

Permafrost Modeling in Alaskan National Parklands

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1. Introduction

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 freezing, such that relatively minor warming could destabilize it entirely, or 2) it contains ice-rich material near the surface that could thaw with climatic warming, leading to major reconfiguration of the landscape. Thaw of permafrost could have many consequences, such as drainage of lakes, creation of new ponds, soil erosion, slumps, siltation of streams and lakes, release of greenhouse gasses, and changes in soil wetness and nutrient supplies.

Permafrost is a subsurface feature that is difficult to observe and map directly. Existing information about the extent and temperature of permafrost in NPS units is weak due to the lack of borehole observations on NPS lands. Modeling of permafrost extent has proven very useful for extrapolating between widely spaced boreholes where direct observations are made. Permafrost distribution and the thickness of the active-layer (the surface layer above permafrost that thaws each summer and refreezes in winter) can be modeled, given sufficient data about soil and ground properties, vegetation, topography, atmospheric climate, and soil temperatures. The same models used to map current permafrost distribution and active-layer thickness can be used to predict the future state of permafrost by using projected future climate data and scenarios.

University of Alaska Fairbanks Permafrost Laboratory (GIPL) has developed a model, GIPL 1.0 "Spatially Distributed Model of Permafrost Dynamics in Alaska", that has successfully mapped permafrost distribution and active-layer thickness at a coarse scale for the State of Alaska. The GIPL 1.0 model gives a good representation of the coupling between permafrost and the atmosphere. It shows an accuracy of $\pm 0.2 - 0.4$ °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 & Romanovsky, 2003). As a part of its inventory and monitoring program, the NPS has obtained or is in the process of gathering data that could be used to make improved runs of the GIPL 1.0 model for NPS units in Alaska.

The goal of this project is to facilitate cooperation between NPS and GIPL to obtain improved 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 (2050 and 2100).

We are in the process of converting NPS environmental (GIS) data (soil and vegetation maps) into a format that is compatible to the GIPL model. We are using these data sets, along with inputs developed previously (modeled current and future climate scenarios obtained from global circulation models), to create maps of permafrost extent and temperature, and active-layer thickness, for the recent past (1950), the present, and the future (2050 and 2100). We will use the NPS (climate stations) soil temperature data to assess the accuracy of Mean Annual Ground Surface Temperature (MAGST, °C) and Mean Annual Ground Temperature (MAGT, °C) calculations by the GIPL model. We will use the permafrost presence/absence and summer

thaw depth data of the sites field surveyed by ABR Inc. to assess the overall accuracy of permafrost and active-layer thickness (ALT) distribution maps produced by the GIPL model.

2. GIPL 1.0 Model

It is a quasi-transitional, spatially distributed, equilibrium model for calculating the active-layer thickness and mean annual ground temperature. It accounts for the effects of snow cover, vegetation, soil moisture and soil thermal properties (Figure 1). See Romanovsky and Marchenko (2012) for details of this model with all input and output parameters.

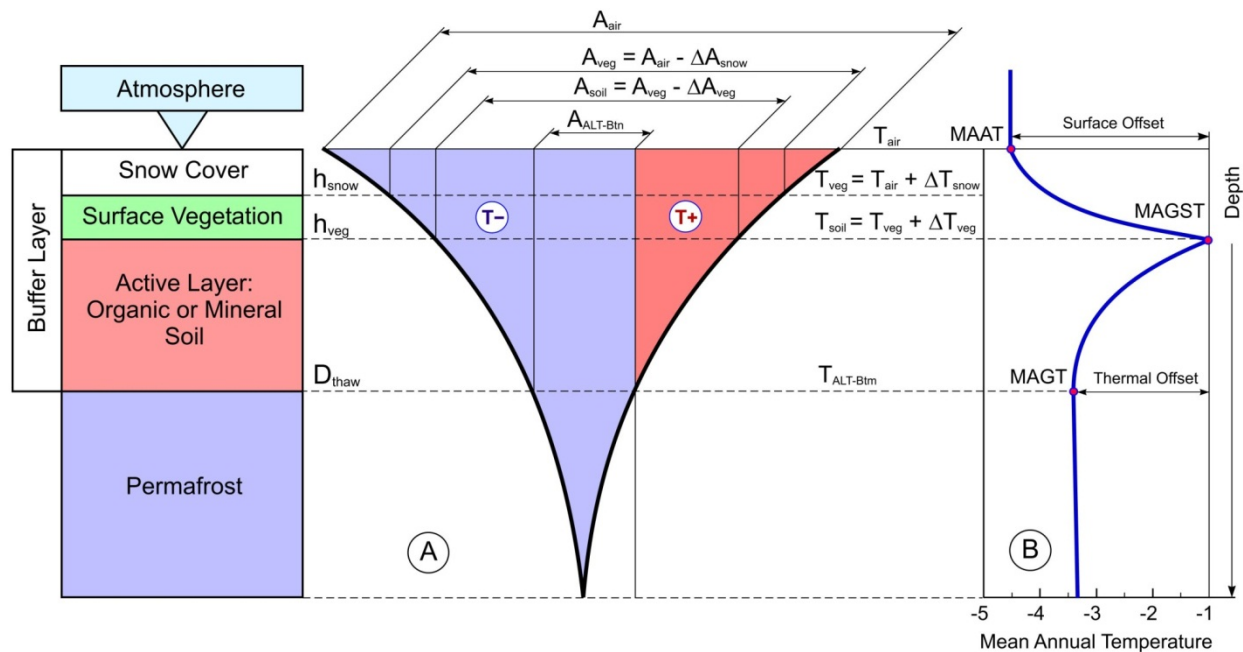


Figure 1: The GIPL 1 model conceptual diagram (A) and the schematic profile of mean annual temperature through the lower atmosphere, active-layer and upper permafrost (B) (Romanovsky and Marchenko, 2012).

3. Input data

3.1. Climate data

Historical (1901 – 2009) monthly average air temperature (°C) and total precipitation (mm) from CRU TS 3.1 climate data, downscaled to 771 m (SNAP, 2012)

Projected (2001 - 2100) monthly average air temperature (°C) and precipitation (mm) from 5 AR4 GCMs (A1B scenario) that perform best across Alaska and the Arctic, downscaled to 771 m (SNAP, 2012).

