# Fate of permafrost in Denali National Park and Preserve - A modeling investigation

Photo credit: Jacob W Frank


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# Outline

- Permafrost and Active-layer
- Permafrost in Denali National Park and Preserve (DENA)
- Permafrost model (GIPL 1.0)
  - *Salient features*
  - *Limitations*
  - *Input data*
  - *Output products*
- Modeling results
  - Accuracy assessment
- Summary

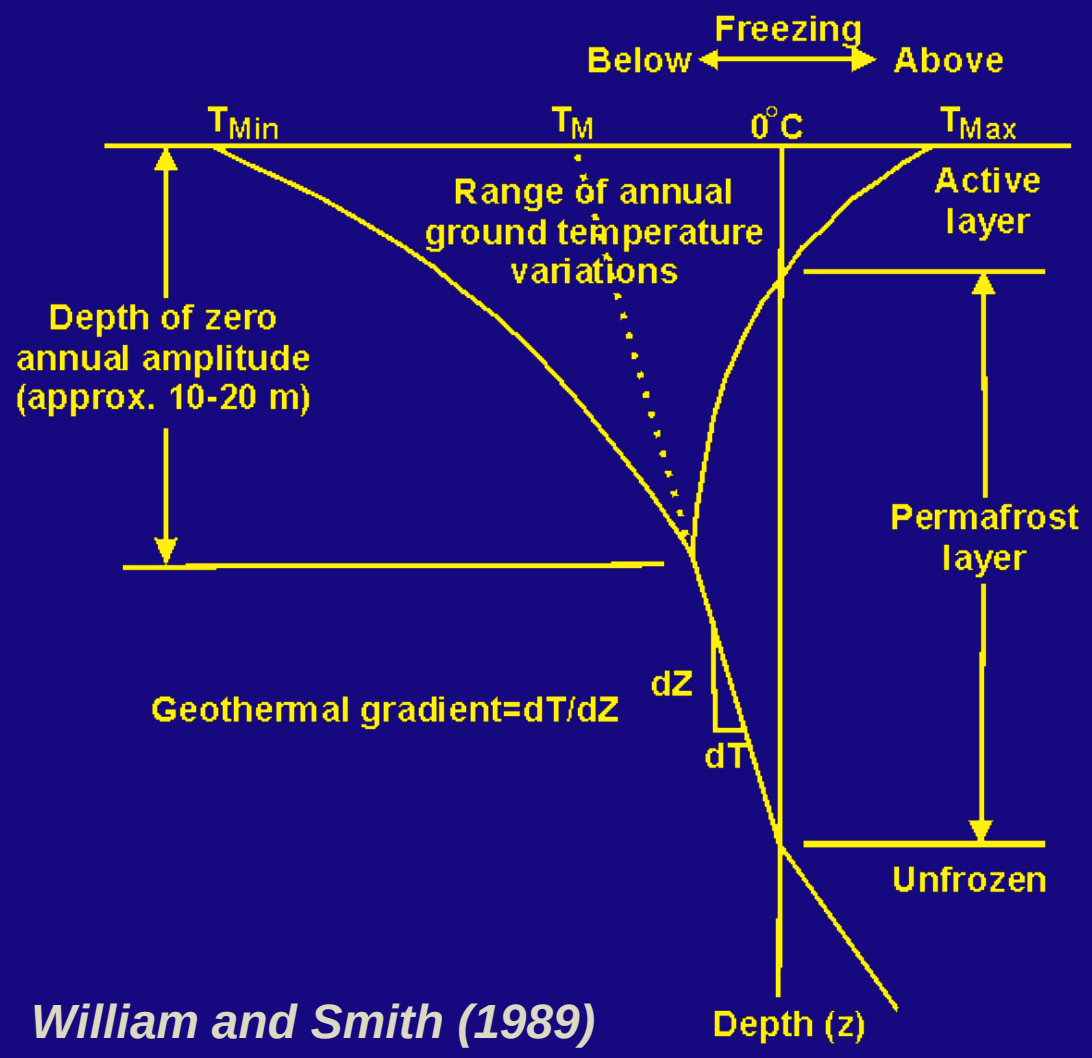
# Permafrost

**Ground (soil or rock and included ice and organic matter) that remains at or below 0 °C for at least two consecutive years, for natural climatic reasons (van Everdingen, 1998).**

*Photo Courtesy: M. Gooseff*

**Left: U.S. Army Permafrost Tunnel at Fox, Fairbanks**
**Right: Ice-rich permafrost near Toolik Field Station, Alaska**

# Active layer

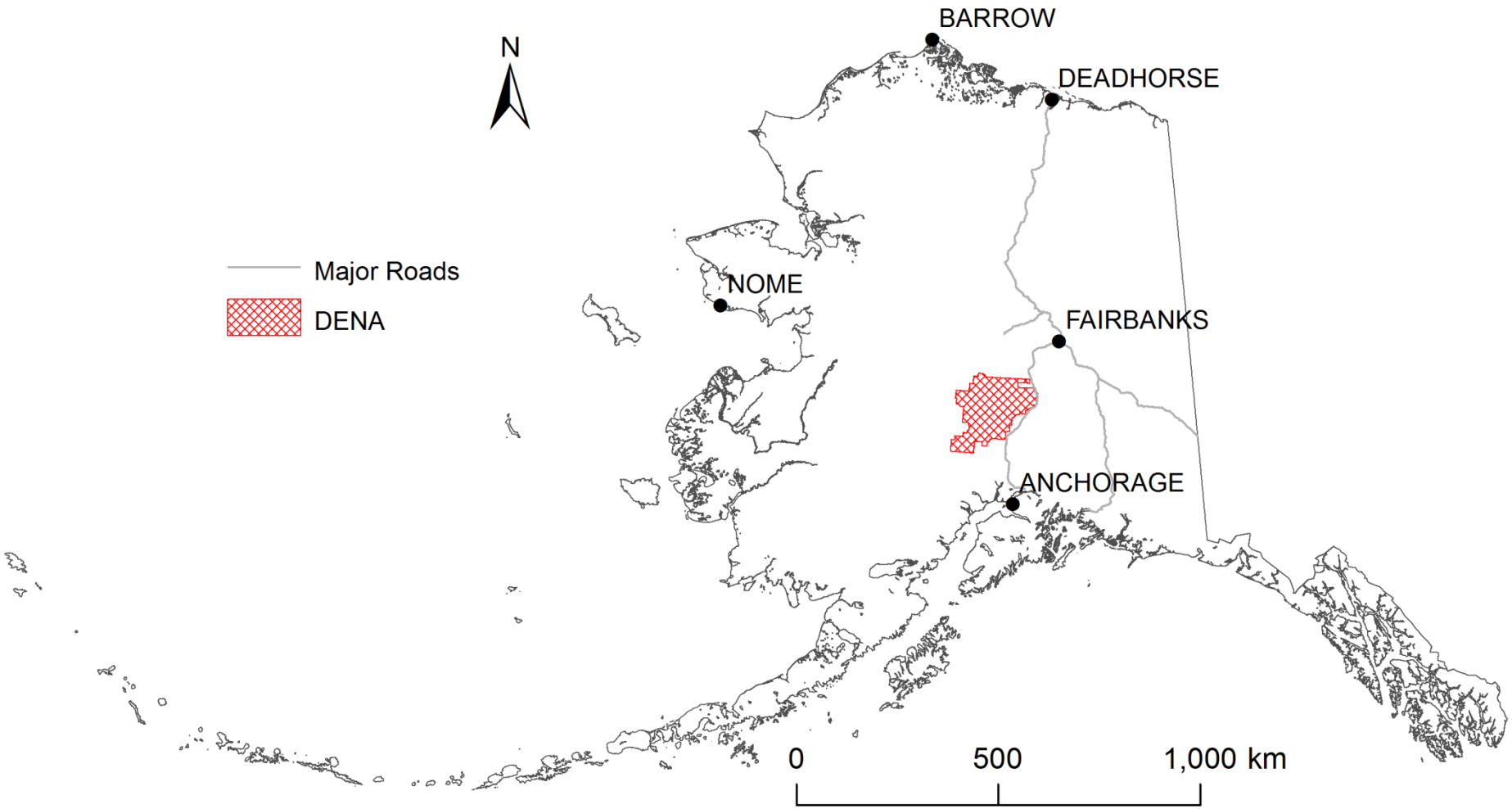



*William and Smith (1989)*

**The layer of the ground above permafrost that thaws in summer and freezes again in winter (*Muller, 1947*).**

# DENA Permafrost

# Location of DENA in Alaska



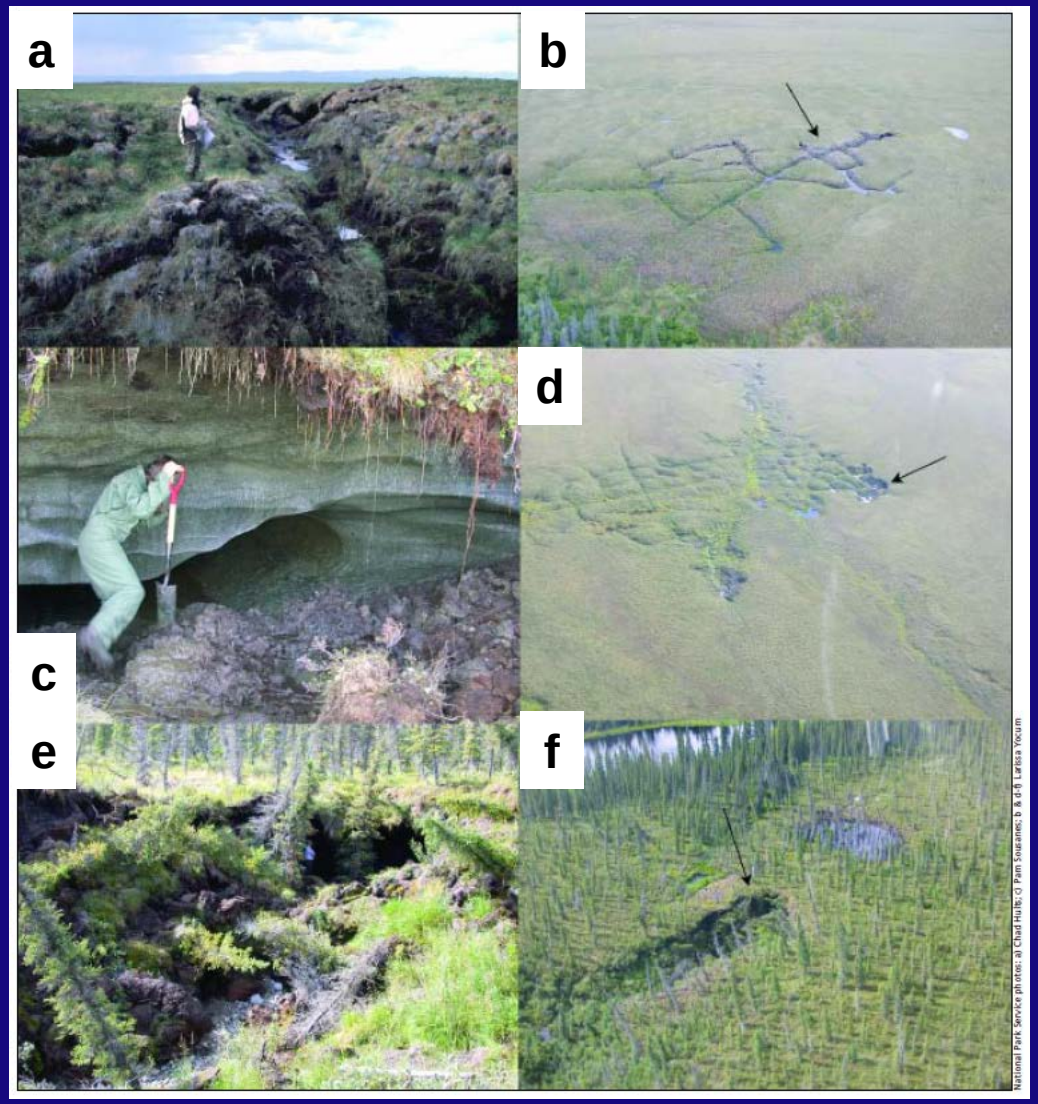
# Why care about DENA permafrost ?

