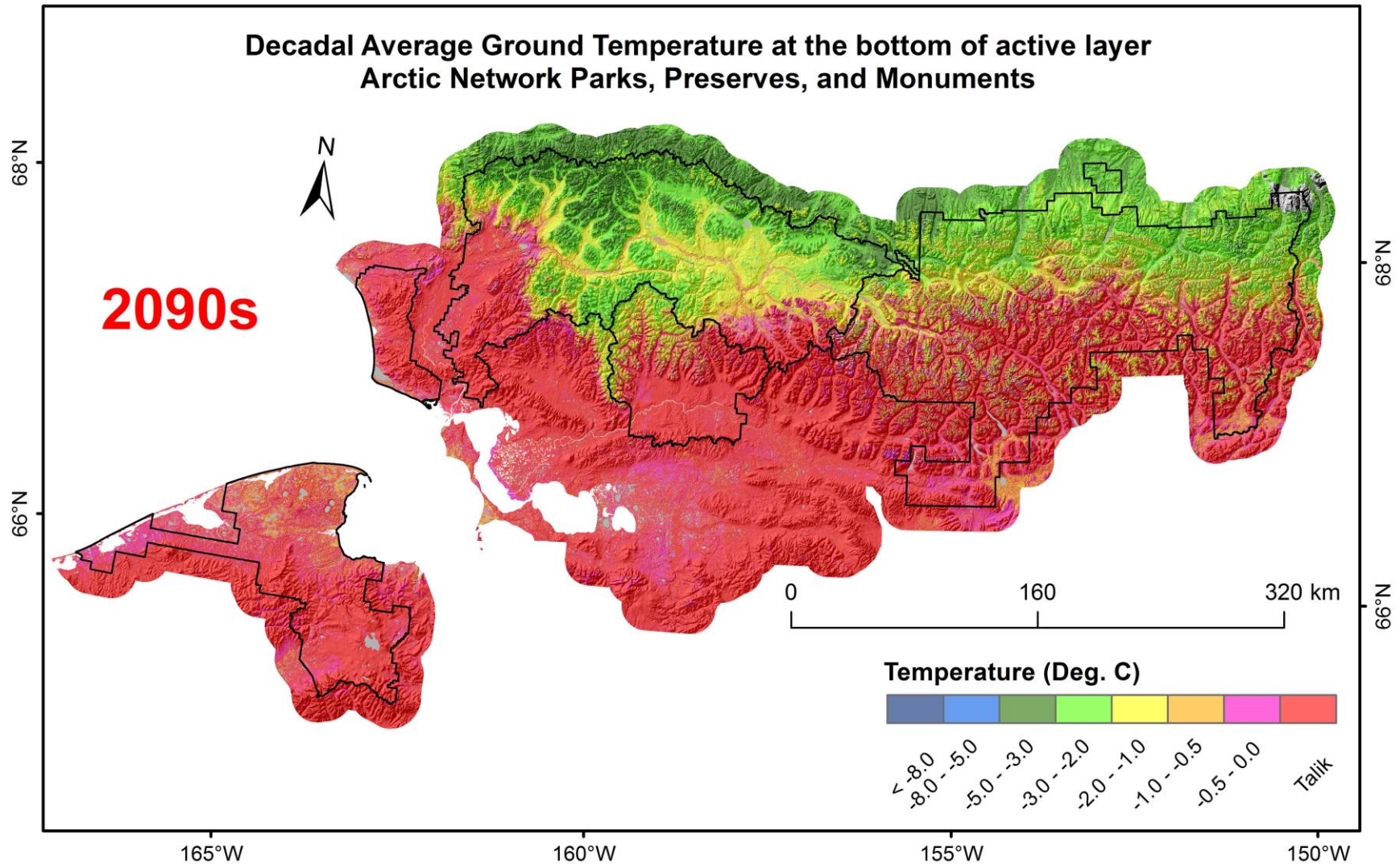


Figure 9. Permafrost map (as per 2091-2100 5-GCM climate forcing) of Arctic Network, Alaska. The negative temperature values indicate presence of near-surface permafrost. The red color identifies areas with Talik—unfrozen ground above permafrost.

