Snow Persistence and Snow Depth Mapping in Alaska using the Landsat Archive

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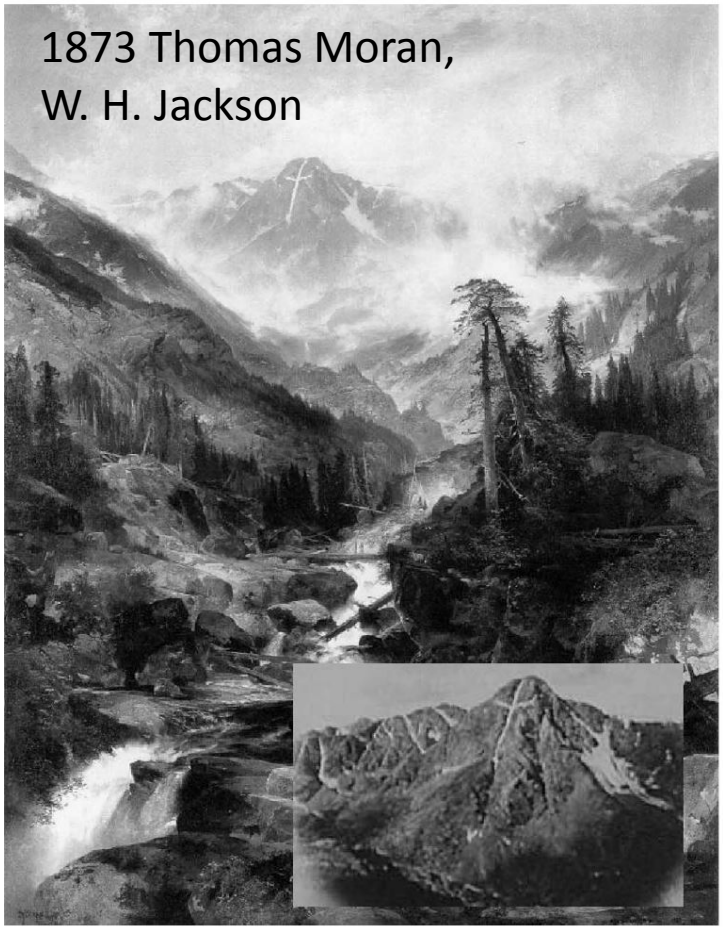
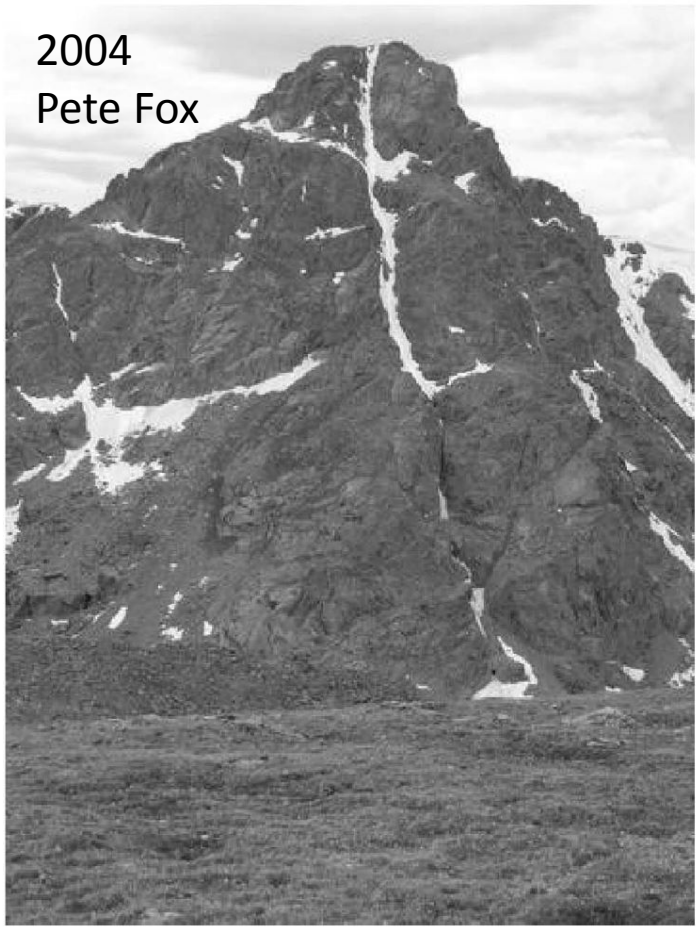
Overview