***"Permafrost is an important driver of Denali's ecosystems because thermal characteristics of the ground directly control or indirectly influence Denali's local hydrology, pattern of vegetation, and wildlife communities*". (*Adema, 2006*)**

- **Permafrost as foundation**
- **State of permafrost**
- **Form and amount of ice**

**Wigand Creek thermokarst developed by thawing of ice-wedge polygons, Toklat Basin, DENA (*Adema, 2006*)**

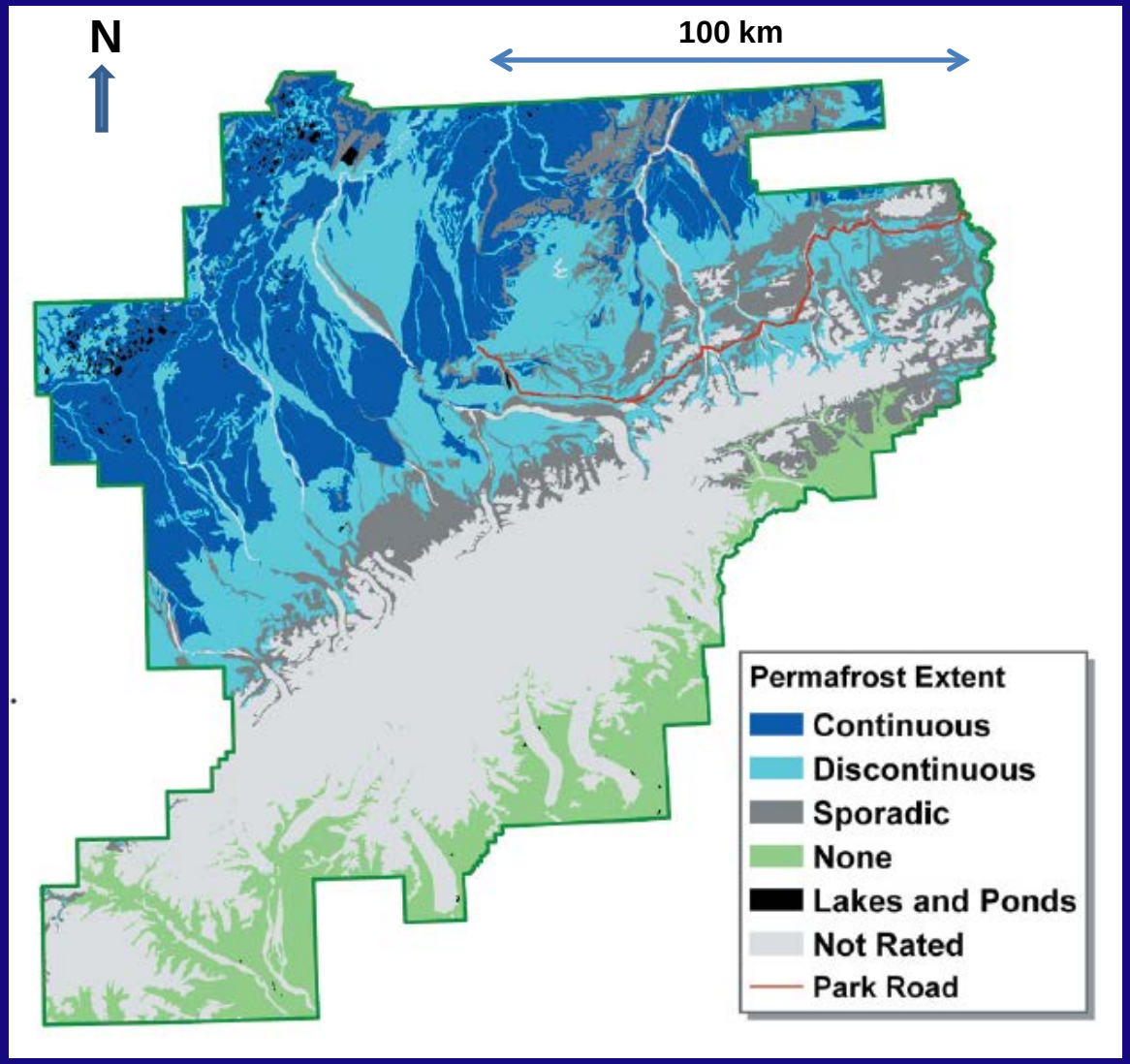
# Thermokarsts, Toklat Basin, DENA




(a-b) Wigand Creek Thermokarst
(c-d) Boundary Thermokarst
(e-f) Hook's Hole Thermokarst

*Yocum et al. (2006)*

# A generalized permafrost map of DENA




A product of the joint NPS-NRCS six year soils survey of DENA (*Clark and Duffy,* 2006)

(>80% of the soil) Continuous
(20 - 80%) Discontinuous
(5-20%) Sporadic

Nearly 45% of the park underlain by continuous or discontinuous permafrost

32% Not rated

1375 Sites in 16,676 $km^2$ area
Or 1 site per 12 $km^2$

# Modeling

1. Permafrost presence or absence
2. State of permafrost
3. Can be improved

# Permafrost model GIPL 1.0

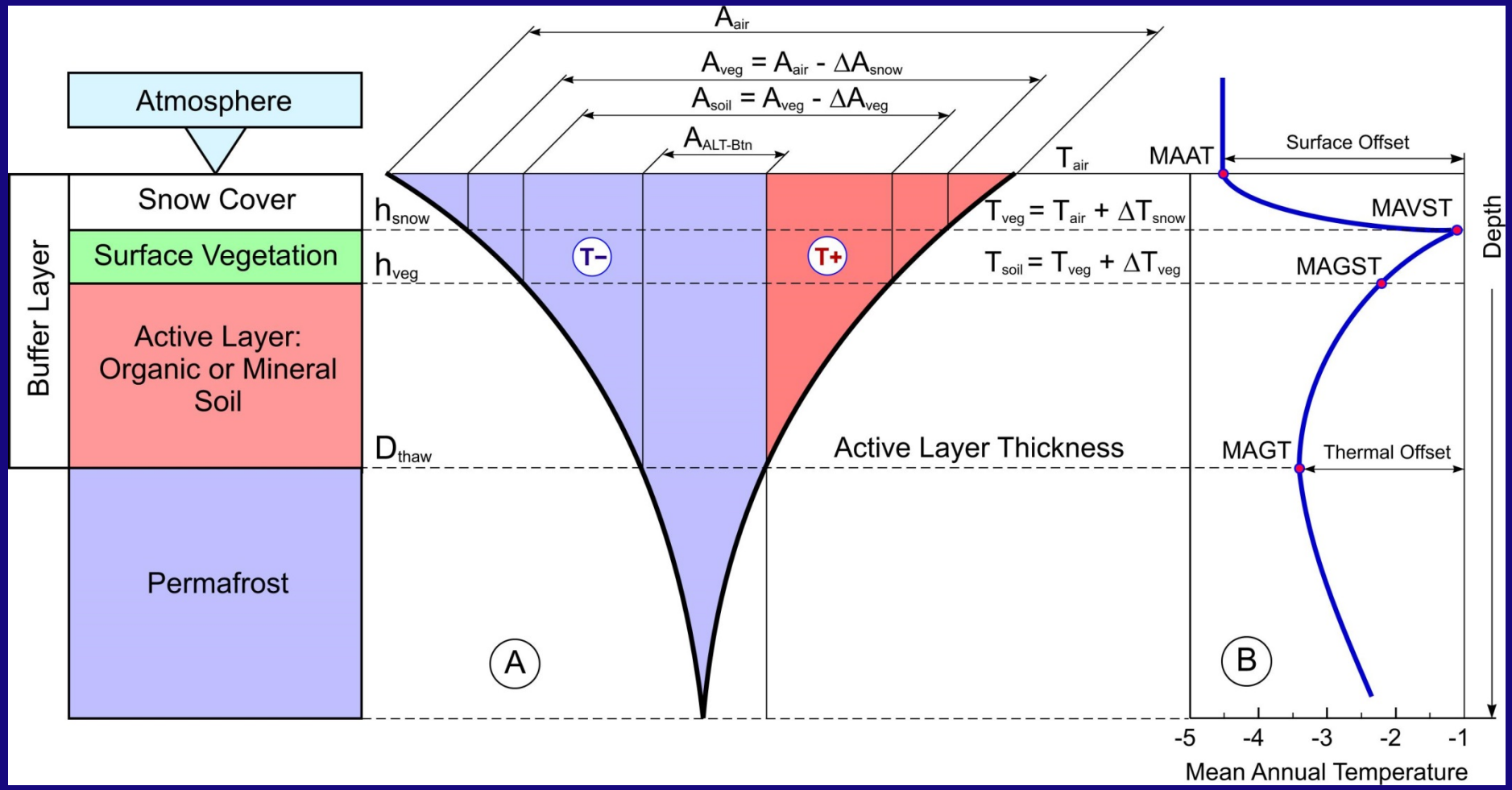
# GIPL 1.0 model salient features

- Models near-surface permafrost
- An equilibrium model (temperature at the bottom of seasonal freeze-thaw layer and its thickness)
- Conductive heat transfer
- Analytical solution of the ground heat equation that includes freezing/thawing processes (*Kudryavtsev et al.* 1974; Romanovsky and Osterkamp 1997)
- Accounts for the effects of snow cover, surface vegetation, soil moisture and soil thermal properties
- Ignores the effect of geothermal heat flux

# GIPL 1.0 model limitations

- **Assumes**
  - Steady state temperature regime (annual or decadal cycle)
  - No within layer variation in thermal properties
  - No change in surface vegetation
- **Does not take into account**
  - Unfrozen water content
  - Effect of wind on snow distribution (thickness)

# GIPL 1.0 model conceptual diagram




*(Marchenko and Romanovsky, 2012)*

# Input Data

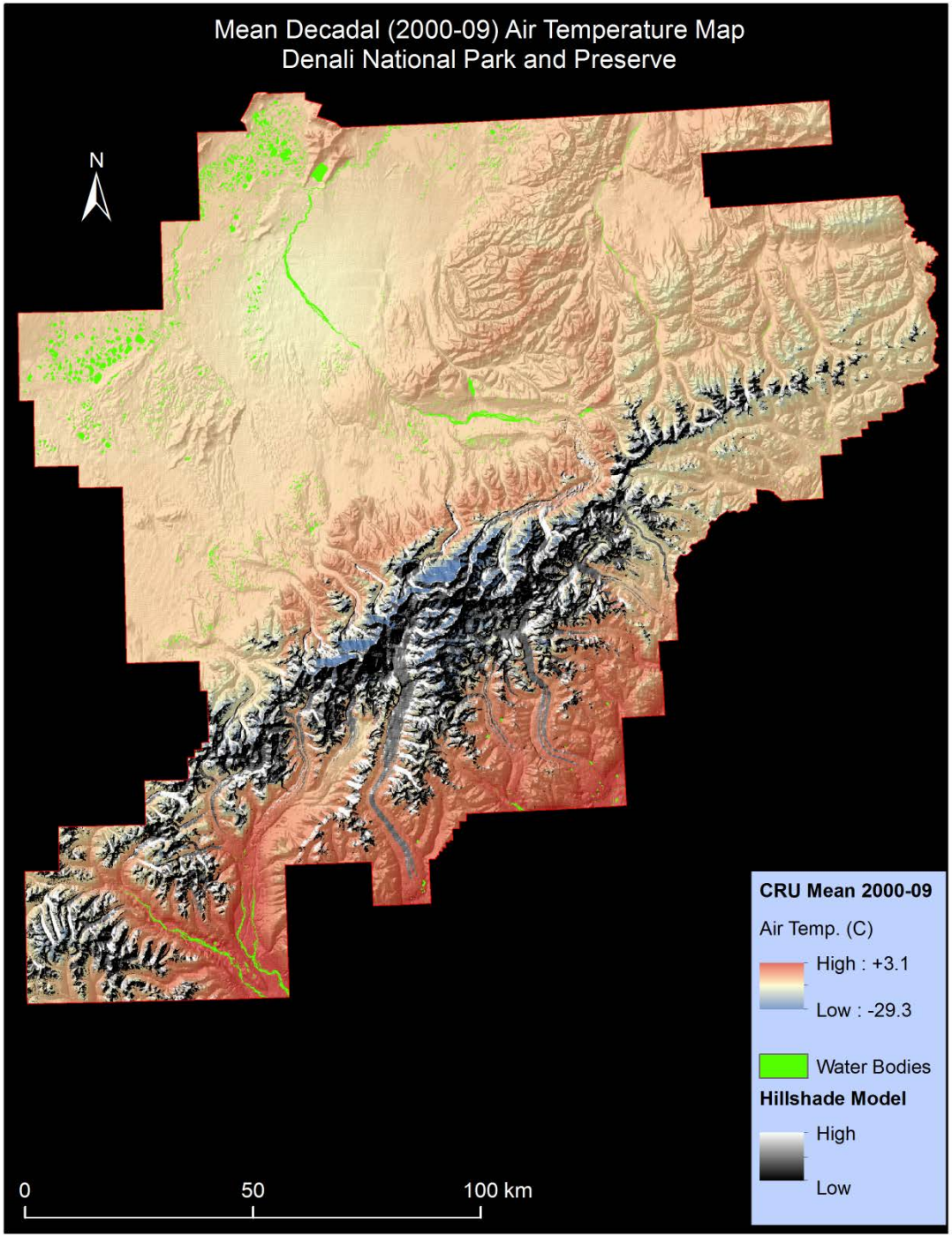
- **Climate data (mean monthly air temperature and monthly total precipitation)**
  - ❑ **CRU Climate data (1901-2009); Decades: 1950-59, 2000-09**
  - ❑ **5-GCM composite A1B Scenario (2001-2100); Decades: 2001-10, 2051-60, 2091-2100**
- **Ecosystem Properties**
  - ❑ **Snow Map: Nine snow classes (*Marchenko, unpublished*)**
    - ▪ **Fresh snow density and maximum snow density**
  - ❑ **Ecotype Map: Twenty Ecotypes (*Stevens et al, 2001*)**
    - ▪ **Surface vegetation thickness**
    - ▪ **Thermal diffusivity in frozen and thawed state**
  - ❑ **Soil Map: One-Hundred-and-Fifty-One soil classes (*Clark and Duffy, 2006*)**
    - ▪ **Volumetric heat capacity in frozen and thawed state**
    - ▪ **Thermal conductivity in frozen and thawed state**
    - ▪ **Volumetric water content**