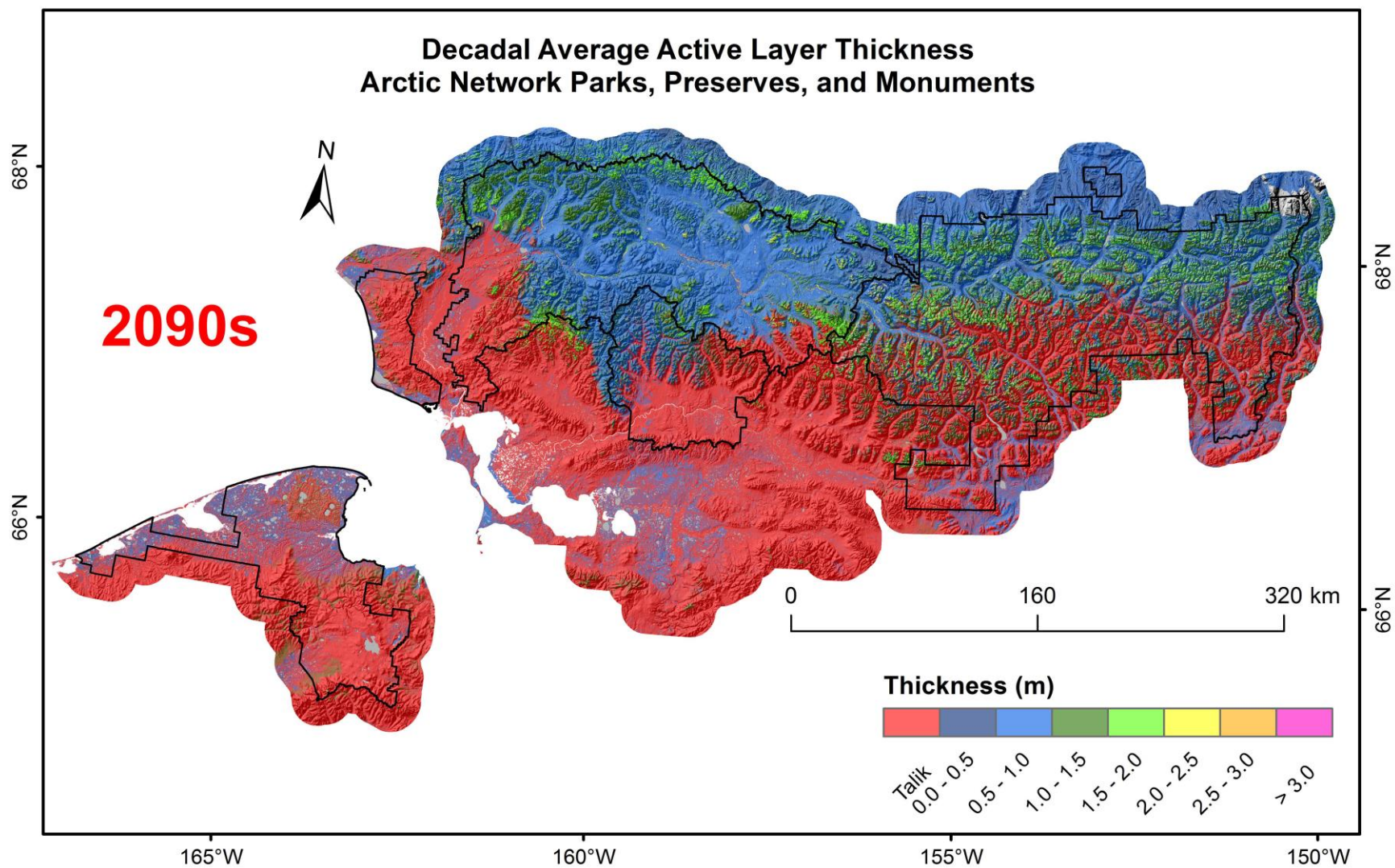


Figure 10. Active-layer thickness map (as per 2091-2100 5-GCM climate forcing) of Arctic Network, Alaska. The red color identifies areas with Taliks—unfrozen ground above permafrost.

Table 2. Summary statistics of climate and modeled permafrost characteristics in the Arctic Network using 5-GCM composite climate forcing.

Characteristics	2000-2009	2051-2060	2091-2100
Climate characteristics			
Decadal air temperature range (°C)	-10.0 to -1.0	-8.0 to 0.5	-5.6 to 2.8
Mean decadal air temperature (°C)	-5.2±1.9	-3.1±1.9	-0.7±1.9
Decadal precipitation range (mm)	270 to 862	291 to 903	351 to 1086
Mean precipitation (mm)	472	499	597
Modeled permafrost characteristics			
Mean decadal permafrost temperature (°C)	-4.0±1.8	-2.6±1.6	-1.8±1.2
Permafrost distribution (% of ARCN area)	99	91	49
Permafrost warmer than -1°C (% of ARCN area)	3.8	15.5	16.6
Decadal ALT range (m)	0.16 to 4.58	0.21 to 4.22	0.33 to 4.02
Mean decadal ALT (m)	0.67±0.26	0.74±0.31	0.88±0.40

5.3. Accuracy Assessment

In order to assess the accuracy of the modeling products we compared the modeled permafrost map for 2000s decade with field observations of permafrost presence/ absence carried out during summer 2002-2008.

Jorgenson et al. (2009) identified presence/absence of permafrost at 694 field sites within ARCN; they found permafrost at 575 sites. At all the field identified permafrost present sites the model predicted presence of near-surface permafrost for 2000 decade. Observed thaw depths are reported for 339 sites out of 575 permafrost present sites. At 238 sites out of 339 sites, the reported thaw depths are shallower than the predicted active layer thicknesses; at these sites very likely the ground was not thawed to the maximum depth at the time of observation (all field work was done during mid-July – mid-August). At 101 sites the reported thaw depths are greater than the predicted active layer thicknesses which suggest the model predicted colder ground temperature and shallower active layer at these sites. At 19 sites the differences between observed thaw depth and predicted active layer thickness are less than 5 cm (within the margin of observation error). At 101 sites where the predicted active layer thicknesses are shallower than the reported thaw depths, on average the predicted active layer thickness is 0.27 ± 0.24 m shallower than observed thaw depths. Comparing observed ground temperature with predicted ground temperature at 33 sites we found on average the predicted ground temperature is 0.4 °C colder than the observed ground temperature (see *Section 5.3.1* for further discussion).

Jorgenson et al. (2009) reported permafrost absent at 119 sites; however, the depths of observation are reported at five sites only. The reported thaw depth varies from 0.20 – 0.48 m at these five sites. At three out of the five sites the reported thaw depth are shallower than the predicted active layer thickness; at these sites the field crew might not have investigated deep enough to confirm the presence of permafrost (Table 3), at the remaining two sites the difference between observed thaw

depths and predicted active layer thicknesses are 0.02 m and 0.03 m which is within the margin of observation error. Since the depths of observation are not reported for most of permafrost absent sites we could not use this data for model accuracy assessment because the field crew might not have investigated deep enough to confirm the presence of permafrost.

Table 3. Comparison of observed thaw depth with model predicted active layer thickness at five sites.

Date of Observation	Observed Thaw Depth, m	Modeled Active layer thickness, m 2000-2009
7/21/2006	0.48	0.47
7/21/2006	0.35	0.45
7/21/2006	0.20	0.47
7/21/2006	0.33	0.45
7/19/2006	0.48	0.45

5.3.1. Comparison with Recorded Ground Temperature

NPS began collecting ground temperature data at twenty-one sites within ARCN since 2011. Soil temperature data from 16 of these sites are now available (Swanson, 2016). At these sites we compared the observed ground temperature with the modeled ground temperatures (Table 4).

At 12 sites the observed (2013-2015) air temperature were 0 to 3.4°C warmer than the CRU decadal (2000-09) air temperature, and at 4 sites the observed (2013-2015) air temperatures were 0.2 to 1.7°C colder than the CRU decadal (2000-09) air temperature. The mean difference between the observed air temperature and the CRU air temperature was 0.74 ± 1.4 °C. These temperature differences are due to the difference in the time period but also could be due to the difference in scale of the two datasets. The observed temperature records are from a single location whereas the CRU temperatures are spatially averaged temperature from a global climate datasets of 0.5° x 0.5° latitude-longitude resolution, downscaled to 771 m by SNAP. SNAP utilized PRISM (Parameter-elevation Regressions on Independent Slope Model) spatial climate data at 771 m spatial resolution for downscaling. The PRISM data are developed with a statistical model that accounts for land features such as slope, elevation and coastlines. So the PRISM data assigns a single slope and elevation value to a 771 m cell, but in reality both slope and elevation can vary substantially within a 771 m cell especially in areas of high relief (Fig. 11). A detail description of the SNAP downscaling procedure can be found here (<http://www.snap.uaf.edu/downscaling.php>). We further resampled the CRU air temperature data by dividing its 771 m cells to 28.5 m cells to make it compatible with the ecotype input for high-resolution modeling.