The 5 AR4 GCMs are:

ccma_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

3.2. *Snow data*

Snow was classified based on the physical properties of the snow (depth, density, thermal conductivity, number of layers, degree of wetting). Each class was then numerically related to climate using three variables (precipitation, wind, and air temperature). A vegetation proxy was used for wind data: tall vegetation equals low wind, short vegetation equals high wind (Sturm et al., 1995). Nine out of the twelve snow classes identified in Alaska based on ecotype (Appendix 1) are present in the Denali National Park & Preserve. The following snow properties are used in the model:

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

Snow cover plays an important role in the heat exchange processes between the land surface and the atmosphere. The warming effect of the snow cover has been 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 media over a given time interval (usually half year increments). The model takes into account only conductive heat transfer through different mediums.

3.3. *Ecotype data*

Vegetation (Ecotype) classes from North America Land Cover Characteristics Data Base Version 2.0 were used in this study (http://edc2.usgs.gov/glcc/nadoc2_0.php). The land covers were classified using multitemporal AVHRR data combined with other ancillary data sets. Seven out of the twelve ecotypes identified in Alaska (Appendix 1) are present in the Denali National Park & Preserve. For other National parks, we will use the land cover (Ecotype) maps produced by ABR Inc. as ecotype input to the GIPL model. The following ecotype properties are used in the model:

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

In the regions of Alaska, the surface vegetation consists of lichens, grass, and moss (sphagnum or feathered mosses). 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 m 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.

3.4. Soil data

Soil classes from the State Surficial Geology Map of Alaska (http://www.inforain.org/copperriver/content/data_and_software/metadata/geology/surfgeol.htm) and the USDA Soil Survey of Denali National Park Area (Clark and Duffy, 2006) were used. Sixteen out of the twenty six soil classes identified in the State Surficial Geology Map of Alaska (Appendix 1) are present in the Denali National Park & Preserve. Also, we will use the detailed (improved) soil maps (e.g. USDA soil survey map and maps produced by ABR Inc.) to make refined runs of the GIPL model. To able to do so, we will have to prescribe soil thermal properties to each soil unit identified in the detailed soil maps. The following soil properties are used in the model:

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

4. Outputs

Active-layer thickness (ALT) in meters.

Mean annual ground surface temperature (MAGST) in $^{\circ}\text{C}$.

Mean annual ground temperature (MAGT) in $^{\circ}\text{C}$ i.e. temperature at the bottom of the active-layer or seasonally frozen layer.

5. Results

5.1. Denali National Park and Preserve

Climate data from Global Circulation Models (GCMs), vegetation data from North America Land Cover Characteristics Data Base Version 2.0, soil data from State Surficial Geology Map of Alaska and USDA Denali Soil Map, and snow data from Sturm et al. (1995) were used as input to the GIPL 1.0 model to map permafrost, its temperature and active-layer thickness distribution in the Denali National Park and Preserve for the decades 1951-60 (past), 2001-2010 (present), 2051-60 (future), and 2091-2100 (future). There are 152 soil classes identified in the Denali Park by USDA soil survey (Clark and Duffy, 2006). We reclassified the 152 USDA soil classes into 16 generalized soil classes (identified in State Surficial Geologic Map of Alaska) for which the required thermal properties for GIPL model run are already known. We used the reclassified

soil map (with 16 soil units) as input to the current model runs. The results of these model runs are presented in the following pages.

The ALT and MAGT model outputs are color coded using ArcGIS program and presented here. The ALT coded in shades of blue represent seasonal freezing i.e. either there is a talik (an unfrozen layer) between seasonally frozen layer and permafrost (at further depth) or no permafrost below seasonally frozen layer (Figure 2, 4, 6, and 8). The ALT coded in shades of red represent seasonal thawing i.e. permafrost is present right beneath the active-layer. The MAGT maps are also coded in shades of red and blue; shades of red represent $MAGT > 0^{\circ}\text{C}$ and shades of blue represent $MAGT < 0^{\circ}\text{C}$. Since MAGT is mean annual ground temperature at the bottom of the active-layer or seasonally frozen layer, the shades of red show an unfrozen layer beneath seasonally frozen layer (i.e. permafrost may or may not be present at further depth) and the shades of blue show permafrost right beneath the active-layer (Figure 3, 5, 7, and 9).