# Output products

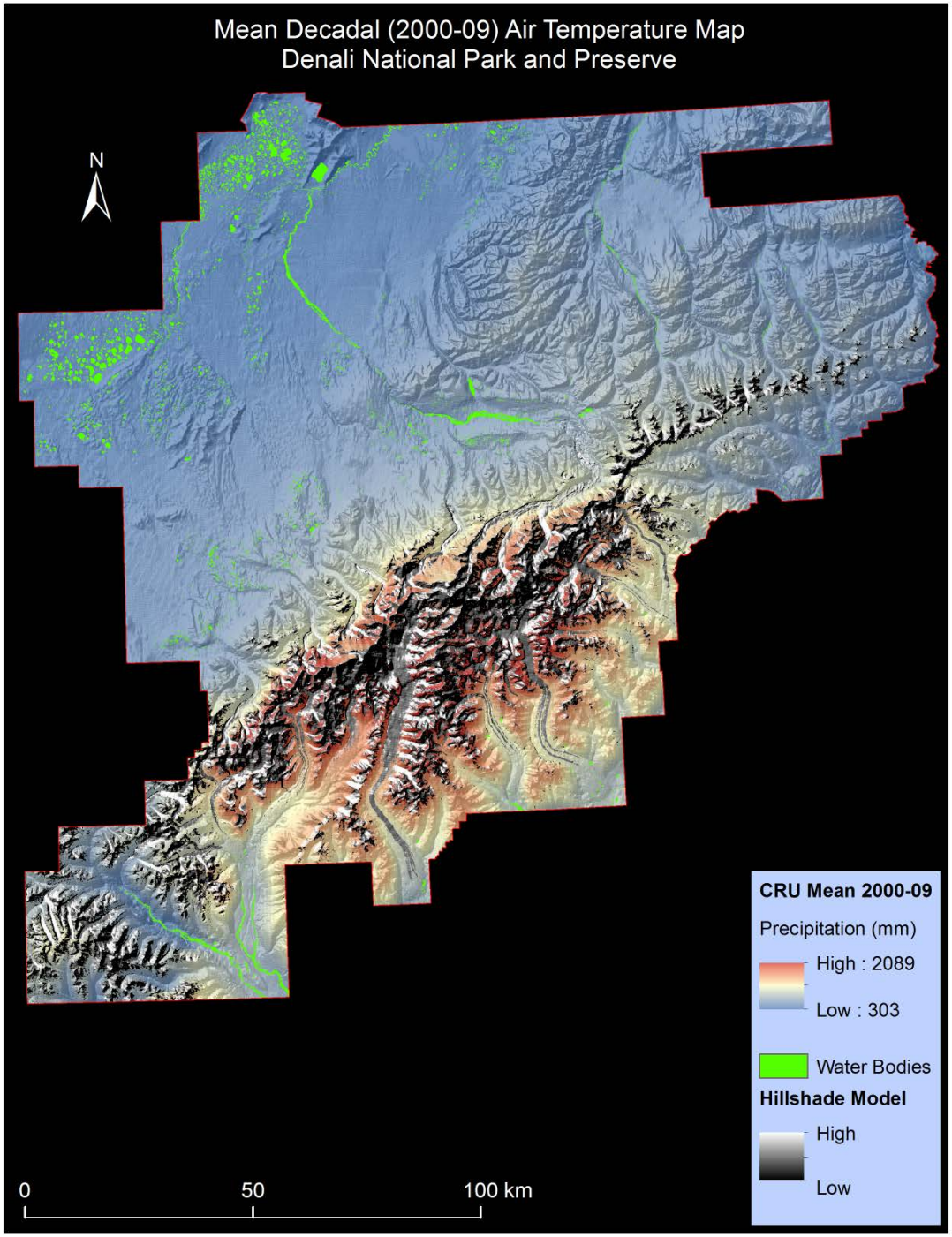
- Average temperature @
  - ground surface
  - soil surface
  - bottom of seasonal freeze-thaw layer
- Thermal offset
- Thickness of seasonal freeze-thaw layer
- Thickness of snow cover

**Input resolution = Output resolution**

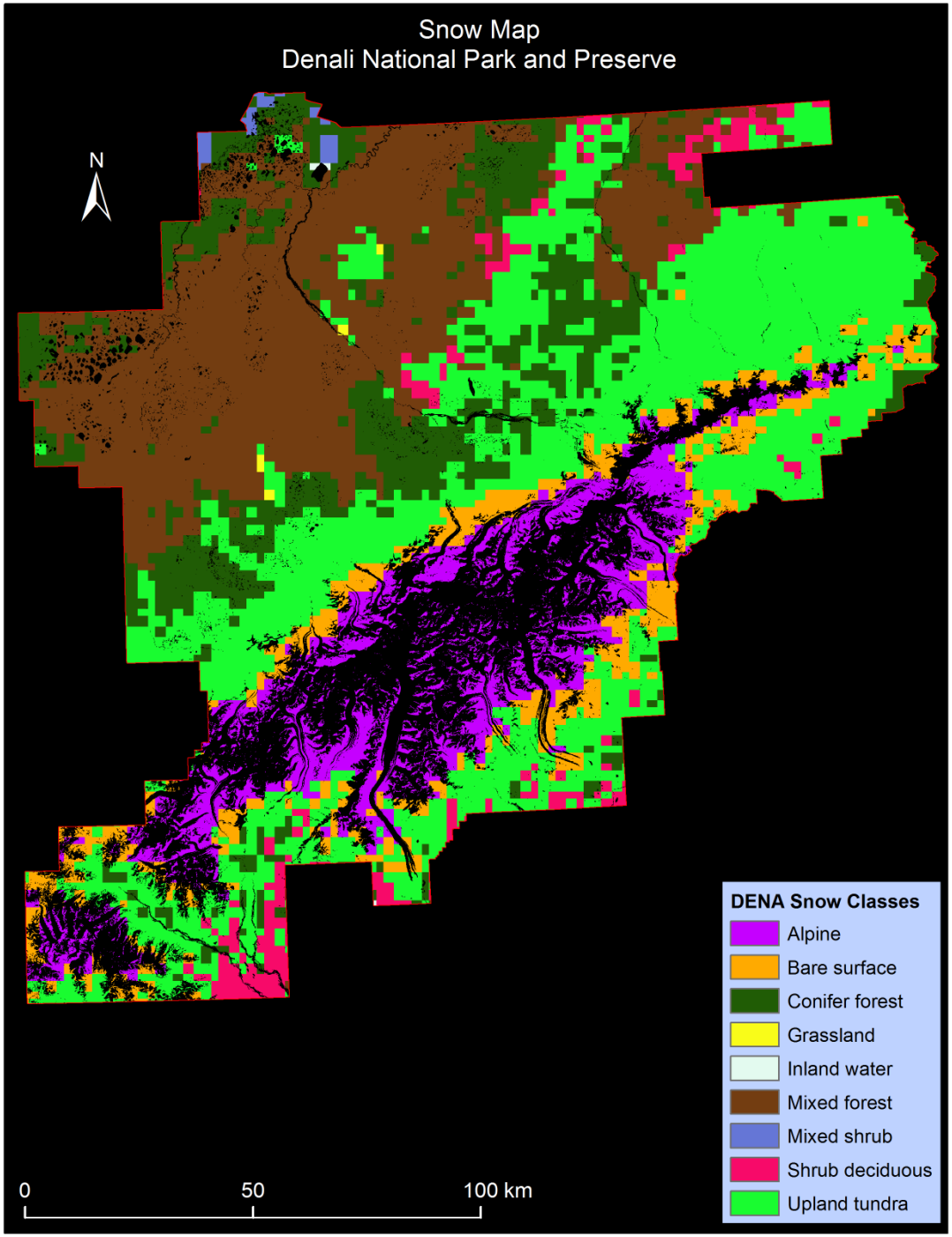
# Input maps for DENA permafrost modeling