At all NPS observation sites except two (Hoodoo Hills and Pamichtuk Lake), the modeled decadal average (2000-2009) ground temperatures at the bottom of active layer are 0.2 to 4.2 °C colder than the recorded (2013 - 2015) ground temperature (at 0.5 m and 0.75 m). At Hoodoo Hills and Pamichtuk Lake the modeled ground temperatures are 0.4 and 0.3 °C warmer than the recorded temperature, respectively. Note: the modeled ground temperatures reported in Table 4 are from the

bottom of the active layer which varies with sites. According to Swanson (2016) the air and soil temperatures at the NPS monitoring sites have increased by 3 – 4 °C during the monitoring period from 2011 – 2015. In light of Swanson's (2016) observations the modeled ground temperature would be very close to the actual ground temperature for the modeled time period (2000-2009). However, it is also evident that to some extent the model underestimates the insulating effect of snow as the modeled insulating effect of snow ranges from 1.3 to 2.8°C whereas the recorded temperatures show 0 to 4.0°C difference between near-surface air and ground temperatures. For example at Kavet Creek station, the modeled insulating effect of snow is 1.3 °C whereas the recorded temperature shows 4.4 °C difference.

Romanovsky and Cable (2014) began collecting ground temperature data at 26 sites within SNWR since 2011. Soil temperature data from 17 of these sites are now available. At these sites we compared the observed ground temperature with the modeled ground temperatures (Table 4). At eleven of these sites the modeled decadal average (2000-2009) ground temperatures at the bottom of active layer are 0.1 – 3.6 °C colder than the recorded (2011 - 2014) ground temperature (at 0.5 m). At the remaining six sites the modeled decadal average (2000-2009) ground temperatures at the bottom of active layer are 0.1 – 1.8 °C warmer than the recorded (2011 - 2014) ground temperature (at 0.5 m). Air temperature data is available only for two sites (SV1 and KC1) within SNWR. The average annual air temperature records show 2.6 and 2.9 °C increase at the two sites during 2012 – 2014. We believe as per these temperature observations the modeled ground temperature would be very close to the actual ground temperature for the modeled time period (2000-2009) at majority of the sites.

The difference in the observed air temperature and soil temperature (50 cm) and the difference in the CRU air temperature and modeled ground temperature at the bottom of active layer should be roughly comparable; if they differ it must be due to modeling error. We found a mean difference of 0.41 ± 1.3 °C; it means that the modeled ground temperature at the bottom of active layer is colder than the observed ground temperature at 50 cm. The average ground temperature at 50 cm would typically be higher than the temperature at the top of permafrost (where active layer is thicker than 50 cm) as thermal offset continues below 50 cm. So if the observed ground temperatures were from the top of permafrost, the difference between observed temperature and modeled temperature at the bottom of active layer would be less than 0.41 °C.

Also, the difference in observed and modeled ground temperature can be attributed to three major factors: 1) scale, 2) ground condition, and 3) snow depth. 1) We compared the ground temperature recorded at a single location with modeled (average) ground temperature that used climate input derived from a global climate dataset of $0.5^\circ \times 0.5^\circ$ latitude-longitude resolution. 2) The difference in ground condition, type and thickness of surface organic layer and seasonal moisture variation, between what really exists at the monitoring site vs. the generalized ecotype used as the model input. 3) The snow depth at the monitoring site could be significantly different than the snow depth estimated by the model because our model uses a simple linear approach to convert the winter precipitation to snow depth by assuming a fixed density of the snow which depends on the type of snow at that location. The snow algorithm does not model the effect of wind on snow distribution.

Also, the precipitation inputs are from km scale climate datasets. So the true snow depth and density at a point location can be different than what used as the model input for that location.

Table 4: Comparison of recorded air and ground temperatures at the NPS and Selawik National Wildlife Refuge (SNWR) climate stations with CRU air temperature and modeled ground temperature at the surface and bottom of active layer. Average annual soil temperature: NPS stations, 2013 – 2015 (after Swanson, 2016); (SNWR) stations, 2012 – 2014 (Romanovsky and Cable, 2014). The stations with one year of data (Aug. 2012 – Jul. 2013) are bold and italicized.

NPS Unit	Station	Recorded Air Temp, °C	Recorded Soil Temp ₅₀ (Soil Temp ₇₅), °C	Air Temp CRU °C	Modeled Ground Temp at the bottom of ALT °C	Modeled active layer thickness m
BELA	Devil Mountain	-3.8	-3.0	-3.9	-3.9	0.76
	Ella Creek	-4.0	-2.3	-4.5	-4.0	0.71
	HooDoo Hills	-3.8	-3.4	-4.2	-3.0	0.57
	Serpentine Hot Springs	-2.8	+0.1	-3.8	-3.0	0.48
CAKR	Mt. Noak	-2.1	-1.5(-1.5)	-3.7	-3.8	0.81
	Tahinichok	-3.1	-3.1(-2.8)	-4.3	-4.2	0.74
GAAR	Chimney Lake	-4.5	-3.2(-3.5)	-5.1	-5.2	0.70
	Killik Pass	-7.0	-4.2	-6.6	-5.5	0.69
	Pamichtuk Lake	-4.8	-5.0	-4.8	-4.7	0.76
	Ram Creek	-5.2	-4.2	-5.0	-4.7	0.65
KOVA	Kavet Creek	-2.4	+1.6	-3.2	-2.6	0.59
NOAT	Asik	-2.3	-2.4	-4.1	-3.9	1.10
	Howard Pass	-6.0	-6.1	-8.4	-7.5	0.65
	Imelyak	-4.8	-3.9	-4.4	-4.1	0.75
	Kaluich	-5.7	-3.2	-4.0	-3.2	0.50
	Sisiak	-4.6	-3.9(-4.0)	-8.0	-6.7	1.10
SNWR	SS-WS		-2.6	-3.0	-2.5	0.73
	STS		-4.1	-3.0	-2.5	0.60
	SS-AWS		-2.6	-3.0	-2.5	0.60
	S2-PB		-2.5	-4.0	-2.6	0.83
	S3-TM		-2.2	-4.1	-2.9	0.53
	S3-AWS		+0.2	-4.2	-3.4	0.54
	S3-BEW		-1.4	-4.2	-3.5	0.54
	S3-LSF		-3.8	-4.1	-3.6	0.62
	KCF		-1.6**	-4.1	-2.0	0.85
	KCT		-3.1*	-4.1	-3.3	0.53
	KC1	-4.6	-4.6	-4.1	-3.3	0.53
	SV1	-4.4	-4.7	-4.0	-2.9	0.51
	S4-AWS		-0.6	-3.9	-3.6	0.49
	S4-LS		-2.1	-3.9	-3.6	0.49
	S4-TM		-3.3	-3.9	-3.6	0.49
	S1-BF		+1.3***	-3.9	-1.3	0.92
	S1-WS		0.0	-4.3	-3.5	0.53