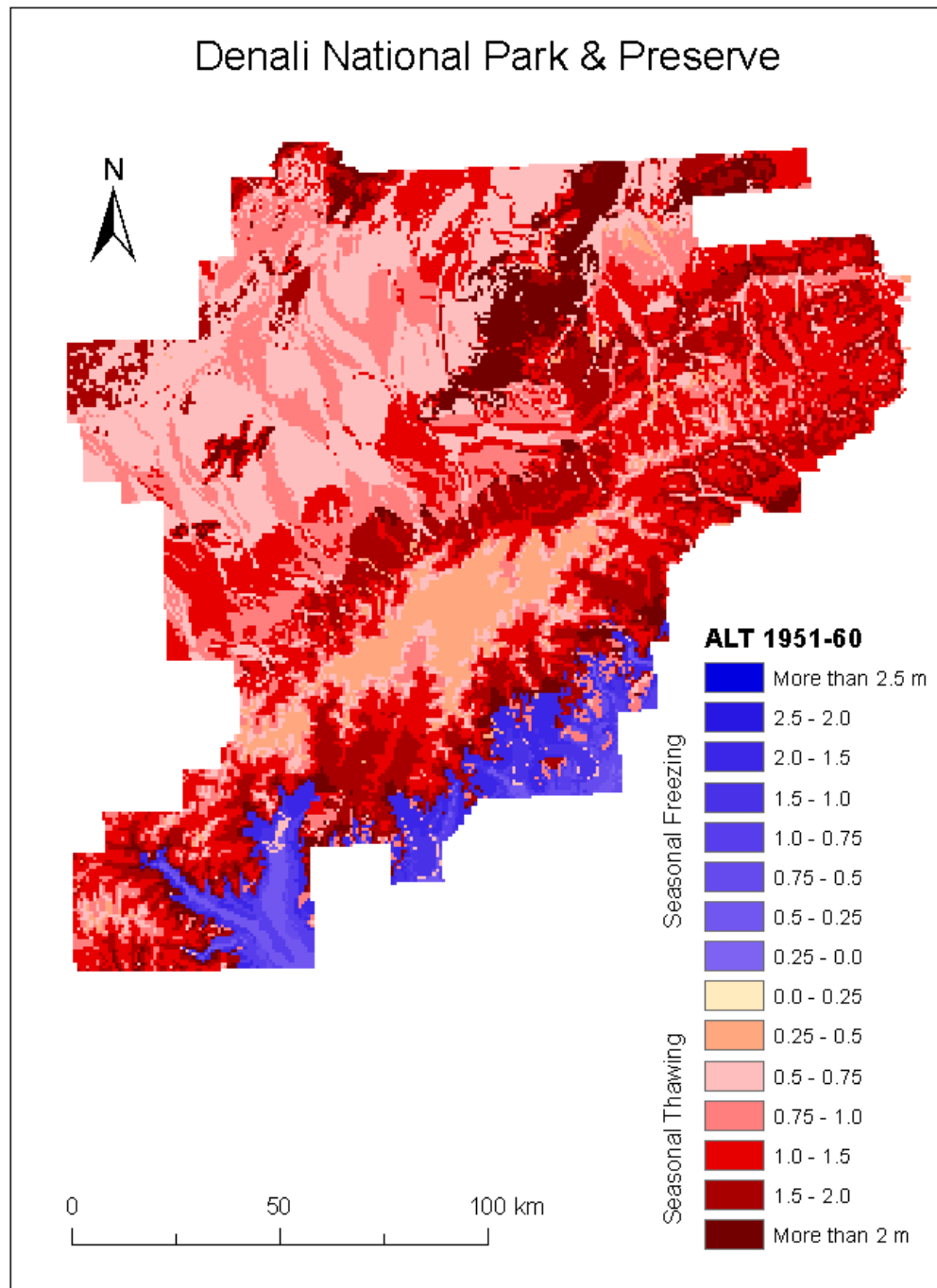


Figure 2: Map of active-layer (ALT) thickness distribution for the decade 1951-60. Shades of red represent seasonal thawing i.e. permafrost right beneath the active-layer and shades of blue represent seasonal freezing i.e. unfrozen layer beneath the active-layer (permafrost may or may not be present at further depth).

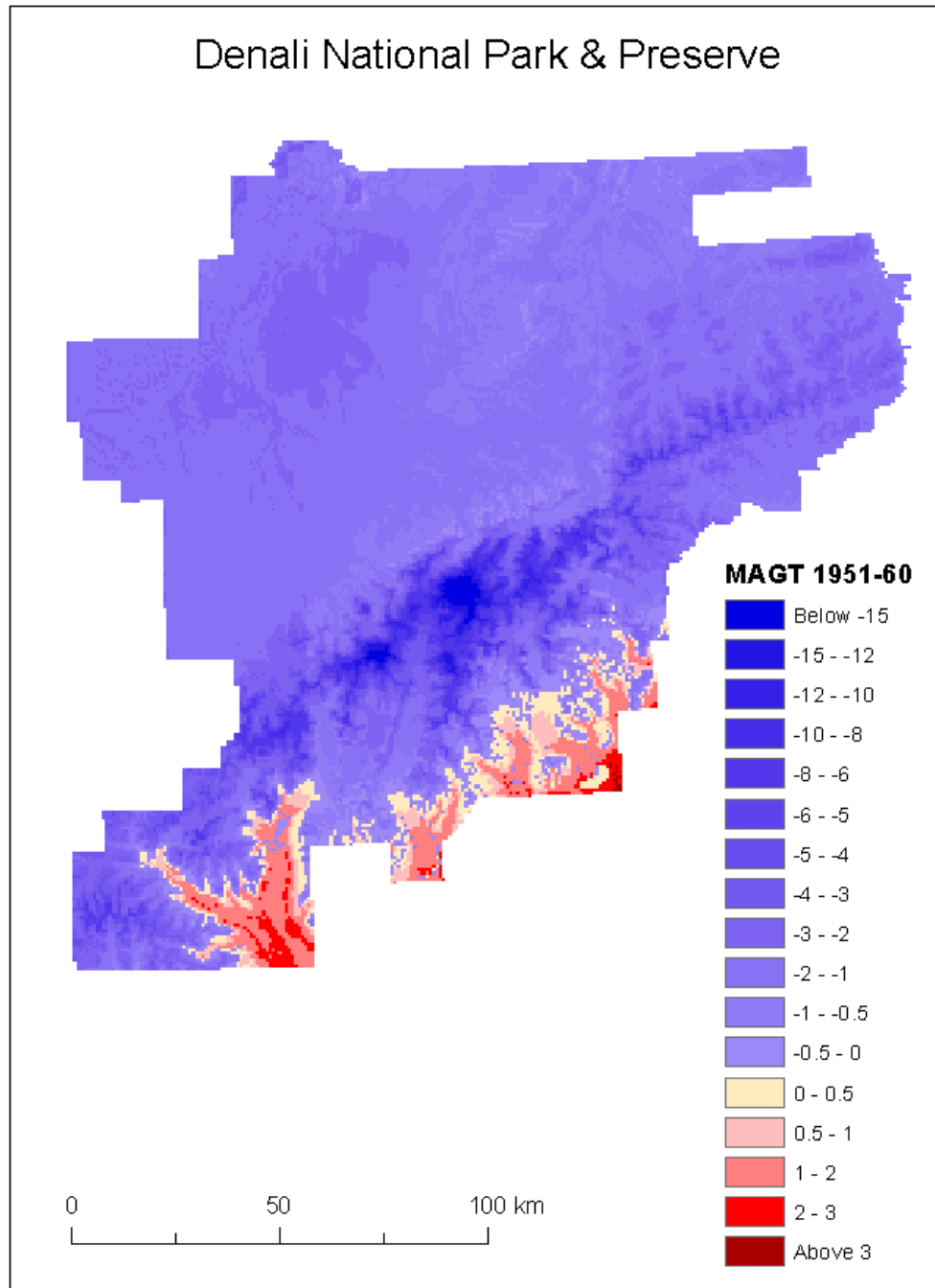


Figure 3: Map of mean annual ground temperature (MAGT) for the decade 1951-60. Shades of red (MAGT > 0 °C) represent an unfrozen layer beneath the active-layer i.e. permafrost may or may not be present at further depth. Shades of blue (MAGT < 0 °C) represent permafrost right beneath the active-layer.