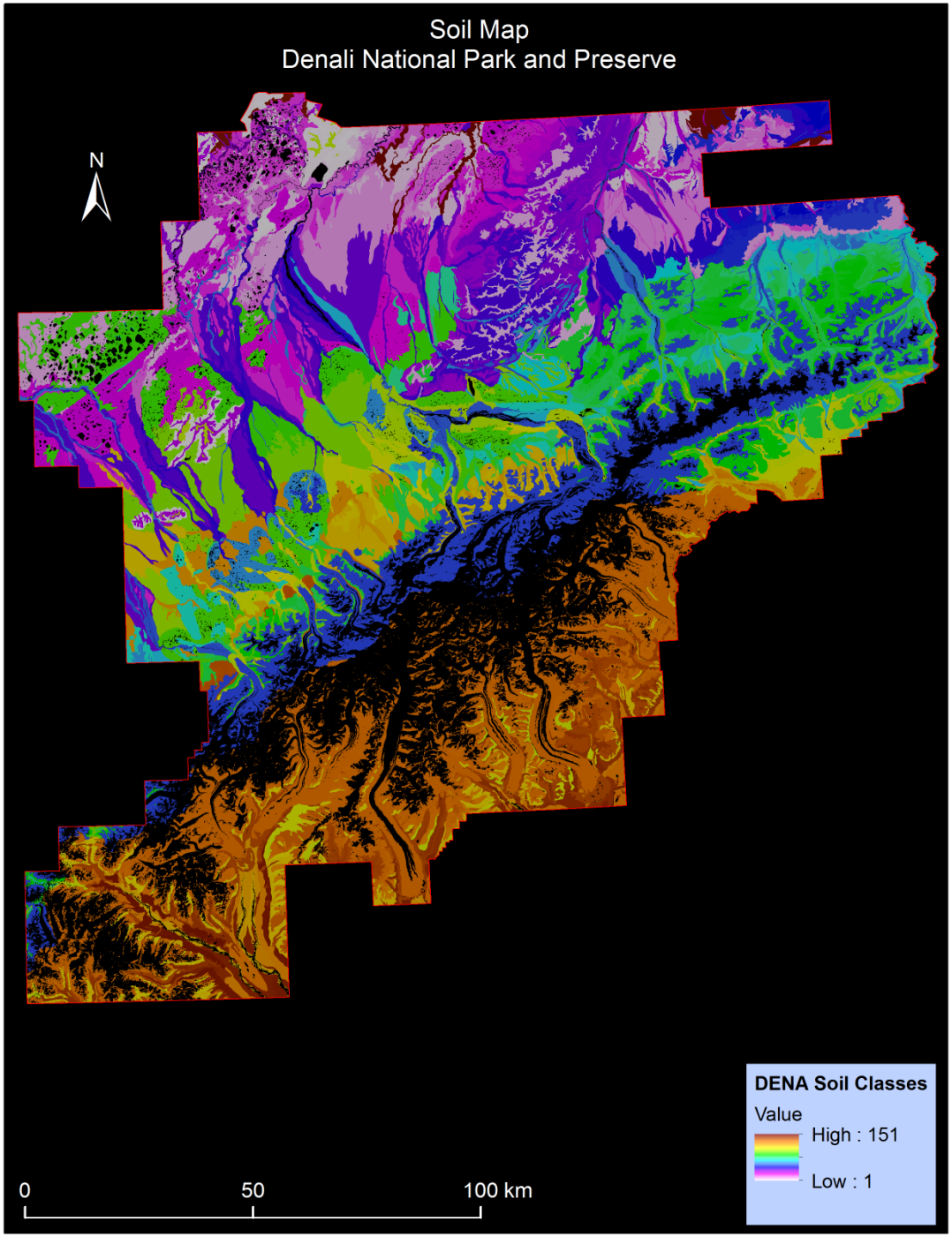

# Input
# Decadal Mean Air Temperature
# CRU 2000-09



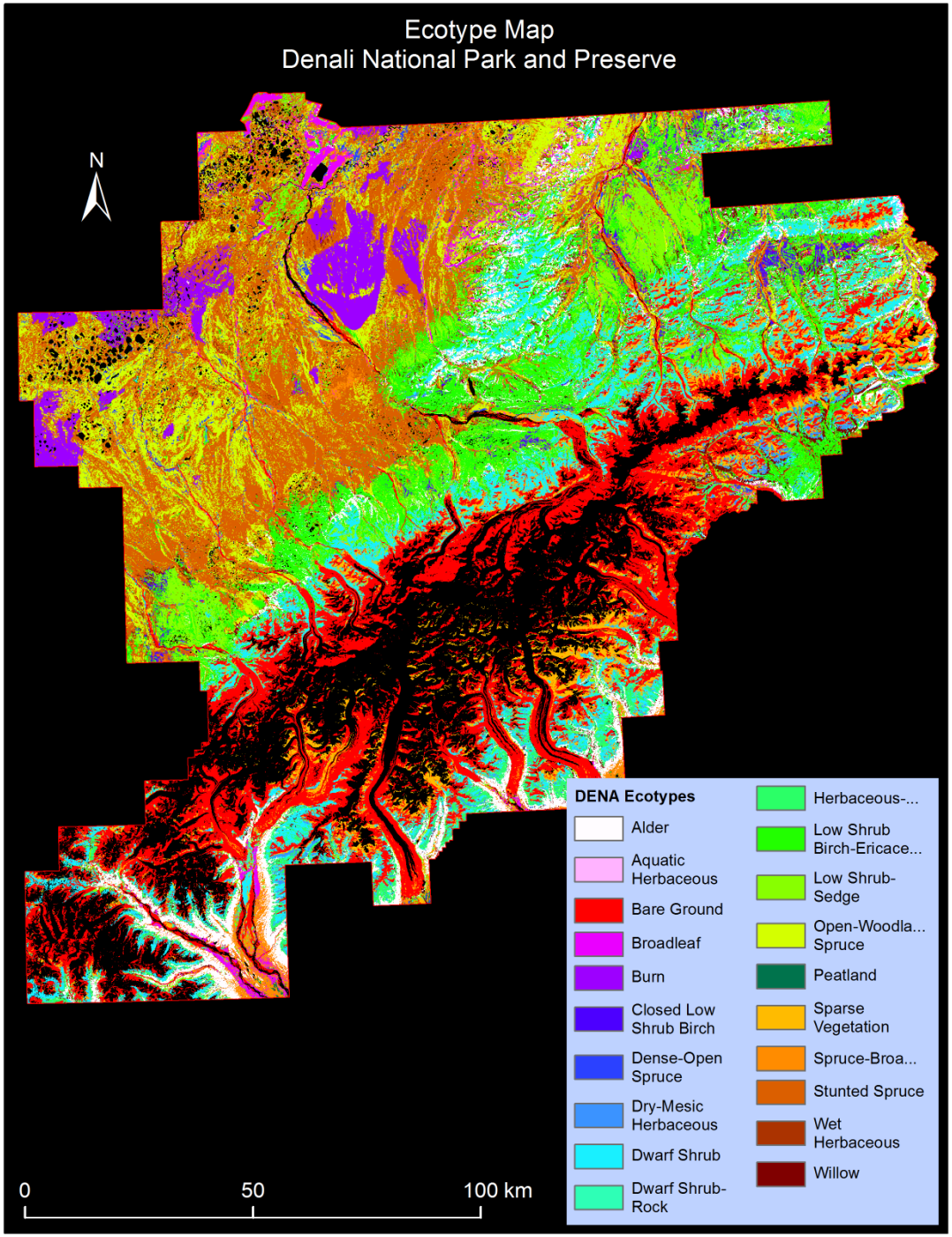

**Input**
**Decadal Mean Annual Precipitation**
**CRU 2000-09**




**Input**
**Snow Map**
***Marchenko* (Unpublished)**




**Input**
**Soil Map**
***Clark and Duffy* (2006)**

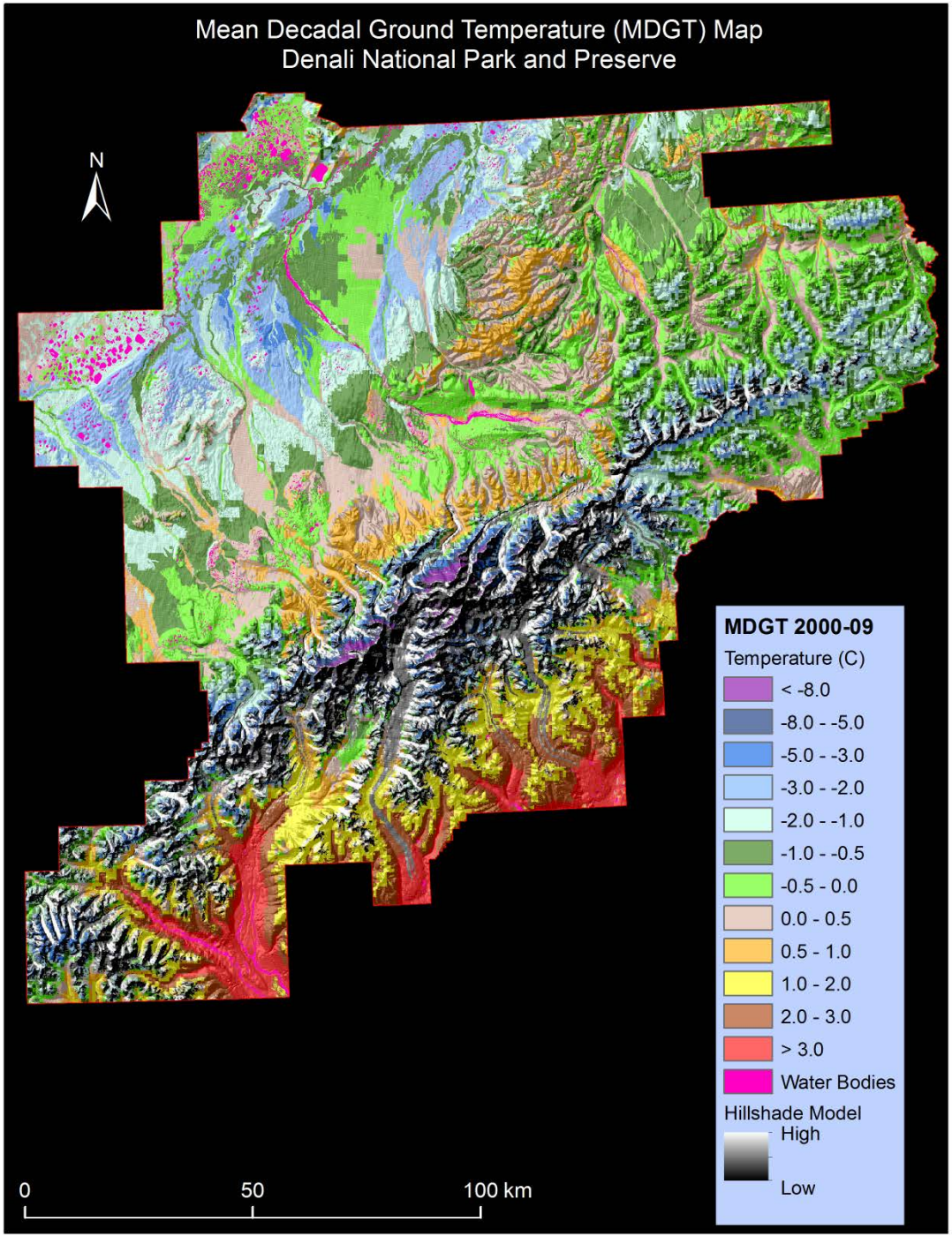



**Input**
**Ecotype Map**
***Stevens et al.* (2001)**

**Derived from Landsat images**

**28 m Spatial resolution**

# Permafrost modeling results




# Permafrost Map CRU 2000-09 forcing

**28 m spatial resolution**

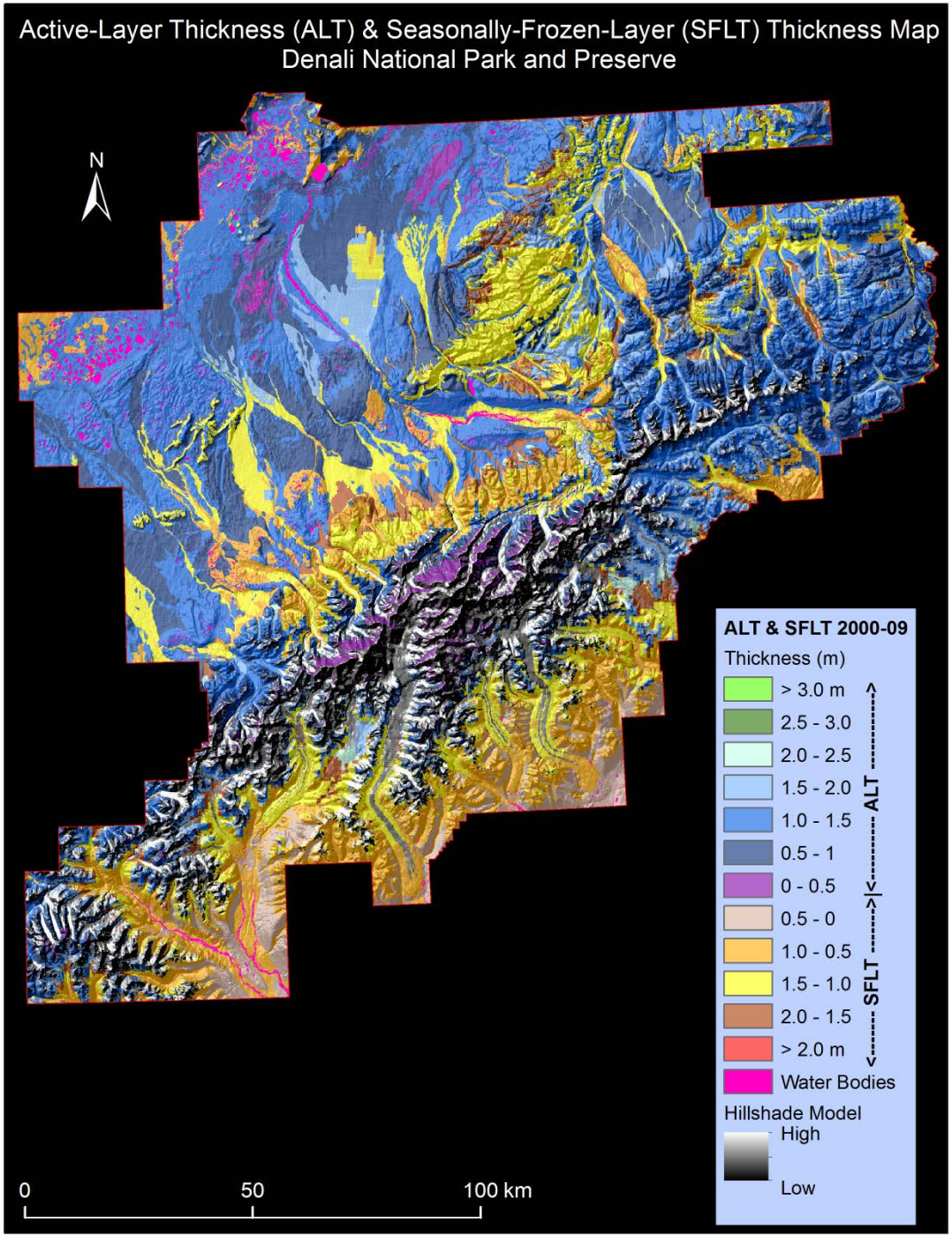
**Ground temperature at the bottom of *seasonal freeze-thaw layer***