*Two year average (Aug. 2011 – July 2013)

**Three years average (Aug. 2011 – July 2014)

***One year average (Aug. 2013 – July 2014)

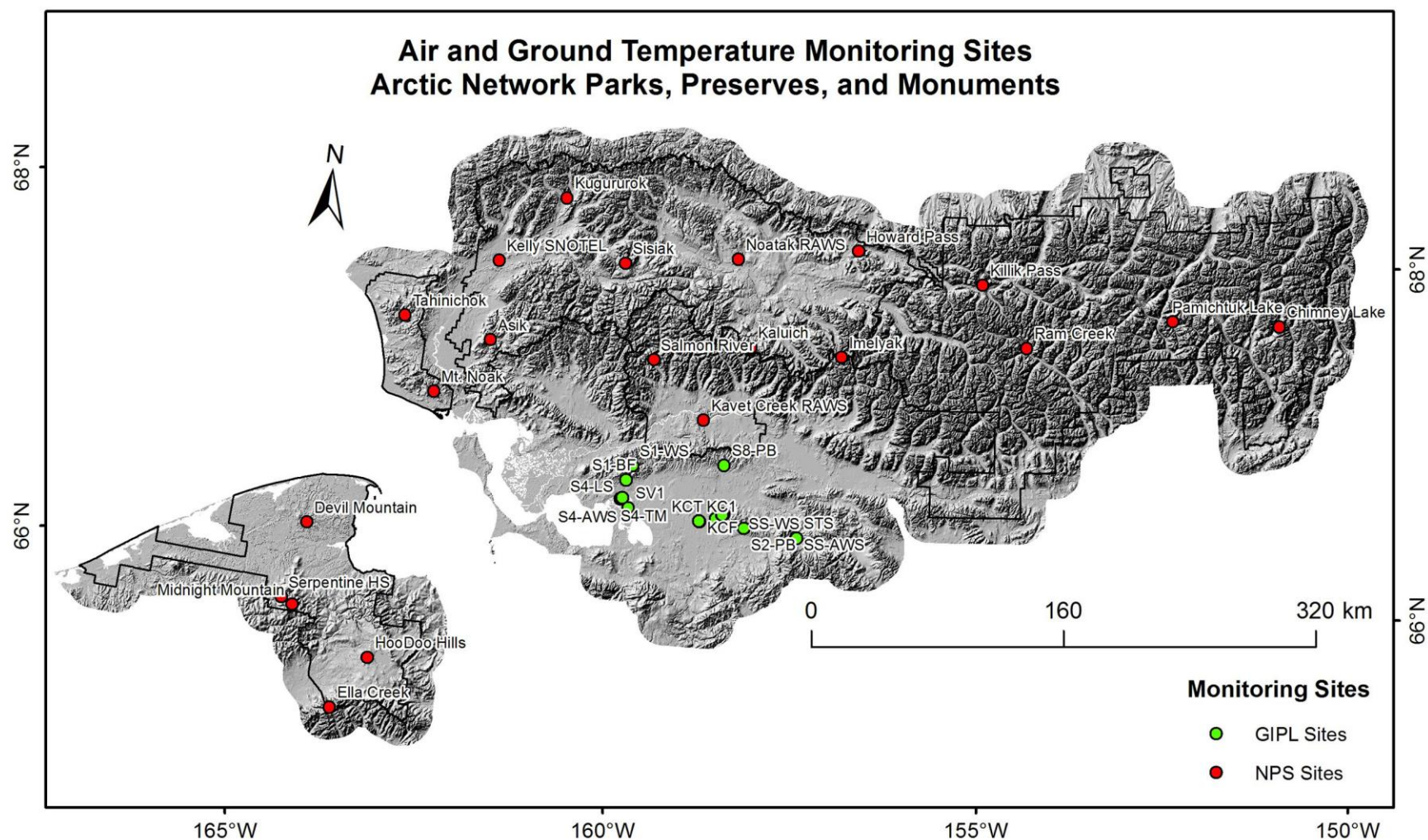


Figure 11. Locations of climate and soil temperature monitoring sites plotted on a Hillshade Model. The Hillshade Model is derived from 2-arc-second (~60 m) spatial resolution National Elevation Dataset Digital Elevation Model. GIPL: Geophysical Institute Permafrost Laboratory; NPS: National Park Service.

6. Deliverables

Deliverables for this project include the following raster (.tif and .png) and legend (.lyr) data files:

- Mean decadal ground temperature, at the bottom of active layer, raster (ARCN-MDGT-####-##.tif) layers of Arctic Network Parks, Preserves and Monuments for the time periods 1950-1959, 2000-2009, 2051-2060, and 2091-2100.
- Mean decadal ground temperature legend (ARCN-MDGT-Legend.lyr) file.
- Mean decadal ground temperature, at the bottom of active layer, maps (ARCN-MDGT-####-##.png) for the time periods 1950-1959, 2000-2009, 2051-2060, and 2091-2100.
- Active-layer thickness raster layers (ARCN-ALT-####-##.tif) of Arctic Network Parks, Preserves and Monuments for the time periods 1950-1959, 2000-2009, 2051-2060, and 2091-2100. For cell where permafrost is present immediately below the active layer, the cell value (or active layer thickness) is positive. For cell where permafrost is absent or talik is present immediately below the active layer, the cell value is negative.
- Active-layer thickness legend (ARCN-ALT-Legend.lyr) file.
- Active-layer and talik maps (ARCN-ALT-####-##.png) for the time periods 1950-1959, 2000-2009, 2051-2060, and 2091-2100.