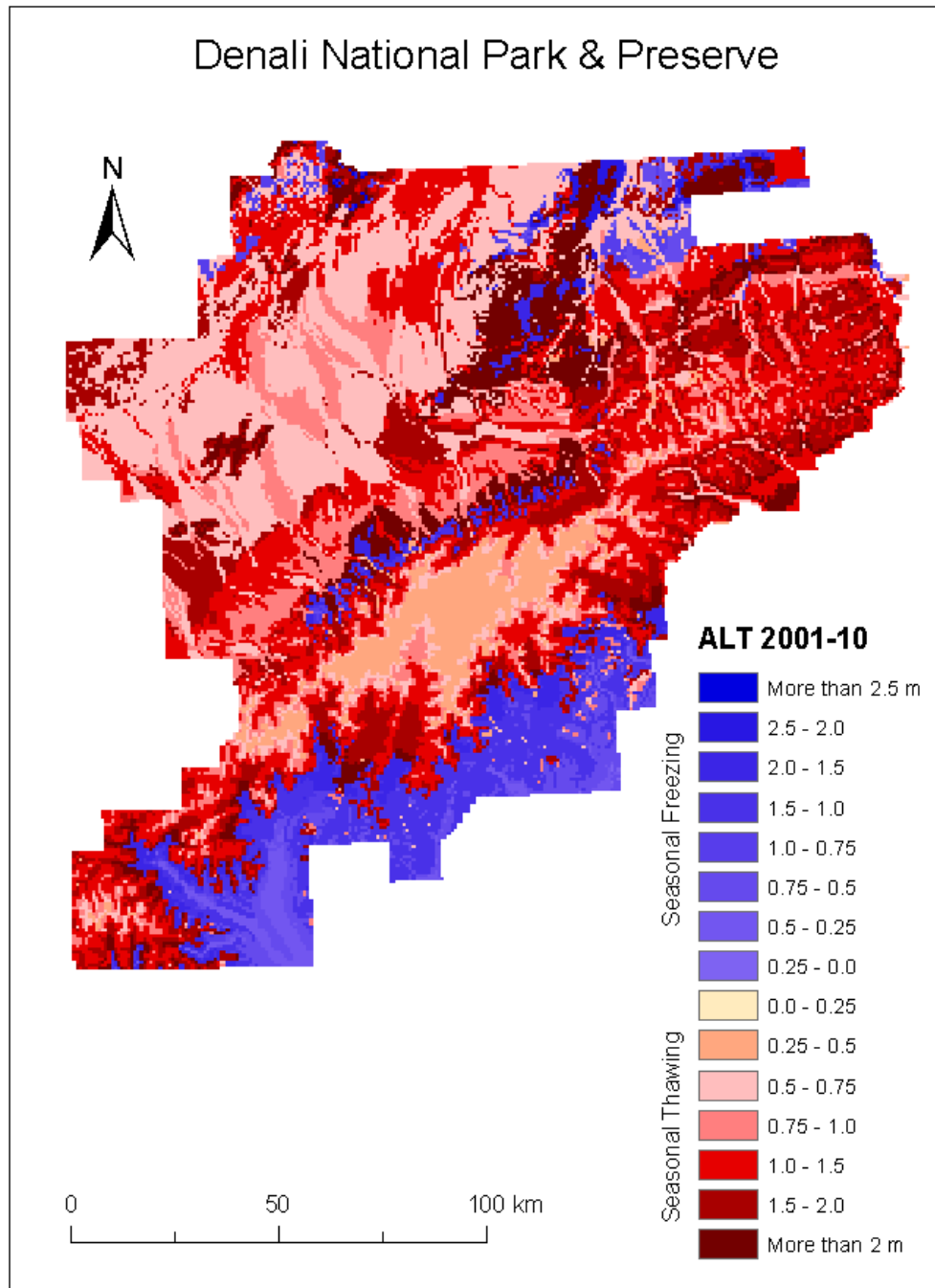


Figure 4: Map of active-layer thickness (ALT) distribution for the last decade (2001-2010). Shades of red represent seasonal thawing i.e. permafrost right beneath the active-layer and shades of blue represent seasonal freezing i.e. unfrozen layer beneath the active-layer (permafrost may or may not be present at further depth).