***Climate input:***

**Decadal mean air temp.: -1.6 °C**
**Decadal mean annual precip.: 651 mm**

***Modeled permafrost characteristics:***

**Near-surface Permafrost @ 51% of DENA**
**Mean decadal permafrost temp.: -1.1 °C**




# Thickness of Seasonal Freeze-Thaw Layer Map CRU 2000-09 forcing

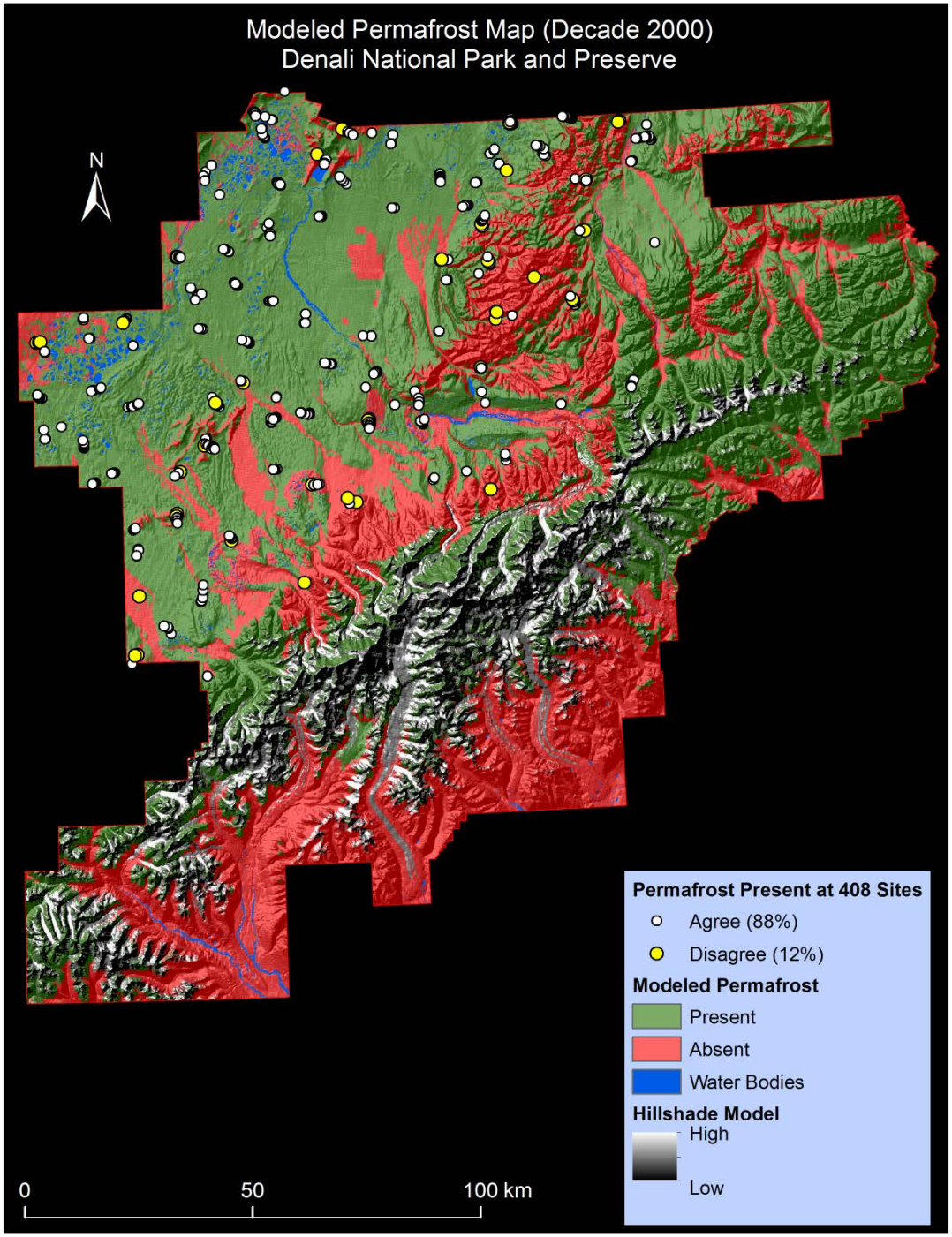
*Climate input:*

**Decadal mean air temp.: -1.6 °C**
**Decadal mean annual precip.: 651 mm**

*Modeled active-layer characteristics:*

**Mean Decadal ALT: 1.1 m**
**Active-Layer Thickness < 1 m: 19 %**

# Products accuracy assessment




# Warm-bias Test CRU 2000-09 forcing

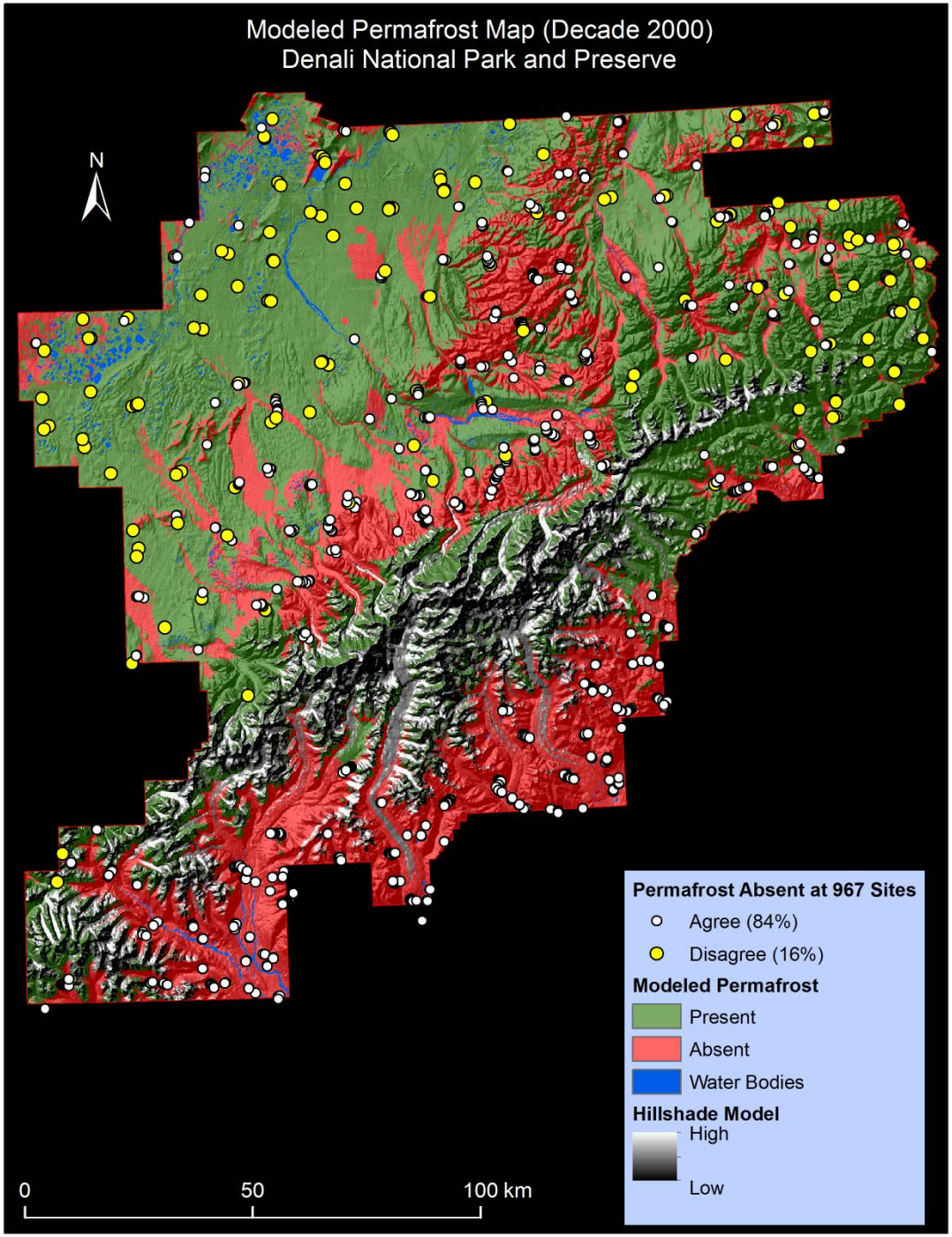
*Clark and Duffy* (2006 )
Field data (Aug.-Sept. 1997-2002)

Permafrost present at 408 Sites
Agree (88%)
Disagree (12%)

| Modeled | Field |
|---|---|
| Present | Present |
| Absent | Present |

Possible reasons of disagreement:

- Scale
- Model limitations




# Cold-bias Test CRU 2000-09 forcing

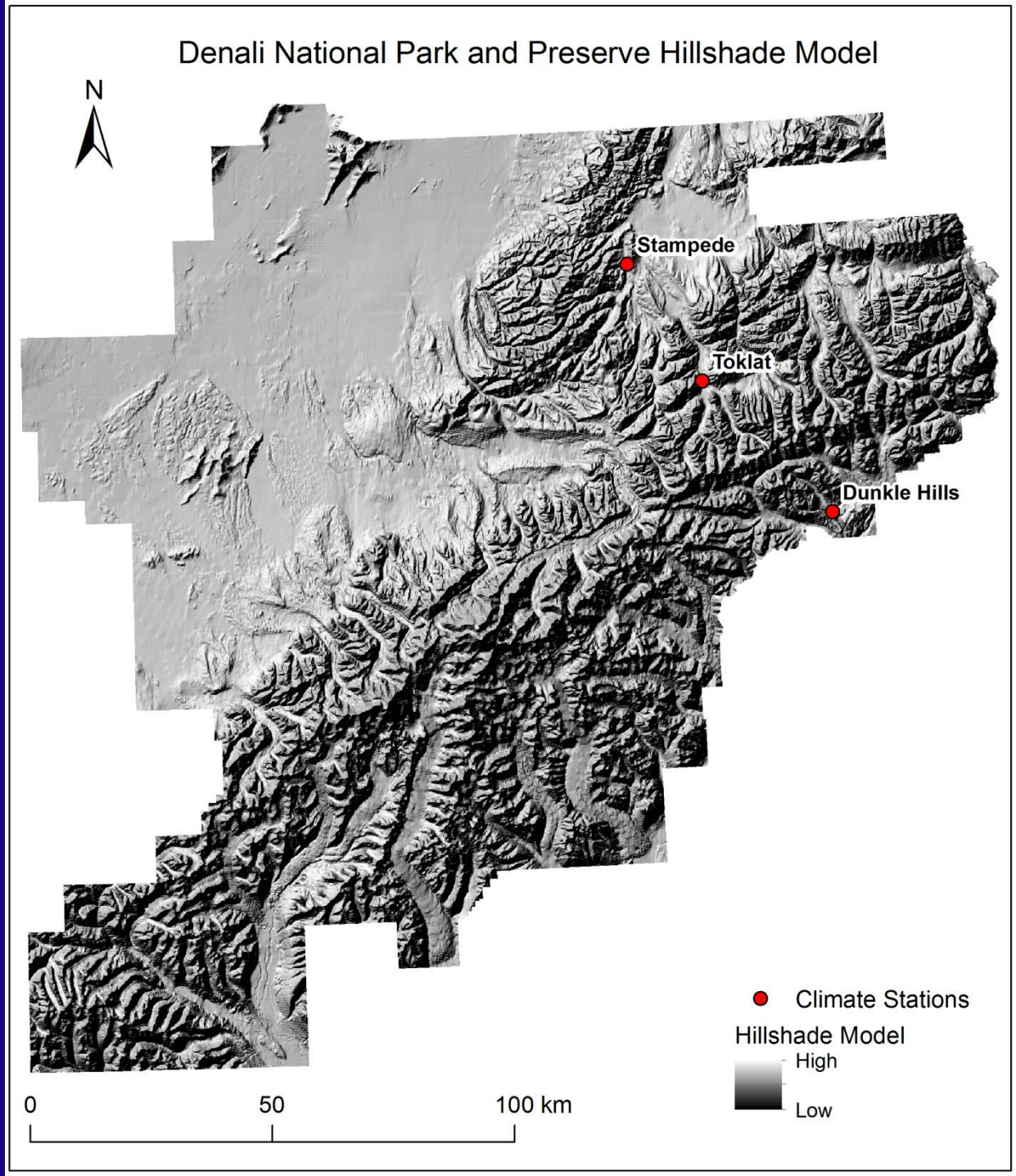
*Clark and Duffy* (2006 )
Field data (Aug.-Sept. 1997-2002)

Permafrost absent at 967 Sites
Agree (84%)
Disagree (16%)

| Modeled | Field |
|---|---|
| Present | Absent |
| Absent | Absent |

Possible reasons of disagreement:

- Scale
- Model limitations

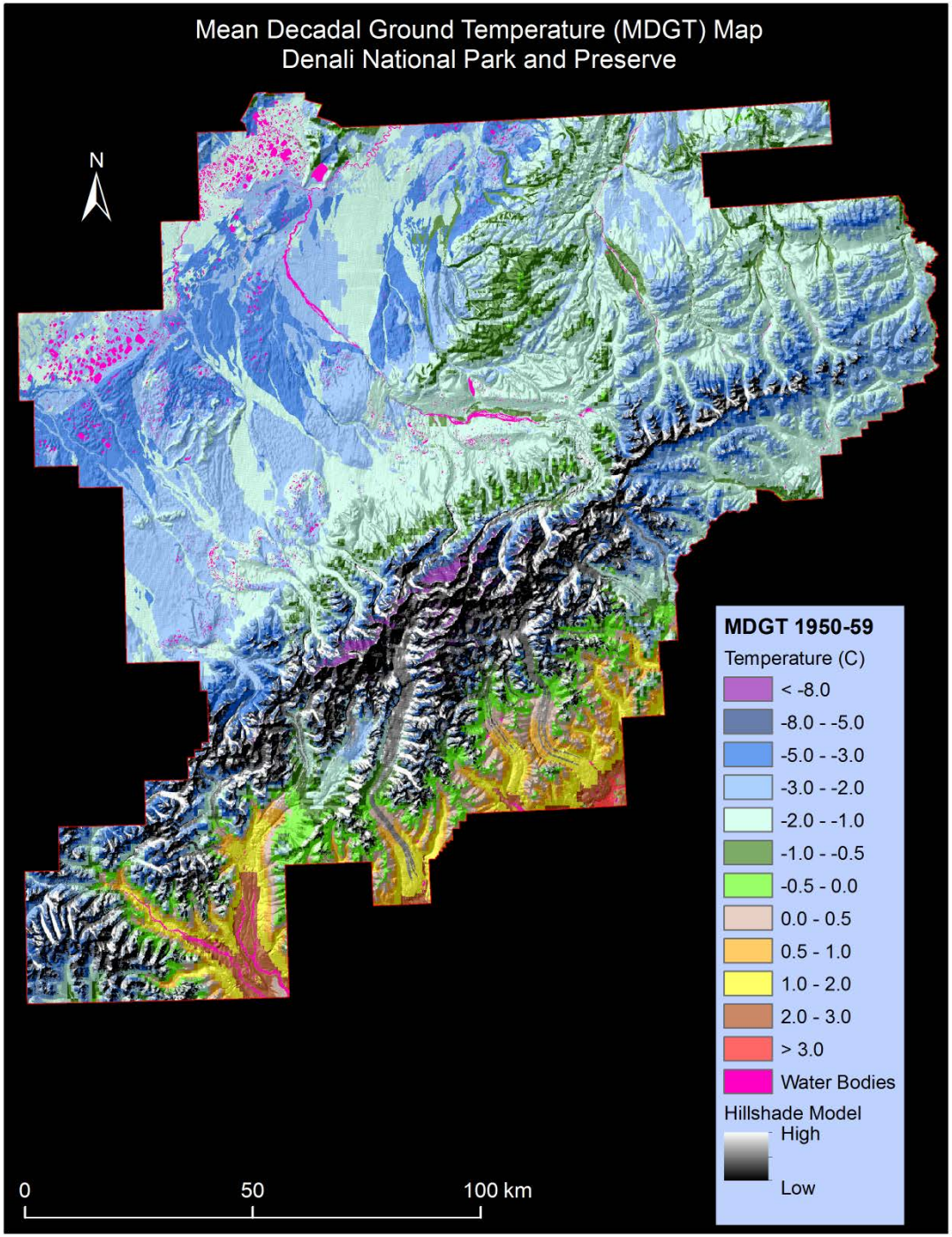

Denali National Park and Preserve Hillshade Model
N
Stampede
Toklat
Dunkle Hills
Climate Stations
Hillshade Model
High
Low
0
50
100 km

# Comparison with recorded ground temperature

| *Recorded at climate stations* | Dunkle Hills | Stampede | Toklat |
|---|---|---|---|
| Average air temperature | -2.8 °C (2005-10) | -4.1 °C (2005-10) | -3.1 °C (2006-10) |
| Average ground temperature at 0.02 m | 1.1 °C (2005-10) | 0.4 °C (2005-10) | 1.0 °C (2006-10) |
| | | | |
| CRU average air temperature (2000-09) | -1.8 °C | -1.6 °C | -1.4 °C |
| *Modeled (2000-09)* | | | |
| Average ground surface temperature | 0.3 °C | 0.9 °C | 0.6 °C |
| Average ground temperature at the bottom of seasonal freeze-thaw layer | 0.1 °C @ 0.75 m | -0.6 °C @ 1.12 m | 0.1 °C @ 1.0 m |

**Smaller (< 1 °C) differences between modeled ground surface temperatures and recorded ground temperatures (at 0.02 m)**

Modeled permafrost maps with past climate forcing




# Permafrost Map CRU 1950-59 forcing

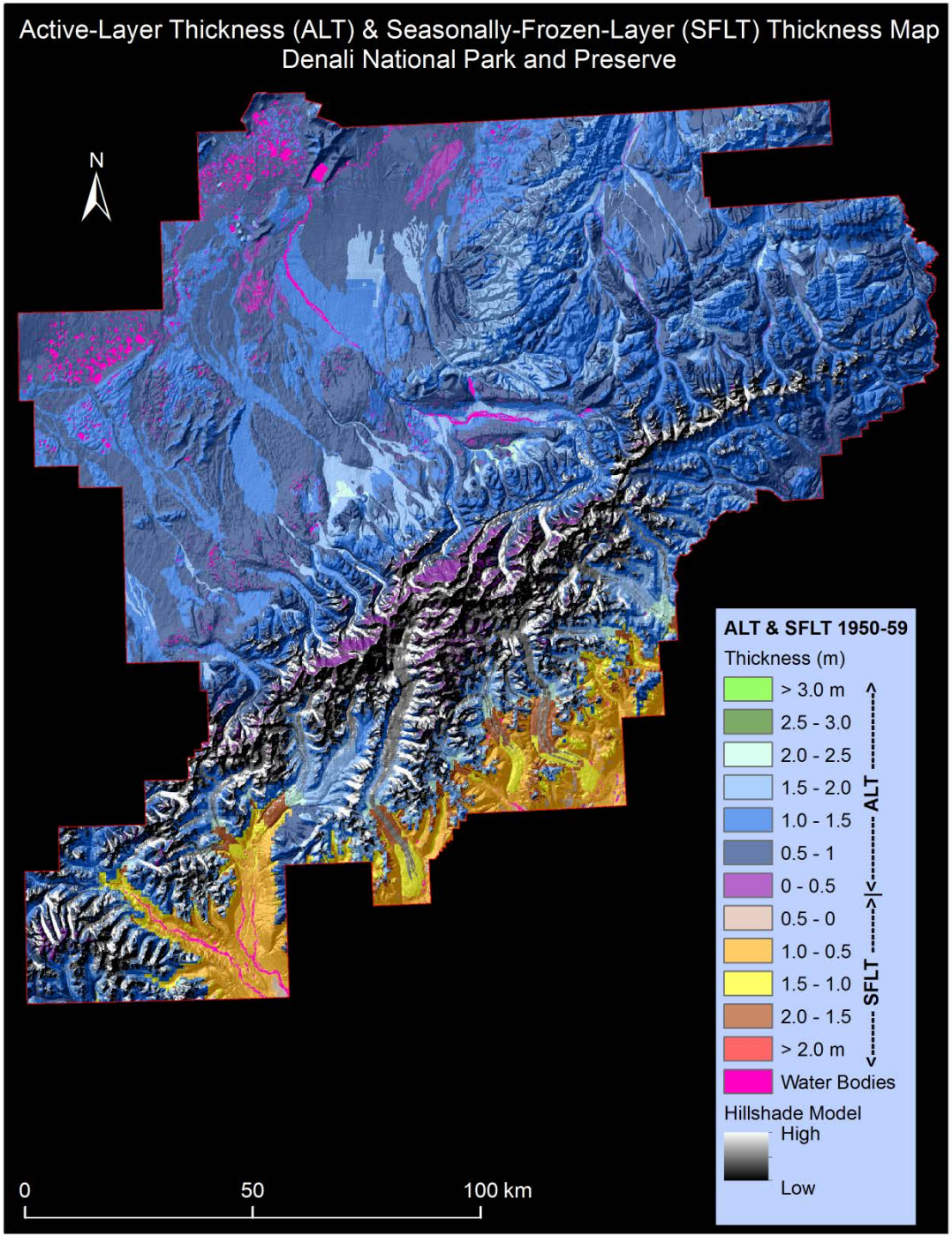
**Ground temperature at the bottom of *seasonal freeze-thaw layer***