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Appendix A. Tables of input thermal properties for Ecotype, Soil landscape, and Snow Classes

After we masked out the water, permanent snow, shadow, and human modified classes within ARCN (Jorgenson et al., 2009), the remaining thirty-seven landcover classes are used as ecotype input to the model. In the absence of thermal diffusivity data for surface organic layer we prescribed these values based on our permafrost modeling experience in other parts of Alaska (Table A1).

Jorgenson et al. (2009) identified the soil type associated with each ecotype. So instead of creating a new soil map we used the ecotype map to prescribe the soil thermal properties according to Yershov (1984)(Table A2).

We linked the snow classes identified by Sturm et al. (1995) with ecotypes and prescribed the snow density accordingly to each ecotype (Table A3).

Table A1. Thermal diffusivity values by ecotype

Ecotype no.	Ecotype name	Thawed diffusivity (m ² /s)	Frozen diffusivity (m ² /s)	Thickness (m)
1	Alpine Wet Sedge Meadow	1.3e ⁻⁷	2.6e ⁻⁷	0.07
2	Alpine Acidic Barrens	2.5e ⁻⁷	5.0e ⁻⁷	0.02
3	Alpine Dryas Dwarf Shrub	1.0e ⁻⁷	2.0e ⁻⁷	0.03
4	Alpine Alkaline Barrens	2.5e ⁻⁷	5.0e ⁻⁷	0.04
5	Alpine Mafic Barrens	2.5e ⁻⁷	5.0e ⁻⁷	0.00
6	Alpine Ericaceous Dwarf Shrub	1.0e ⁻⁷	2.0e ⁻⁷	0.035
7	Coastal Brackish Sedge-Grass Meadow	1.2e ⁻⁷	2.4e ⁻⁷	0.15
8	Lowland Ericaceous Shrub Bog	1.1e ⁻⁷	2.2e ⁻⁷	0.51
9	Lowland Sedge Fen	1.0e ⁻⁷	1.2e ⁻⁷	0.39
10	Lowland Birch-Ericaceous-Willow Low Shrub	3.0e ⁻⁷	4.0e ⁻⁷	0.16
11	Lowland Black Spruce Forest	1.5e ⁻⁷	1.7e ⁻⁷	0.16
12	Lowland Alder Tall Shrub	1.1e ⁻⁷	2.2e ⁻⁷	0.15
13	Lowland Willow Low Shrub	1.0e ⁻⁷	1.2e ⁻⁷	0.16
14	Riverine Dryas Dwarf Shrub	1.0e ⁻⁷	1.2e ⁻⁷	0.03
15	Riverine Barrens	2.0e ⁻⁷	2.2e ⁻⁷	0.02
16	Riverine Poplar Forest	2.0e ⁻⁷	4.0e ⁻⁷	0.03
17	Riverine White Spruce-Poplar Forest	1.3e ⁻⁷	1.5e ⁻⁷	0.035
18	Riverine White Spruce-Willow Forest	1.3e ⁻⁷	5.2e ⁻⁷	0.06
19	Riverine Willow Low Shrub	2.0e ⁻⁷	4.0e ⁻⁷	0.03
20	Riverine Alder or Willow Tall Shrub	2.0e ⁻⁷	2.2e ⁻⁷	0.09

Ecotype no.	Ecotype name	Thawed diffusivity (m ² /s)	Frozen diffusivity (m ² /s)	Thickness (m)
21	Riverine Birch-Willow Low Shrub	1.6e ⁻⁷	1.8e ⁻⁷	0.04
22	Riverine Wet Sedge Meadow	1.4e ⁻⁷	1.6e ⁻⁷	0.10
23	Upland Willow Low Shrub	1.4e ⁻⁷	2.8e ⁻⁷	0.095
24	Upland Dwarf Birch-Tussock Shrub	1.0e ⁻⁷	1.2e ⁻⁷	0.22
25	Upland Birch-Ericaceous-Willow Low Shrub	1.6e ⁻⁷	1.8e ⁻⁷	0.09
26	Upland Sedge-Dryas Meadow	1.2e ⁻⁷	2.4e ⁻⁷	0.07
27	Upland Alder-Willow Tall Shrub	1.8e ⁻⁷	2.0e ⁻⁷	0.09
28	Upland Birch Forest	1.9e ⁻⁷	3.8e ⁻⁷	0.04
29	Upland Spruce-Birch Forest	1.4e ⁻⁷	2.8e ⁻⁷	0.13
30	Upland White Spruce Forest	1.5e ⁻⁷	1.7e ⁻⁷	0.09
31	Upland White Spruce-Lichen Woodland	1.2e ⁻⁷	1.4e ⁻⁷	0.02
32	Upland Sandy Barrens	1.0e ⁻⁷	1.2e ⁻⁷	0.00
33	Coastal Barrens	1.0e ⁻⁷	2.0e ⁻⁷	0.00
34	Coastal Crowberry Dwarf Shrub	1.0e ⁻⁷	2.0e ⁻⁷	0.01
35	Lowland Sedge-Dryas Meadow	1.0e ⁻⁷	1.2e ⁻⁷	0.39
36	Coastal Dunegrass Meadow	1.0e ⁻⁷	2.0e ⁻⁷	0.03
37	Upland Mafic Barrens	2.5e ⁻⁷	5.0e ⁻⁷	0.035

Table A2. Soil thermal properties by ecotype.