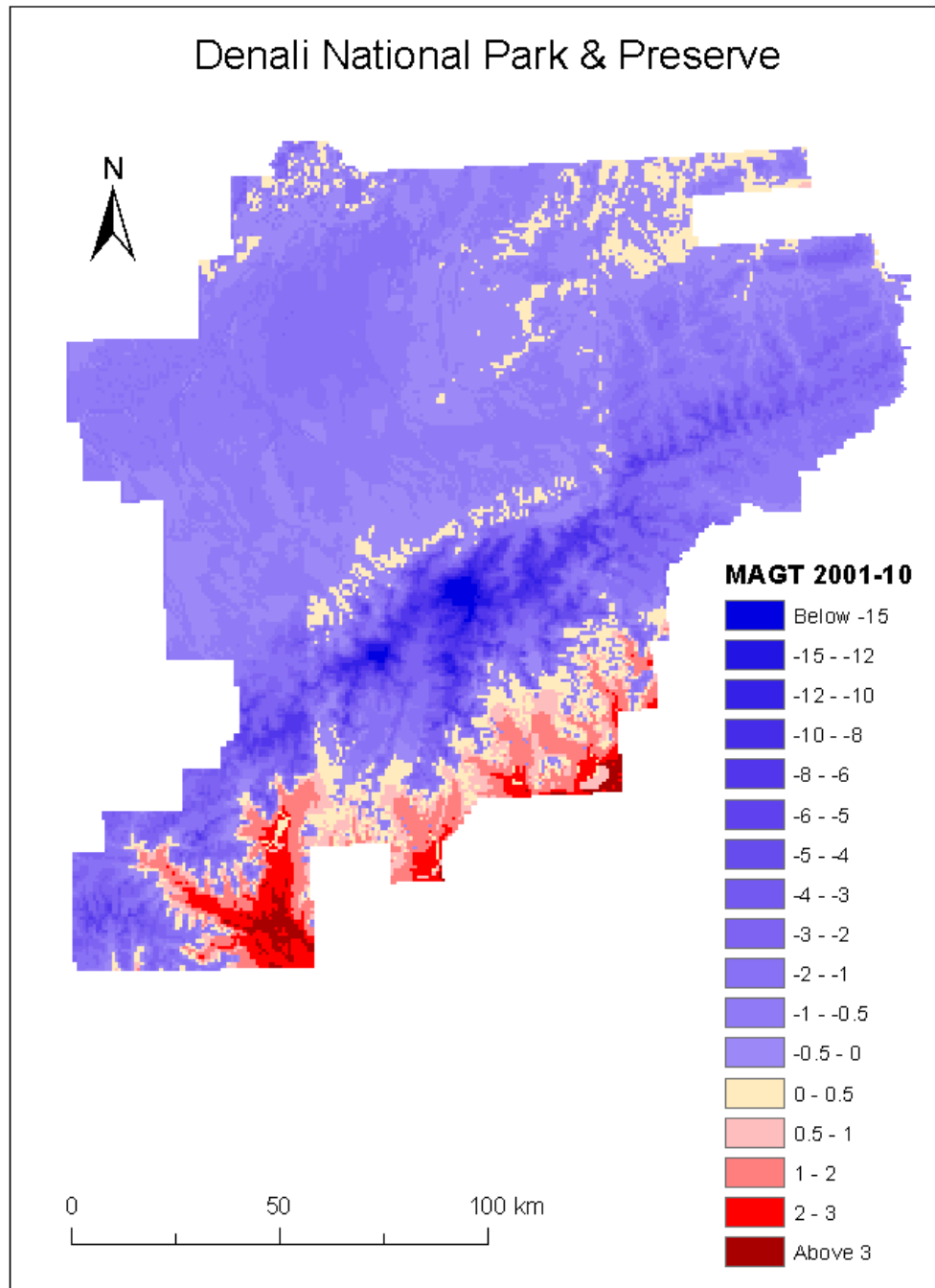


Figure 5: Map of mean annual ground temperature (MAGT) for the last decade (2001-2010). Shades of red (MAGT > 0 °C) represent an unfrozen layer beneath the active-layer i.e. permafrost may or may not be present at further depth. Shades of blue (MAGT < 0 °C) represent permafrost right beneath the active-layer.

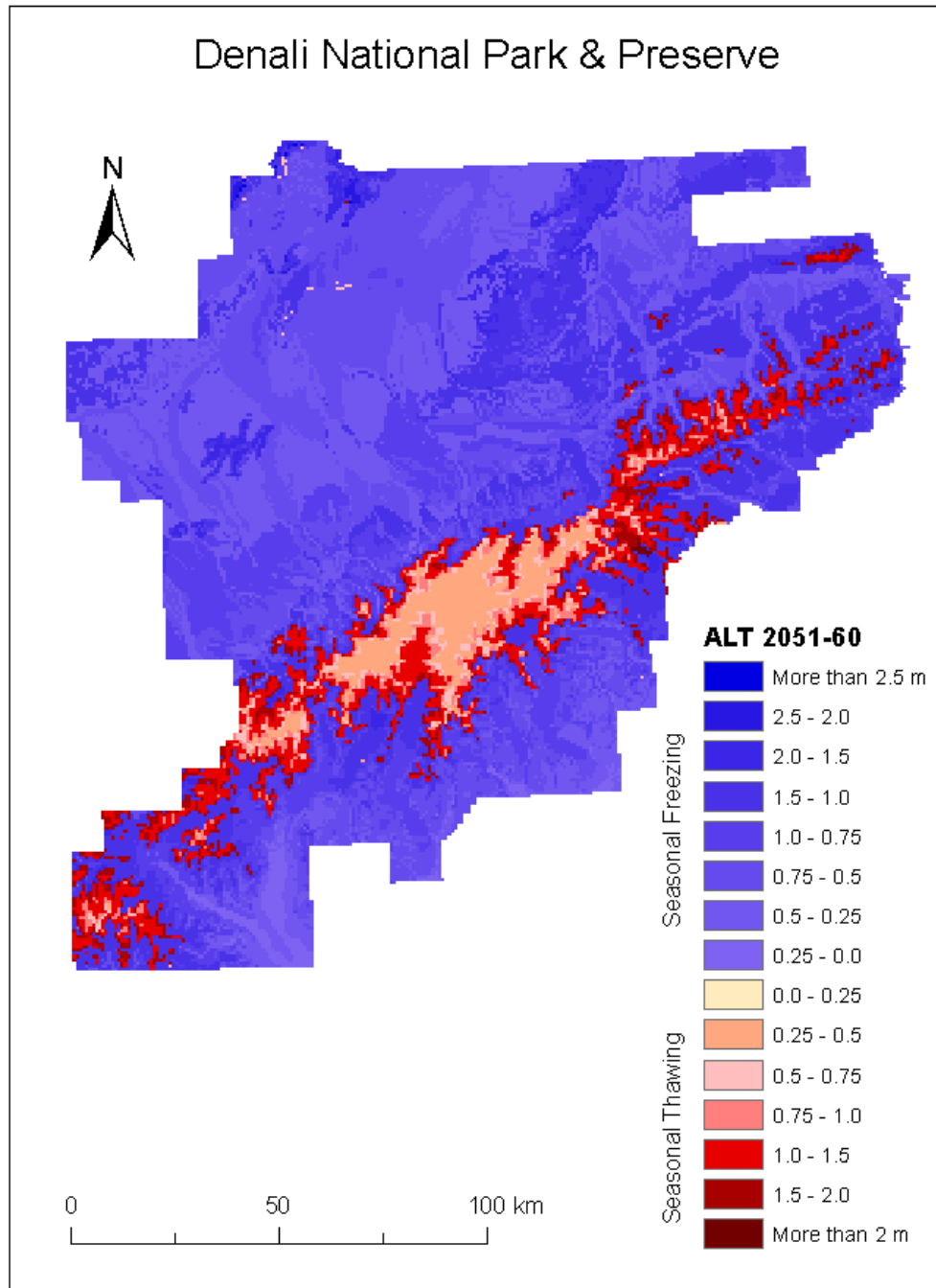


Figure 6: Map of active-layer thickness (ALT) distribution for the decade 2051-2060. Shades of red represent seasonal thawing i.e. permafrost right beneath the active-layer and shades of blue represent seasonal freezing i.e. unfrozen layer beneath the active-layer (permafrost may or may not be present at further depth).