***Climate input:***

**Decadal mean air temp.: -3.5 °C**
**Decadal mean annual precip.: 679 mm**

***Modeled permafrost characteristics:***

**Near-surface permafrost @ 75% of DENA**
**Mean decadal permafrost temp.: -2.1 °C**




# Thickness of Seasonal Freeze-Thaw Layer Map CRU 1950-59 forcing

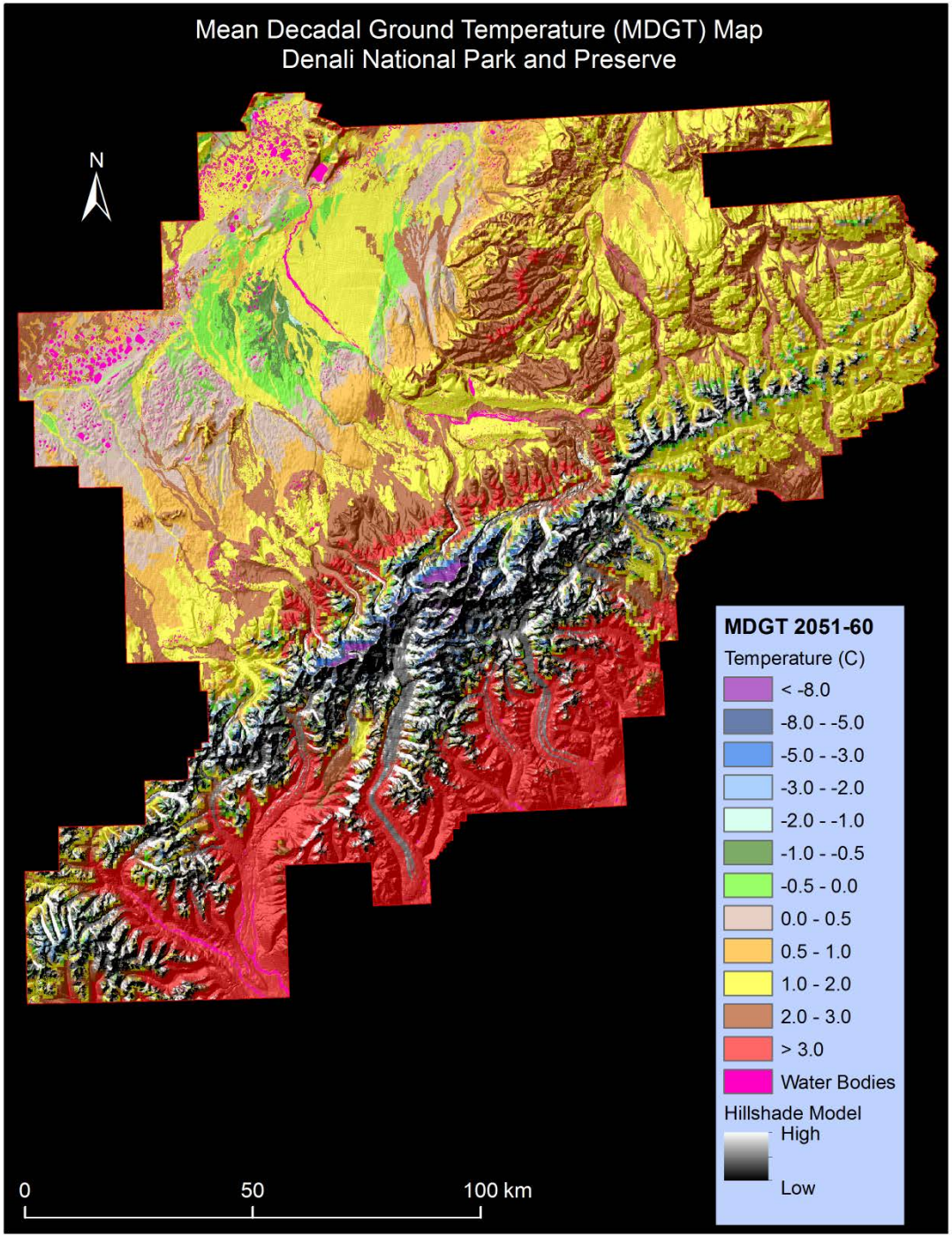
*Climate input:*

**Decadal mean air temp.: -3.5 °C**
**Decadal mean annual precip.: 679 mm**

*Modeled permafrost characteristics:*

**Mean Decadal ALT: 1.1 m**
**Active-Layer Thickness < 1 m: 38%**

Modeled permafrost maps with future climate forcing




# Permafrost Map 5-GCM 2051-60 forcing

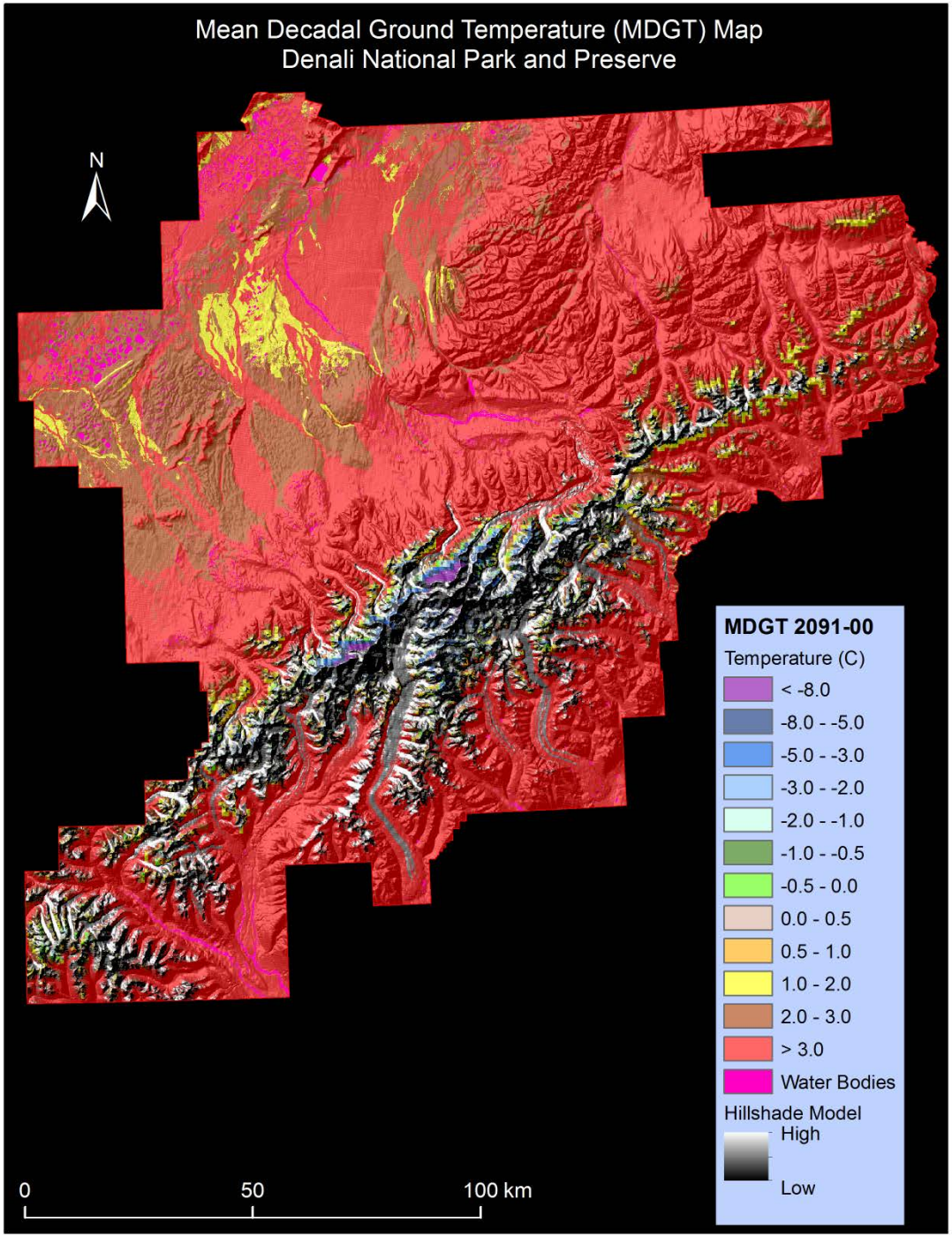
**Ground temperature at the bottom of *seasonal freeze-thaw layer***

***Climate input:***

**Decadal mean air temp.: -0.7 °C**
**Decadal mean annual precip.: 845 mm**

***Modeled permafrost characteristics:***

**Near-surface permafrost @ 6% of DENA**
**Mean decadal permafrost temp.: -1.3 °C**




# Permafrost Map 5-GCM 2091-00 forcing

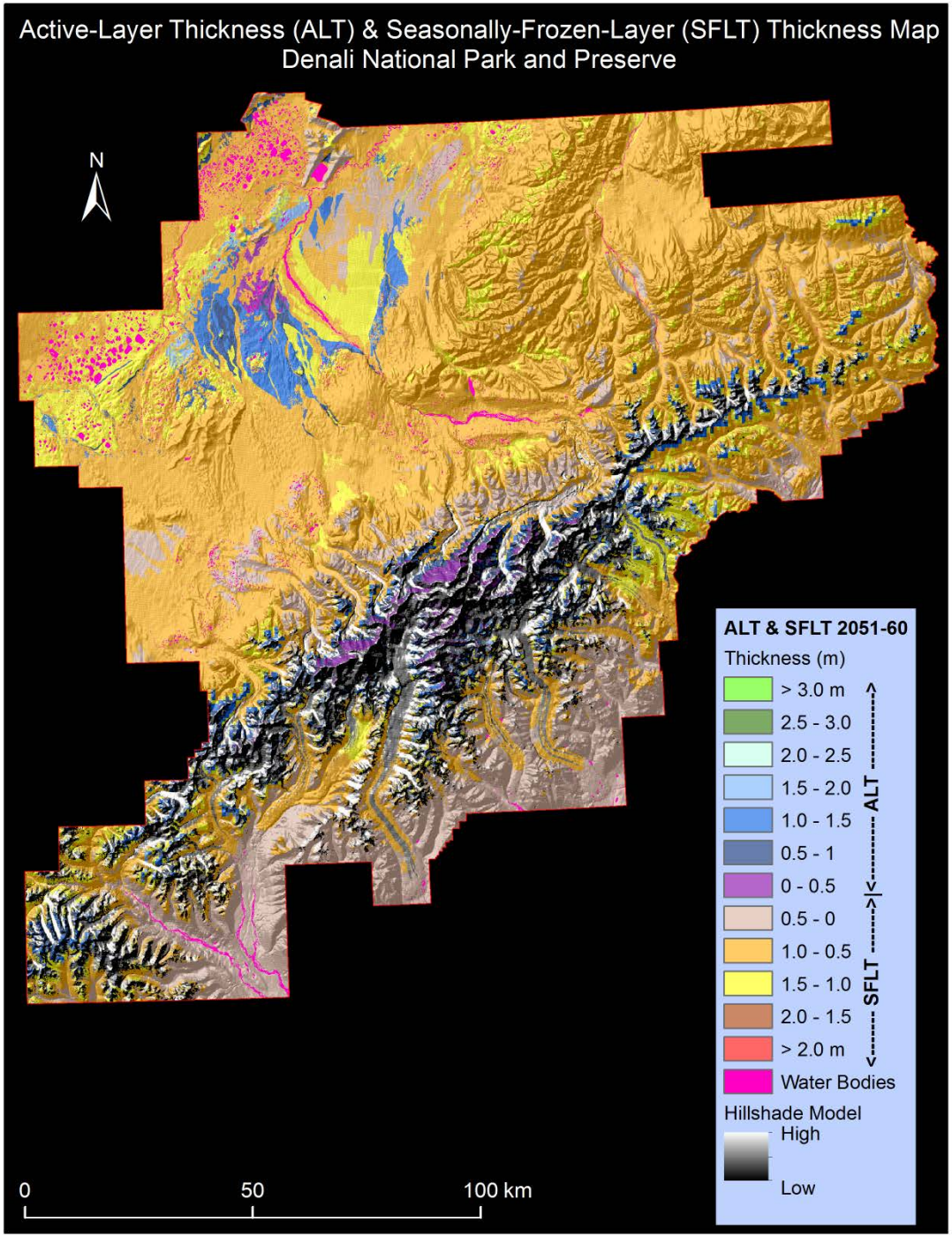
**Ground temperature at the bottom of *seasonal freeze-thaw layer***