No.	Landtype association	Thawed heat capacity (MJ/m ³ .K)	Frozen heat capacity (MJ/m ³ .K)	Thawed thermal conductivity (W/m.K)	Frozen thermal conductivity, (W/m.K)	Volumetric water content, (%)
1	Alpine Wet Sedge Meadow	2.0	1.6	1.2	2.2	0.20
2	Alpine Acidic Barrens	2.0	1.95	1.85	1.9	0.05
3	Alpine Dryas Dwarf Shrub	2.0	1.6	1.2	2.2	0.10
4	Alpine Alkaline Barrens	2.0	1.6	1.2	2.2	0.05
5	Alpine Mafic Barrens	2.0	1.6	1.2	2.2	0.05
6	Alpine Ericaceous Dwarf Shrub	2.0	1.6	1.5	2.2	0.10
7	Coastal Brakish Sedge-Grass Meadow	2.2	2.0	1.2	1.8	0.20
8	Lowland Ericaceous Shrub Bog	2.0	1.6	1.0	2.0	0.30
9	Lowland Sedge Fen	2.0	1.6	1.0	2.0	0.20
10	Lowland Birch-Ericaceous-Willow Low Shrub	2.2	2.0	1.05	1.95	0.30
11	Lowland Black Spruce Forest	2.2	2.0	1.05	1.95	0.30
12	Lowland Alder Tall Shrub	2.2	2.0	1.05	1.95	0.20
13	Lowland Willow Low Shrub	2.2	2.0	1.05	1.95	0.20
14	Riverine Dryas Dwarf Shrub	2.2	2.0	1.35	1.65	0.15
15	Riverine Barrens	2.2	2.0	1.35	1.65	0.05
16	Riverine Poplar Forest	2.2	1.8	1.35	1.95	0.25
17	Riverine White Spruce-Poplar Forest	2.2	1.8	1.35	1.95	0.25
18	Riverine White Spruce-Willow Forest	2.2	1.8	1.35	1.95	0.25
19	Riverine Willow Low Shrub	2.2	2.0	1.35	1.65	0.15
20	Riverine Alder or Willow Tall Shrub	2.2	2.0	1.35	1.65	0.20
21	Riverine Birch-Willow Low Shrub	2.2	1.8	1.35	1.85	0.35
22	Riverine Wet Sedge Meadow	2.2	1.8	1.35	1.85	0.45
23	Upland Willow Low Shrub	1.9	1.6	1.2	2.2	0.10
24	Upland Dwarf Birch-Tussock Shrub	2.2	1.8	1.45	1.85	0.40

No.	Landtype association	Thawed heat capacity (MJ/m ³ .K)	Frozen heat capacity (MJ/m ³ .K)	Thawed thermal conductivity (W/m.K)	Frozen thermal conductivity, (W/m.K)	Volumetric water content, (%)
25	Upland Birch-Ericaceous-Willow Low Shrub	1.9	1.7	1.2	1.9	0.30
26	Upland Sedge-Dryas Meadow	1.9	1.6	1.2	2.2	0.10
27	Upland Alder-Willow Tall Shrub	2.0	1.8	1.45	1.85	0.20
28	Upland Birch Forest	2.0	1.8	1.45	1.85	0.20
29	Upland Spruce-Birch Forest	2.0	1.8	1.45	1.85	0.15
30	Upland White Spruce Forest	1.8	1.75	1.55	1.65	0.20
31	Upland White Spruce-Lichen Woodland	1.9	1.8	1.8	1.9	0.10
32	Upland Sandy Barrens	1.9	1.8	1.8	1.9	0.03
33	Coastal Barrens	2.2	2.0	1.6	1.8	0.20
34	Coastal Crowberry Dwarf Shrub	2.0	1.9	1.8	1.9	0.15
35	Lowland Sedge-Dryas Meadow	2.2	2.0	1.05	1.95	0.15
36	Coastal Dunegrass Meadow	2.0	1.9	1.8	1.9	0.15
37	Upland Mafic Barrens	2.0	1.6	1.2	2.2	0.05

Table A3. Snow density by ecotype

Class no.	Class name	Density of fresh snow (kg/m³)	Maximum density of snow (kg/m³)
1	Alpine Wet Sedge Meadow	120	400
2	Alpine Acidic Barrens	120	400
3	Alpine Dryas Dwarf Shrub	110	400
4	Alpine Alkaline Barrens	100	400
5	Alpine Mafic Barrens	110	400
6	Alpine Ericaceous Dwarf Shrub	110	400
7	Coastal Brakish Sedge-Grass Meadow	115	287
8	Lowland Ericaceous Shrub Bog	90	225
9	Lowland Sedge Fen	100	300
10	Lowland Birch-Ericaceous-Willow Low Shrub	100	300
11	Lowland Black Spruce Forest	100	250
12	Lowland Alder Tall Shrub	70	175
13	Lowland Willow Low Shrub	70	175
14	Riverine Dryas Dwarf Shrub	80	200
15	Riverine Barrens	120	300
16	Riverine Poplar Forest	80	200
17	Riverine White Spruce-Poplar Forest	70	175
18	Riverine White Spruce-Willow Forest	120	300
19	Riverine Willow Low Shrub	70	175
20	Riverine Alder or Willow Tall Shrub	70	175
21	Riverine Birch-Willow Low Shrub	120	300
22	Riverine Wet Sedge Meadow	120	300
23	Upland Willow Low Shrub	70	175
24	Upland Dwarf Birch-Tussock Shrub	120	350
25	Upland Birch-Ericaceous-Willow Low Shrub	100	300
26	Upland Sedge-Dryas Meadow	110	400
27	Upland Alder-Willow Tall Shrub	100	300
28	Upland Birch Forest	100	250
29	Upland Spruce-Birch Forest	105	262
30	Upland White Spruce Forest	70	175
31	Upland White Spruce-Lichen Woodland	70	175
32	Upland Sandy Barrens	70	175
33	Coastal Barrens	135	337
34	Coastal Crowberry Dwarf Shrub	130	325

Class no.	Class name	Density of fresh snow (kg/m³)	Maximum density of snow (kg/m³)
35	Lowland Sedge-Dryas Meadow	110	275
36	Coastal Dunegrass Meadow	110	275
37	Upland Mafic Barrens	100	250

Appendix B. The GIPL Model for Estimation of Temporal and Spatial Variability of the Active-Layer Thickness and Mean Annual Ground Temperatures

Sergey S. Marchenko and Vladimir E. Romanovsky

The Geophysical Institute Permafrost Lab (GIPL) model was developed specifically to assess the effect of a changing climate on permafrost. The GIPL 1.0 model is a quasi-transitional, spatially distributed, equilibrium model for calculating the active-layer thickness and mean annual ground temperature. It accounts effectively for the effects of snow cover, vegetation, soil moisture, and soil thermal properties. It allows for the calculation of maximum active-layer thickness (ALT) and mean annual ground temperatures (MAGT) at the bottom of the active layer. Our approach to determine the ALT and MAGT is based on an approximate analytical solution that includes freezing/thawing processes and provides an estimation of thermal offset due to the difference in frozen and thawed soil thermal properties (Kudryavtsev et al. 1974). It uses the idea of applying the Fourier temperature wave propagation theory to a medium with phase transitions, such as freezing/thawing ground. Application of this approach resulted in the discovery of the thermal offset and an understanding of the laws that govern the dynamics of the ground thermal regime. These discoveries led to an understanding of the effects that the thermal properties of the ground have upon the MAGT and ALT, and how periodically (seasonally) varying climatic parameters affect permafrost dynamics. The output parameters of this method are given as annual averages. Input and output parameters are listed in Table B1. The effect of geothermal heat flux is ignored because it is considered to have a minimal impact on the MAGT and ALT values. For the areas with permafrost, the MAGT is the same as a mean annual temperature at the permafrost table (upper surface of permafrost). Where permafrost is absent, the MAGT is the mean annual temperature at the bottom of seasonally-frozen layer.