- Repeated Snow Patterns Background
- Time-series Remote Sensing of Snow Depth Patterns (Lidar)
- Time-series Remote Sensing of Snow Persistence Patterns (Landsat)
- Predicting Snow Depth from Snow Persistence Patterns

Spatial Variability and Repeated Patterns in Snow Distribution

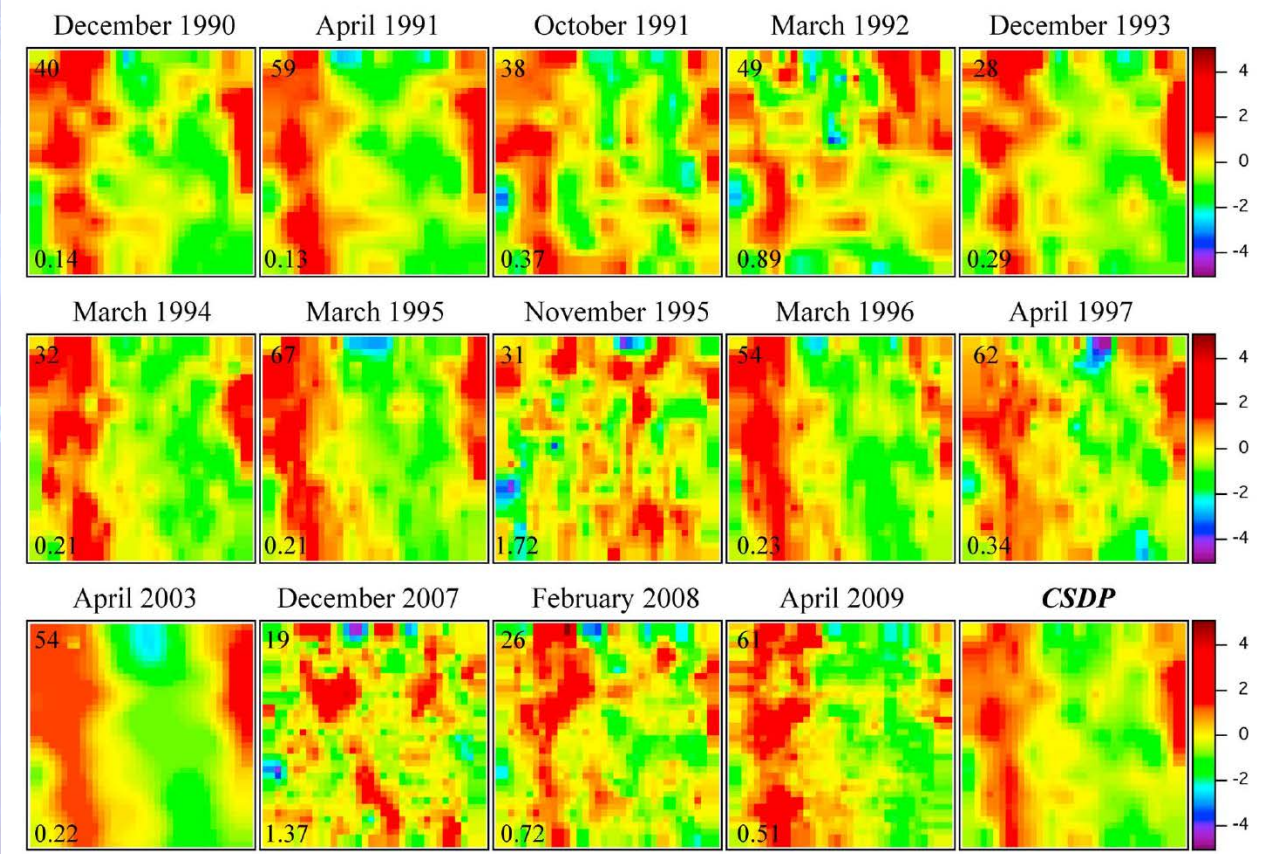




Sturm and Wagner, 2010. Using repeated patterns in snow distribution modeling: An Arctic example. Water Resources Research 46: W12549.