***Climate input:***

**Decadal mean air temp.: +2.7 °C**
**Decadal mean annual precip.: 938 mm**

***Modeled permafrost characteristics:***

**Near-surface permafrost @ 1% of DENA**
**Mean decadal permafrost temp.: -3.3 °C**



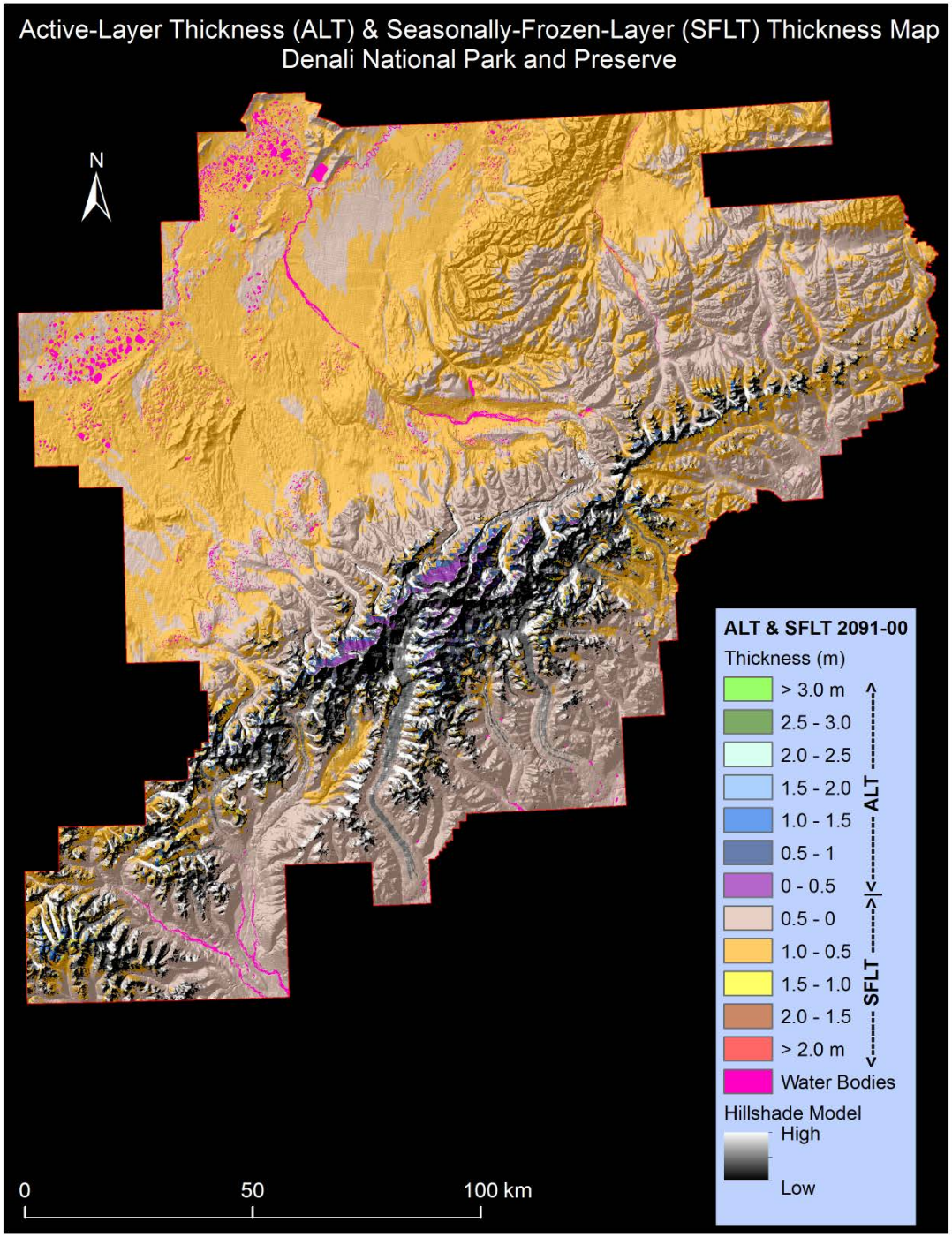

# Thickness of Seasonal Freeze-Thaw Layer Map 5-GCM 2051-60 forcing

*Climate input:*

**Decadal mean air temp.: -0.7 °C**
**Decadal mean annual precip.: 845 mm**

*Modeled active-layer characteristics:*

**Mean Decadal ALT: 1.1 m**
**Active-Layer Thickness < 1 m: 2 %**



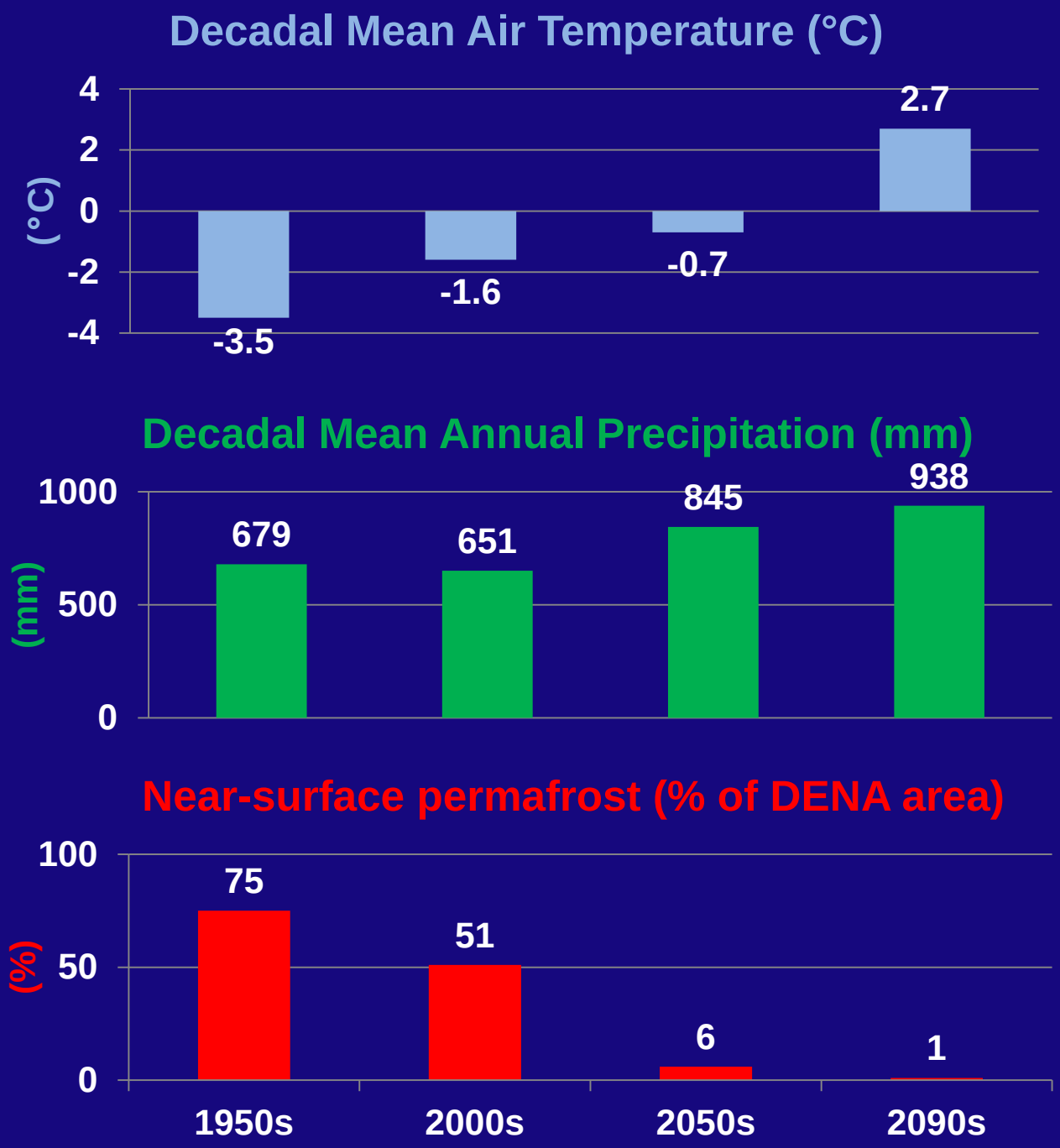

# Thickness of Seasonal Freeze-Thaw Layer Map 5-GCM 2091-00 forcing

*Climate input:*

**Decadal mean air temp.: +2.7 °C**
**Decadal mean annual precip.: 938 mm**

*Modeled active-layer characteristics:*

**Mean Decadal ALT: 0.8 m**
**Active-Layer Thickness < 1 m: 0.7 %**


Decadal Mean Air Temperature (°C)
(°C)
4
2
0
-2
-4
-3.5
-1.6
-0.7
2.7
Decadal Mean Annual Precipitation (mm)
(mm)
1000
500
0
679
651
845
938
Near-surface permafrost (% of DENA area)
(%)
100
50
0
75
51
6
1
1950s
2000s
2050s
2090s

# Summary

- ✓ Improved high-resolution (28 m) permafrost maps
- ✓ 86% agreement with field observations
- ✓ Smaller (< 1 °C) differences between modeled and recorded ground temperatures
- ✓ Scale and model limitations
- ✓ Near-surface ‘stable’ permafrost distribution is predicted to decline from present 51% of DENA area to a mere 6% by 2050s and to 1% by 2090s
- ✓ Only tiny areas of bedrock terrain at highest elevations are predicted to maintain ‘stable’ permafrost

# Broader impacts

- How permafrost distribution may evolve in response to changing climate?
- Identify sites with higher risk of permafrost thawing
- Enable informed decision making

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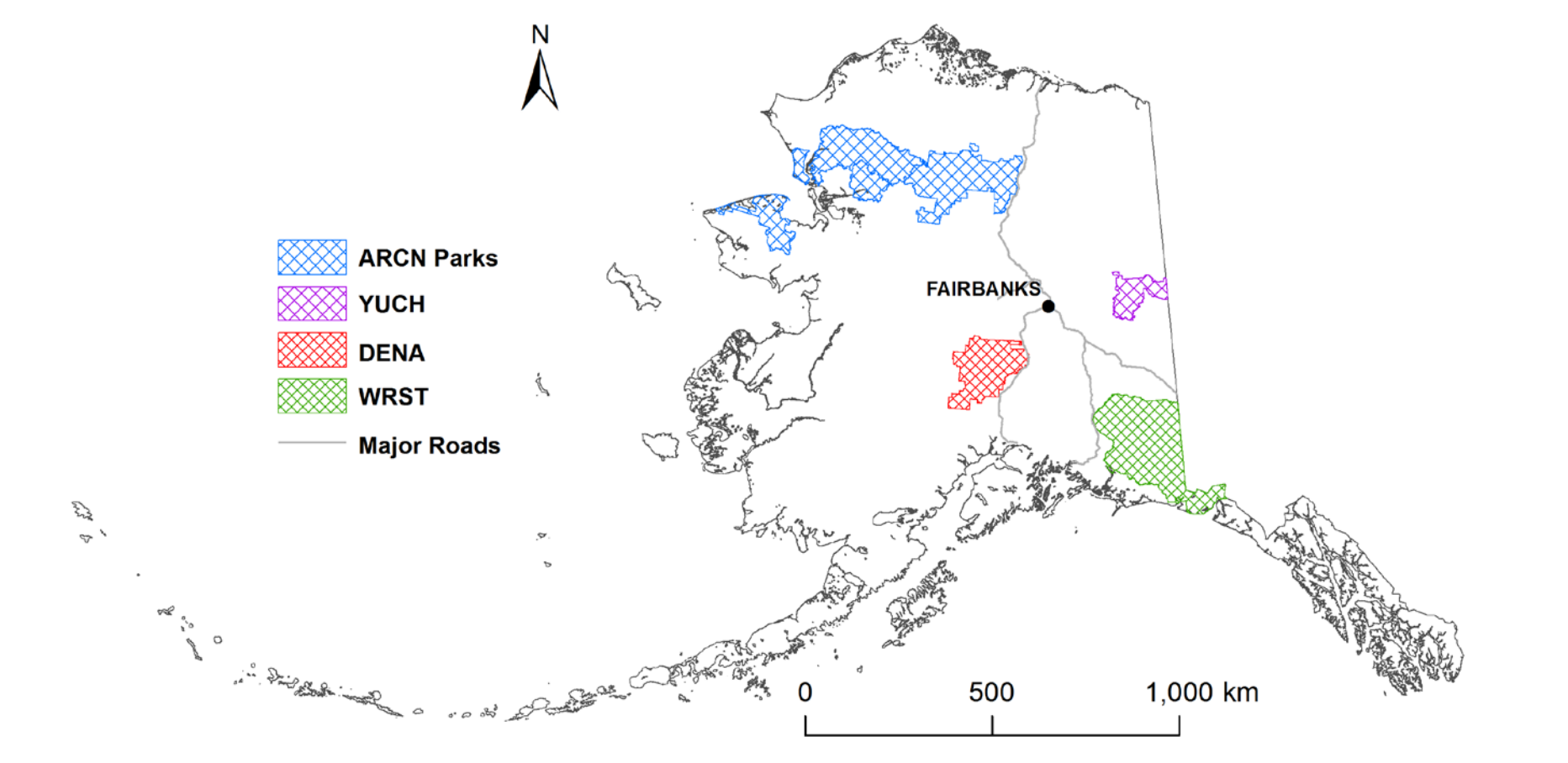
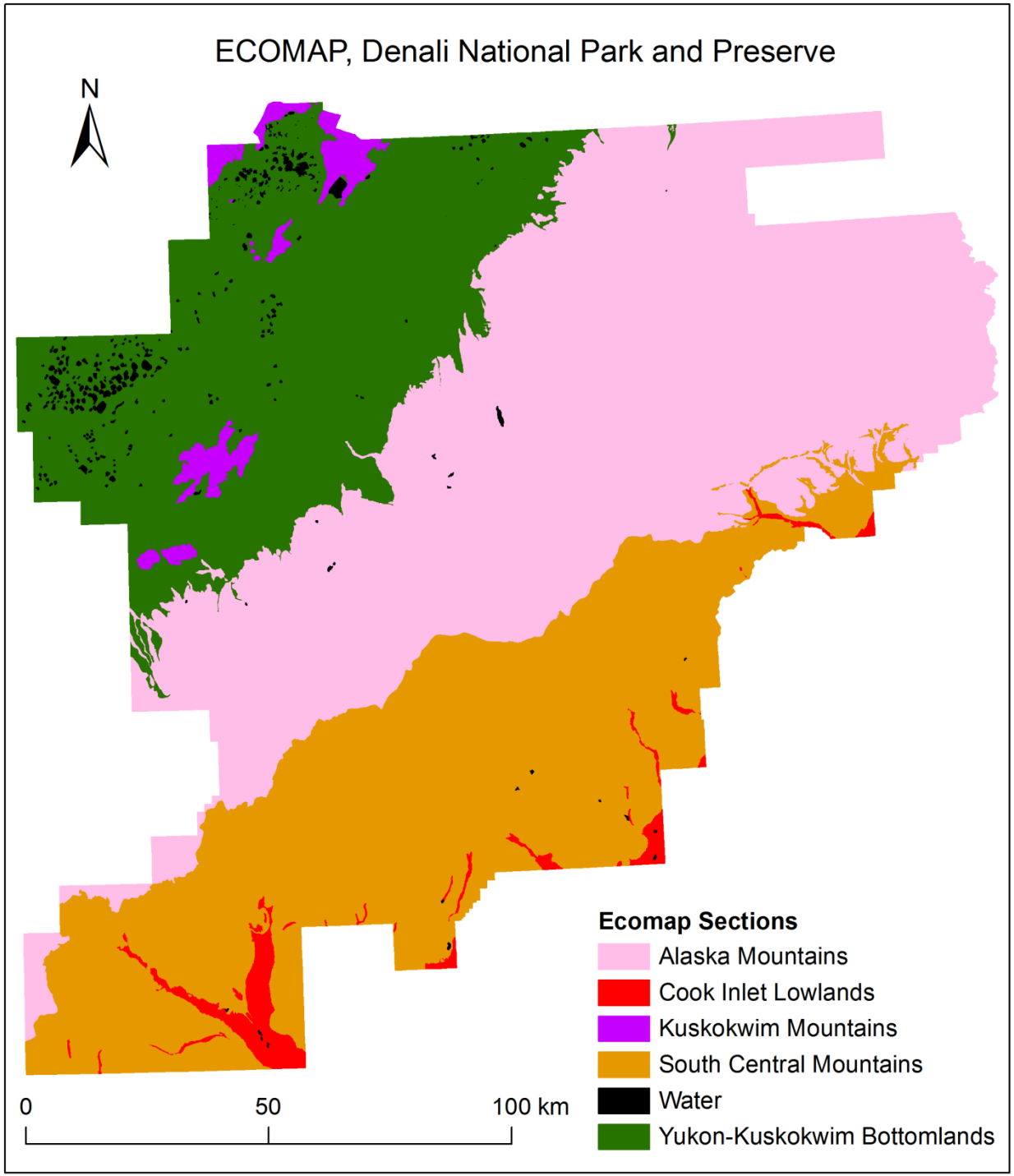
# Permafrost-affected NPS Units




*http://permafrost.gi.alaska.edu/project/permafrost-modeling-alaskan-national-park-lands*


Thank you for your time and attention.
Photo credit: Daniel A. Leifheit


ECOMAP, Denali National Park and Preserve
N
Ecomap Sections
Alaska Mountains
Cook Inlet Lowlands
Kuskokwim Mountains
South Central Mountains
Water
Yukon-Kuskokwim Bottomlands
0
50
100 km

# Summary statistics of climate and modeled permafrost characteristics

| *Climate characteristics* | *1950-59* | *2000-09* | *2051-60* | *2091-00* |
|---|---|---|---|---|
| Mean decadal air temperature (°C) | -3.5 | -1.6 | -0.7 | +2.7 |
| Mean decadal precipitation (mm) | 679 | 651 | 845 | 938 |
| *Modeled permafrost characteristics* | | | | |
| Permafrost distribution (%) | 75 | 51 | 6 | 1 |
| Mean decadal permafrost temperature (°C) | -2.1 | -1.1 | -1.3 | -3.3 |
| Mean decadal active-layer thickness (m) | 1.1 | 1.1 | 1.1 | 0.8 |