Mean Annual Ground Temperature at the Bottom of the Active Layer

Throughout the years, simplified analytical solutions for temperature modeling in the ALT have been applied for structural engineering and other practical purposes. Most of these methods have been based on the Stefan solutions, and they do not yield a good level of accuracy (Romanovsky and Osterkamp 1997). It was determined that the best method for computation of the ALT and MAGT was a modified version of Kudryavtsev's approach (Romanovsky and Osterkamp 1997). This approach is the core of the GIPL 1.0 model, which treats the complex system including air, snow cover, surface vegetation, and active layer, as a set of individual layers with different thermal properties (Fig. B1). In the regions of Alaska and East-Siberia that were analyzed, surface vegetation consists of lichens, grass, and moss (sphagnum or feather mosses) (Brown and Kreig 1983, Feldman et al. 1988). The upper level of vegetation consisting of trees and shrubs is not considered in the model. This upper level vegetation affects the thickness and density of the snow cover, along with the amount of solar radiation reaching the ground surface. The model takes into account only low-level vegetation (surface vegetation) that is less than 0.5 meter high, because the information about higher vegetation such as trees and tall shrubs is already incorporated into the monthly surface air temperature data, which were used as input data in the model.

Table B1a. Model input variables.

Input Variables	Notation	Units
Seasonal range of air temperature variations (amplitude)	A_a	°C
Mean annual air temperature	T_a	°C
Snow Water Equivalent	SWE	m
Height of vegetation cover	H_v	m
Thermal diffusivity of vegetation in frozen state	D_{vf}	m^2/s
Thermal diffusivity of vegetation in thawed state	D_{vt}	m^2/s
Thermal conductivity of frozen soil	K_f	$W/(m \cdot K)$
Thermal conductivity of thawed soil	K_{th}	$W/(m \cdot K)$
Volumetric water content	VWC	Fraction of 1
Volumetric latent heat of ice fusion	334e6	J/m^3
Volumetric heat capacity of snow cover	C_{sn}	J/m^3K
Volumetric heat capacity of thawed ground	C_{th}	J/m^3K
Volumetric heat capacity of frozen ground	C_f	J/m^3K

Table B1b. Model output variables.

Output Variables	Notation
Correction to air temperature accounting for snow cover effect, °C	ΔT_{sn}
Correction to air temperature amplitude accounting for snow cover effect, °C	ΔA_{sn}
Correction to air temperature accounting for vegetation cover, °C	ΔT_v
Correction to air temperature amplitude accounting for vegetation cover, °C	ΔO_v
Seasonal range of temperature variations at the ground surface, °C	A_{gs}
Mean annual temperatures at the ground surface, °C	T_{gs}
Snow density, kg/m^3	ρ_{sn}
Snow thermal conductivity, $W/(m \cdot K)$	K_{sn}
Thermal offset, °C	ΔT_k
Mean annual soil surface temperature, °C	MAGST
Mean annual soil temperature at the bottom of ALT, °C	MAGT
Active-layer thickness, m	ALT

Snow cover plays an important role in heat exchange processes between the surface of the ground and the atmosphere. The warming effect of the snow cover has been calculated using approximate formulas derived by A. Lachenbruch (1959) and V. Romanovsky (1987), which incorporate ground properties, vegetation cover, and their respective effect on heat turnovers through the snow. Heat turnovers are defined as the quantity of incident heat (during the heating period), or out-going heat (during the cooling period) throughout the media over a given time interval (usually half year increments). Thus, the heat turnover is

$$Q = \int_{t_1}^{t_2} q(t) dt ,$$

where t_1 and t_2 are the times when the regime changes from ground heating to ground cooling, or from cooling to heating periods, and $q(t)$ is the heat flux through the ground surface as a function of time.

Our model takes into account only conductive heat transfer through the surface vegetation (lichens, moss, and grasses). The rate of heat turnover between the ground and atmosphere has been shown to have a strong dependence on vegetation cover. In summer, surface vegetation prevents solar radiation from penetrating into the ground and warming it. In wintertime, surface vegetation acts as an insulator and keeps heat in the ground.