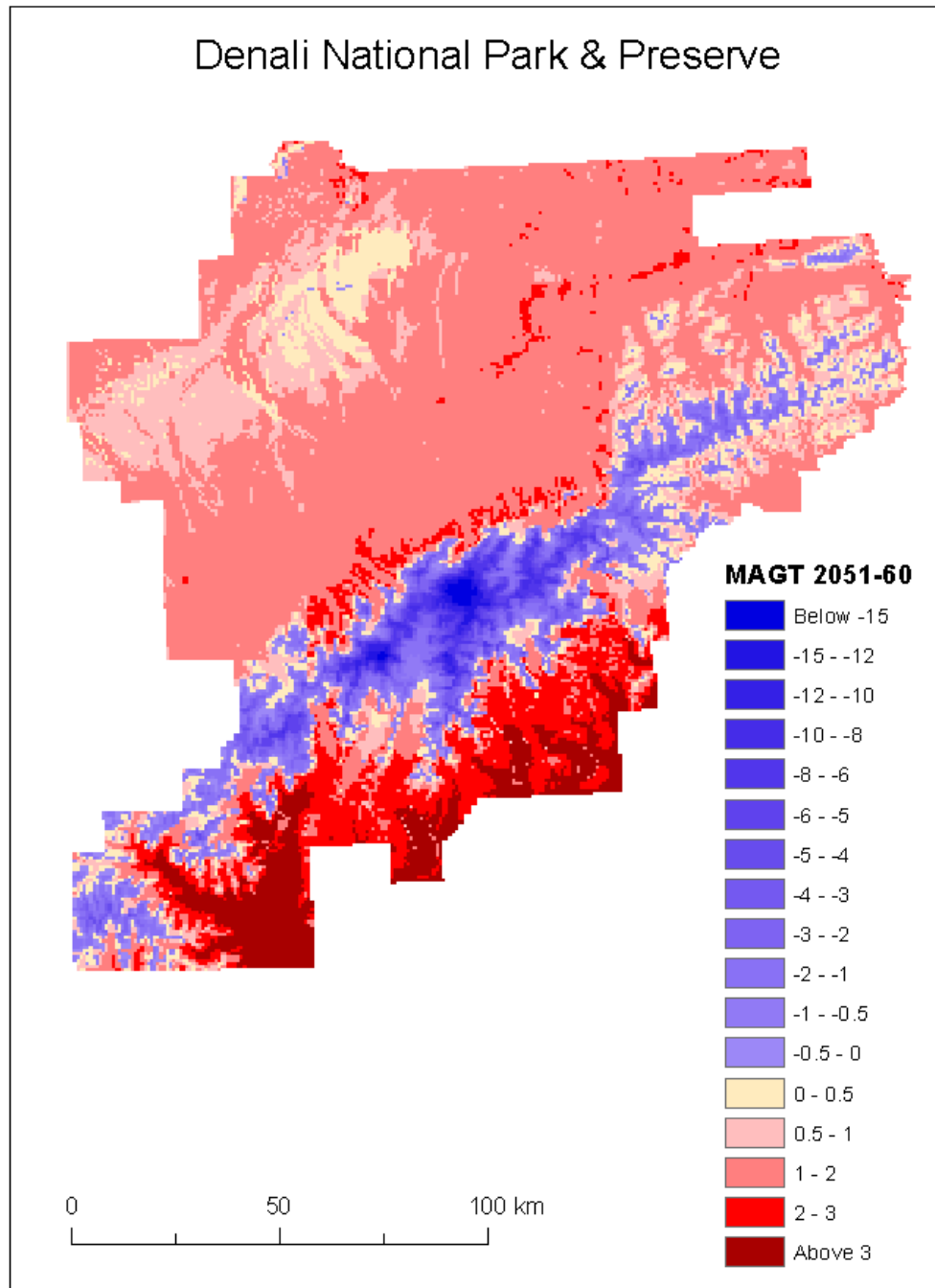


Figure 7: Map of mean annual ground temperature (MAGT) for the decade 2051-2060. Shades of red (MAGT > 0 °C) represent an unfrozen layer beneath the active-layer i.e. permafrost may or may not be present at further depth. Shades of blue (MAGT < 0 °C) represent permafrost right beneath the active-layer.