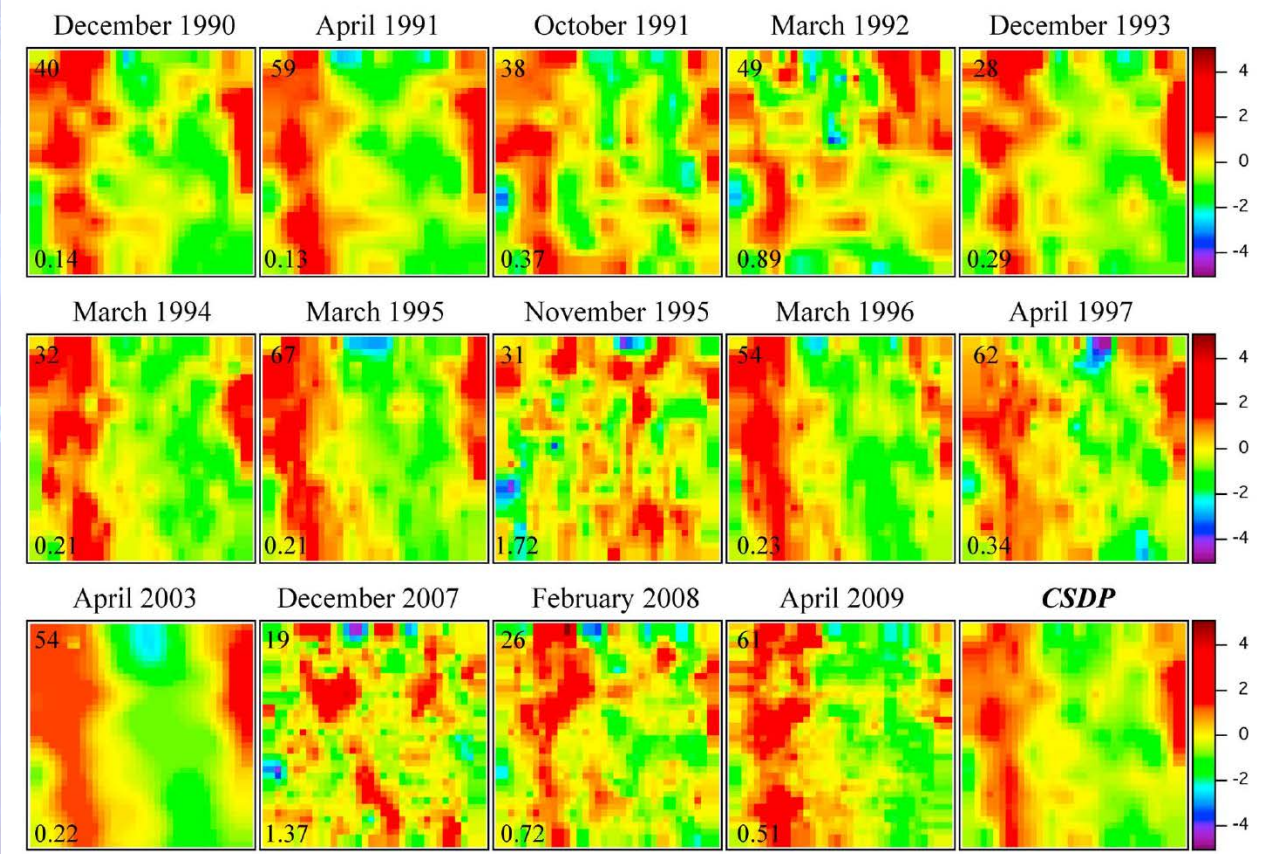
Characterizing Snow Persistence Patterns

- Sturm and Wagner 2010: Repeat manual measurements on 1 km x 1 km Imnavait grid



Characterizing Snow Persistence Patterns

- Climatalogical Snow Distribution Pattern (CSDP): Mean normalized snow depth (z-score)



Spatial Variability and Repeated Patterns in Snow Distribution

- Topography
- Vegetation
- Consistent Synoptic Weather Patterns

Topography

- Elevation
  - Temperature (Rain vs. Snow)
  - Orographic precipitation
  - Extra 1” snow per 1000’ elevation around Fairbanks
- Drift Traps
- Exposure / Shading