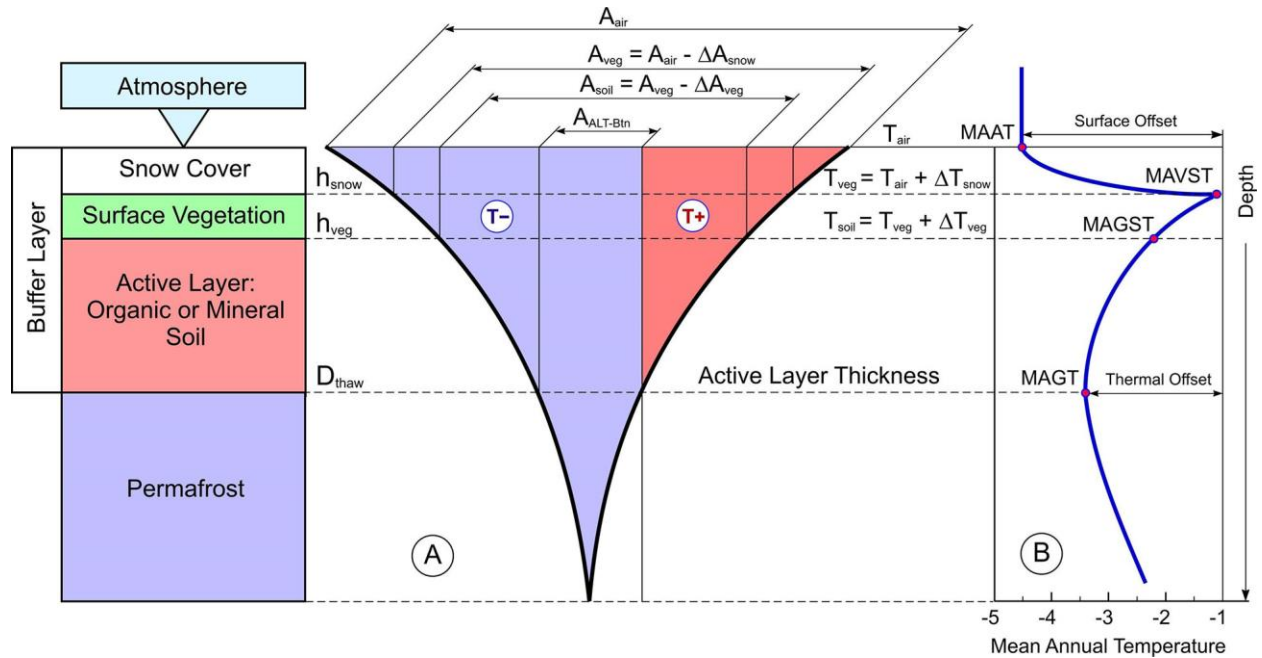


Figure B1. The GIPL 1.0 model conceptual diagram (A) and schematic profile of mean annual temperature through the lower atmosphere, active layer and upper permafrost (B). Acronyms: MAAT (Mean Annual Air Temperature), MAGST (Mean Annual Ground Surface Temperature), MAGT (Mean Annual Ground Temperature), ALT (Active-Layer Thickness).

The seasonal freezing and thawing cycles cause changes in the thermal properties of soils within the active layer. Typically, this effect leads to a decrease in MAGTs with depth within the active layer. The thermal offset is defined as the difference between the mean annual temperature MAGT at the bottom of the active layer and the mean annual temperature at the ground surface (Kudryavtsev et al. 1974, Goodrich 1978, Burn and Smith 1988). The thermal offset depends on soil moisture content and thermal properties, and has the most pronounced effect within a peat layer (Marchenko and Romanovsky 2007). The analytical equation to estimate the thermal offset was given by Kudryavtsev (1981) (no derivation was published), and was formally derived by V. Romanovsky (Romanovsky and Osterkamp 1995).

The approach to simulate MAGT in the GIPL 1.0 model is the consecutive layer-by-layer introduction of thermal effects of snow, ground surface vegetation, and the soils within the active layer on mean annual temperatures and seasonal amplitudes at each considered level (snow surface, vegetation surface, and ground and permafrost table). However, this scheme is not totally additive because the estimation of the impact of each new layer already includes the thermal effects of all layers above it. Moreover, in this approach, the thermal effect of snow reflects the thermal properties and temperature field dynamics in the subsurface layers through the heat turnover estimation. As a result, this approach takes into account some negative and positive feedbacks between designated layers in the “atmosphere-permafrost” system.

The Active-Layer Thickness

Calculation of the ALT is the final step in the GIPL 1.0 model (Romanovsky and Osterkamp 1997). The formula was derived for homogeneous ground, but in actuality, even if the soil properties are the same throughout the active layer, the moisture content or mode of heat flow may vary significantly. This can make the active layer inhomogeneous with regard to its thermal properties. Also, the model does not take into account unfrozen water, which can exist in the frozen active layer even at temperatures below zero Celsius, and has a significant effect on the ground's thermal properties (Williams 1964, Williams and Smith 1989). The assumption of a periodically steady state temperature regime seems to be a good approximation when applied to the annual temperature cycle, which varies from year to year (Romanovsky and Osterkamp 1997). Considering the advantages along with the shortcomings, the GIPL 1.0 model appears to give a good representation of the coupling between permafrost and the atmosphere. When applied to long-term (decadal and longer time scale) averages, this approach shows an accuracy of +0.2-0.4°C for the mean annual ground temperatures and +0.1 – 0.3 m for the active-layer thickness calculations (Sazonova and Romanovsky 2003). The relative errors do not exceed 32% for the ALT calculations, but typically they are between 10 and 25%. The differences in 0.2-0.4°C between calculated and measured mean annual ground temperatures were obtained for the long-term multi-year average estimations.

The Input Dataset

At the present stage of development, the GIPL 1.0 model is combined with ArcGIS to facilitate preparation of input parameters (climate forcing from observations or from Global or Regional Climate Models) and visualization of simulated results in a form of digital maps (Fig. B2).

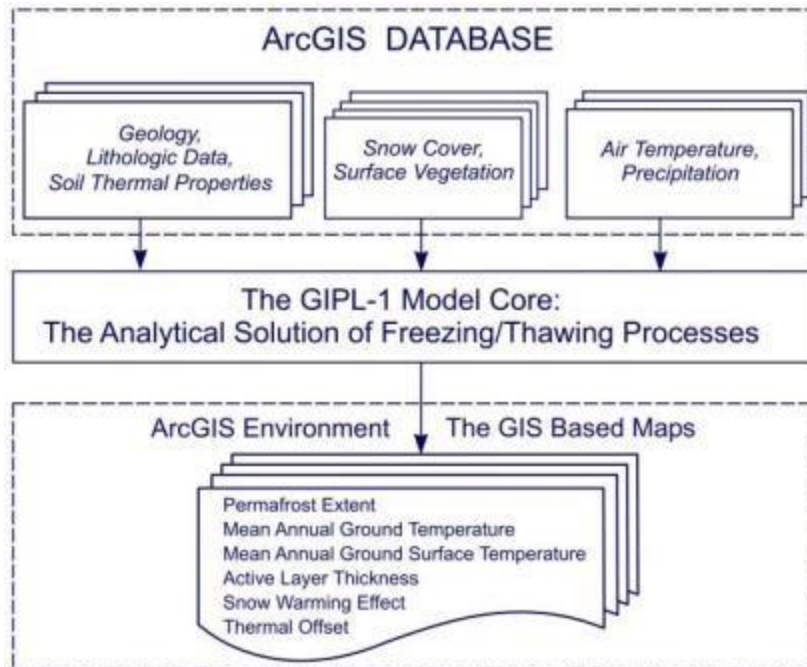


Figure B2. A schematic representation of integration of GIS with GIPL 1.0 model.

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