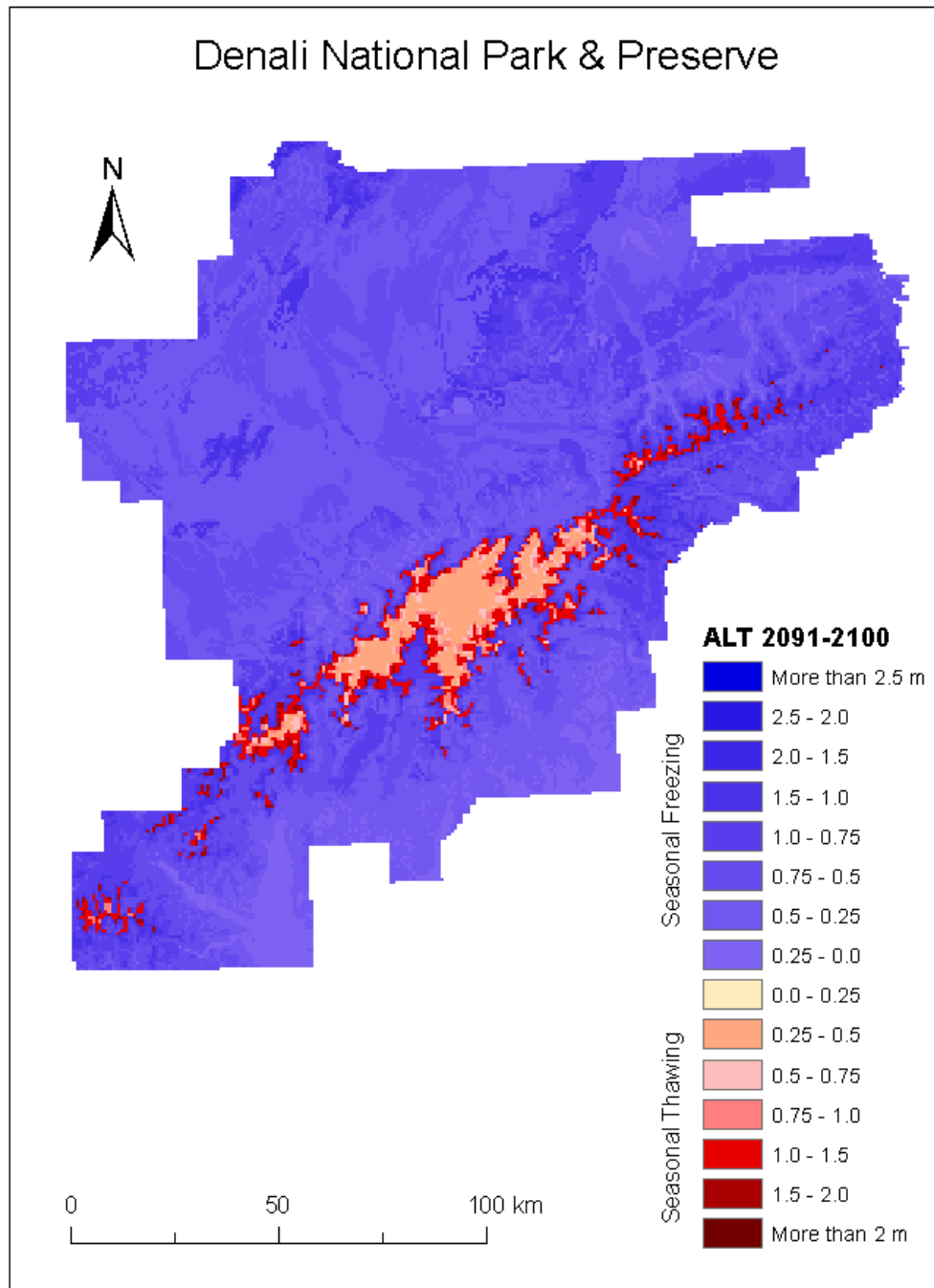


Figure 8: Map of active-layer thickness (ALT) distribution for the decade 2091-2100. Shades of red represent seasonal thawing i.e. permafrost right beneath the active-layer and shades of blue represent seasonal freezing i.e. unfrozen layer beneath the active-layer (permafrost may or may not be present at further depth).

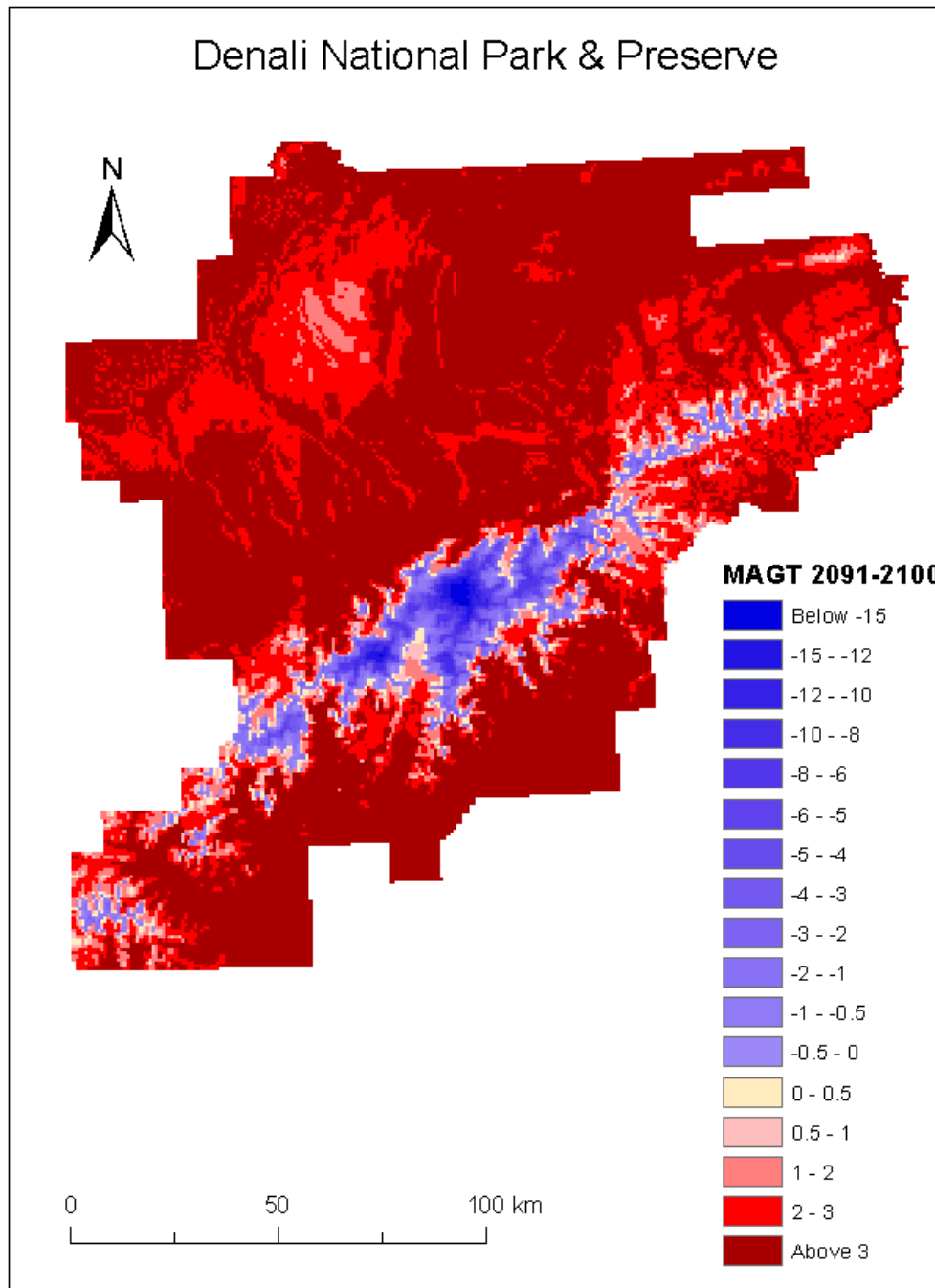


Figure 9: Map of mean annual ground temperature (MAGT) for the decade 2091-2100. Shades of red (MAGT > 0 °C) represent an unfrozen layer beneath the active-layer i.e. permafrost may or may not be present at further depth. Shades of blue (MAGT < 0 °C) represent permafrost right beneath the active-layer.

Table 1: Percentage of Denali Park area with MAGT > 0 °C in the past (1951-60), present (2001-10) and future (2051-60 and 2091-2100) decades according to GIPL 1.0 model output.

Decade	Area (km ²) of MAGT > 0 °C in the Denali Park	% of MAGT > 0 °C in the Denali Park
1951-60	1,874	7.7
2001-10	3,920	16
2051-60	20,609	84.5
2091-2100	22,694	93

The increase in the percentage of MAGT > 0 °C area with time in the Denali Park suggest degradation of permafrost (i.e. either talik development or complete disappearance of permafrost) due to warming climate projected by GCMs (Table 1). Compared to the percentage of areas with deeper permafrost or no permafrost in 1951-60 the percentage of areas with degrading permafrost doubled by 2001-10. The GIPL 1.0 model projects ~84% and ~93% of the park area will be either devoid of permafrost or underlain by degrading permafrost by 2060 and 2100, respectively. The projected increase in air temperatures (GCMs) will likely result in dramatic degradation of the permafrost in the park. The GIPL 1.0 model output does not distinguish between areas devoid of permafrost and areas with a talik (an unfrozen layer lies between the active-layer and the permafrost).

As mentioned in section 1 (page 5 and paragraph 4) of this report, the goal of the project is to produce refined maps of permafrost and active-layer thickness distribution for NPS parklands by using detailed (or improved) NPS soil and vegetation maps of Alaskan parklands. In order to achieve this goal, currently, we are in the process of prescribing thermals properties (see section 3.3 and 3.4) to Denali and Wrangell St. Elias parks detailed soil and vegetation map units for refined GIPL model runs. Once, we finalize this task, we should be able to make refined runs of GIPL and be able to compare the permafrost and active-layer thickness maps produced using generalized (Figure 2-9) and detailed soil and vegetation maps.

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Acknowledgements

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Appendix 1

Snow was classified based on the physical properties of the snow (depth, density, thermal conductivity, number of layers, degree of wetting). Each class was then numerically related to climate using three variables (precipitation, wind, and air temperature). A vegetation proxy was used for wind data: tall vegetation equals low wind, short vegetation equals high wind (Sturm et al., 1995). The following 12 snow classes were identified in Alaska:

- 1 BARE DESERT
- 2 UPLAND TUNDRA
- 3 BROOKS RANGE
- 4 INLAND WATER
- 5 SEA WATER
- 6 SHRUB DECIDUOUS
- 7 COOL CONIFER FOREST
- 8 COLD GRASSLAND
- 9 BARREN TUNDRA
- 10 SMALL LEAF MIXED WOODS
- 11 NARROW CONIFERS
- 12 WOODED TUNDRA

Vegetation (Ecotype) classes from North America Land Cover Characteristics Data Base Version 2.0 were used in this study (http://edc2.usgs.gov/glcc/nadoc2_0.php). It was classified using

multitemporal AVHRR data combined with other ancillary data sets. The following 12 ecotype classes were identified in Alaska:

- 1 WATER
- 2 MOIST TUNDRA
- 3 WET TUNDRA
- 4 ALPINE TUNDRA
- 5 Coastal Western Hemlock - Sitka Spruce F
- 6 Bottomland Spruce - Poplar Forest
- 7 Upland Spruce - Hardwood Forest
- 8 Lowland Spruce - Hardwood Forest
- 9 High Brush
- 10 Low Brush - Muskeg - Bog
- 11 WATER
- 12 ICE

Soil classes from State Surficial Geology Map of Alaska were used.

(http://www.inforain.org/copperriver/content/data_and_software/metadata/geology/surfgeo/.htm). The following 26 soil classes were identified in Alaska:

- 1 ICE
- 2 BEACH / COASTAL DELTA
- 3 COARSE & FINE RUBBLE / MOUNTAIN ALLUVIUM & COLLUVIUM
- 4 VALLEY LOESS & ALLUVIUM / EOLIAN
- 5 UPLAND LOESS / EOLIAN
- 6 LIGHTLY MODIFIED MORaine / GLACIAL MORAINES & DRIFT
- 7 CURRENT MORaine / GLACIAL MORAINES & DRIFT
- 8 RIVER / WATER
- 9 LAKE / WATER
- 10 PROGLACIAL LAKE / GLACIO-LACUSTRINE
- 11 OLD GLACIAL OUTWASH / GLACIO-FLUVIAL
- 12 PRO-GLACIER LAKE OVER MORaine / GLACIO-LACUSTRINE
- 13 CURRENT GLACIAL OUTWASH / GLACIO-FLUVIAL
- 14 ALLUVIAL TERRACE / FLUVIAL
- 15 ALLUVIAL FAN / FLUVIAL

- 16 FLOODPLAIN / FLUVIAL
- 17 UNDIFFERENTIATED MOSAIC / UNDIFFERENTIATED ALLUVIUM & COLLUVIUM
- 18 COASTAL DELTA / COASTAL
- 19 FINE RUBBLE / MOUNTAIN ALLUVIUM & COLLUVIUM
- 20 BEDROCK & COARSE RUBBLE / MOUNTAIN ALLUVIUM & COLLUVIUM
- 21 SAND DUNE / EOLIAN
- 22 OLD MARINE & ALLUVIUM / COASTAL
- 23 VOLCANIC / MOUNTAIN ALLUVIUM & COLLUVIUM
- 24 ALLUVIUM OVER OLD ALLUVIUM / MOUNTAIN ALLUVIUM & COLLUVIUM
- 25 MODERATELY MODIFIED MORaine / GLACIAL MORAINEs & DRIFT
- 26 HIGHLY MODIFIED MORaine / GLACIAL MORAINEs & DRIFT