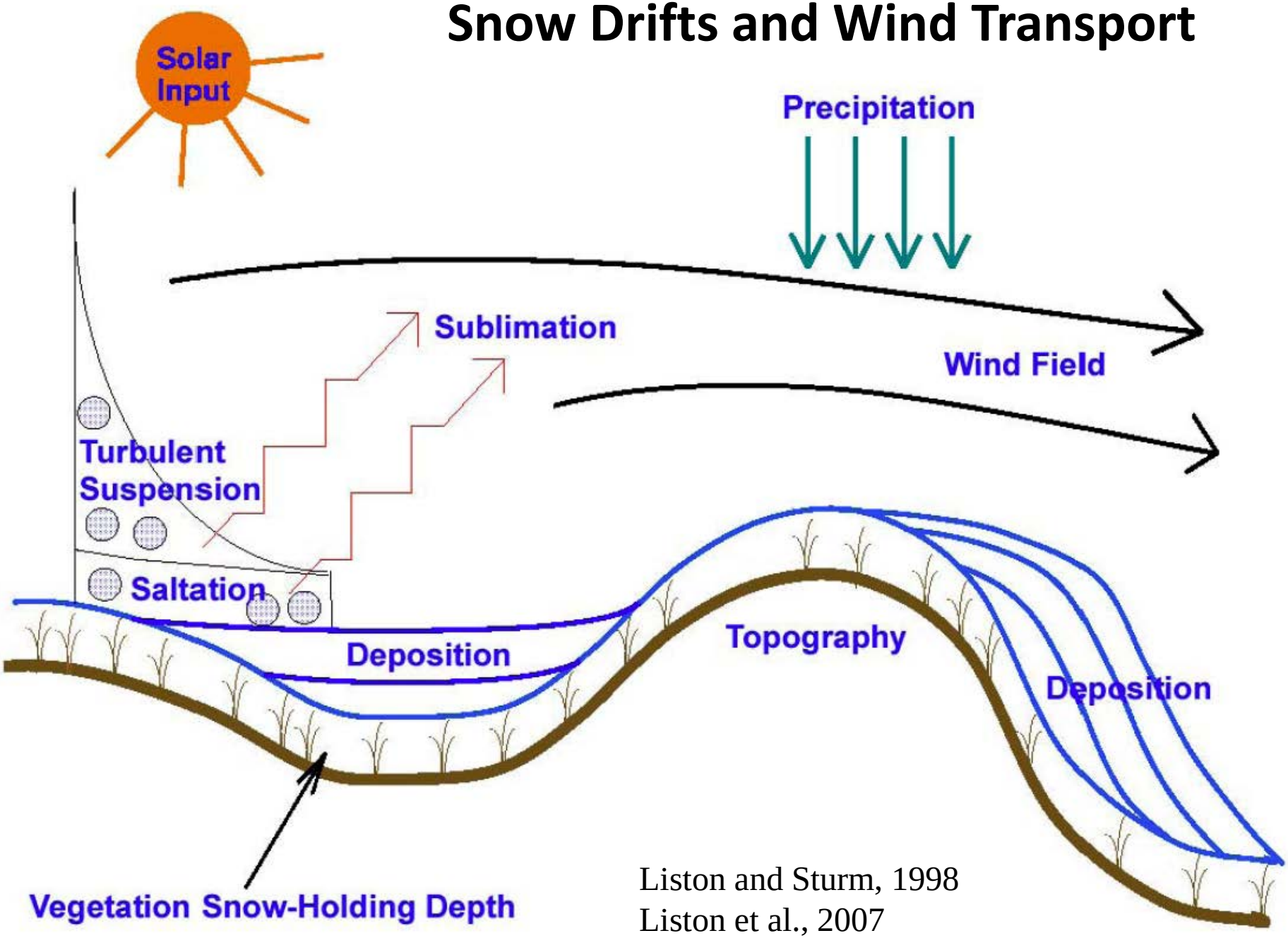
Vegetation

- Canopy Interception
- Albedo
- Shading
- Drift Traps

Weather

- Precipitation
- Temperature
- Storm Tracks
- Wind

Snow Drifts and Wind Transport



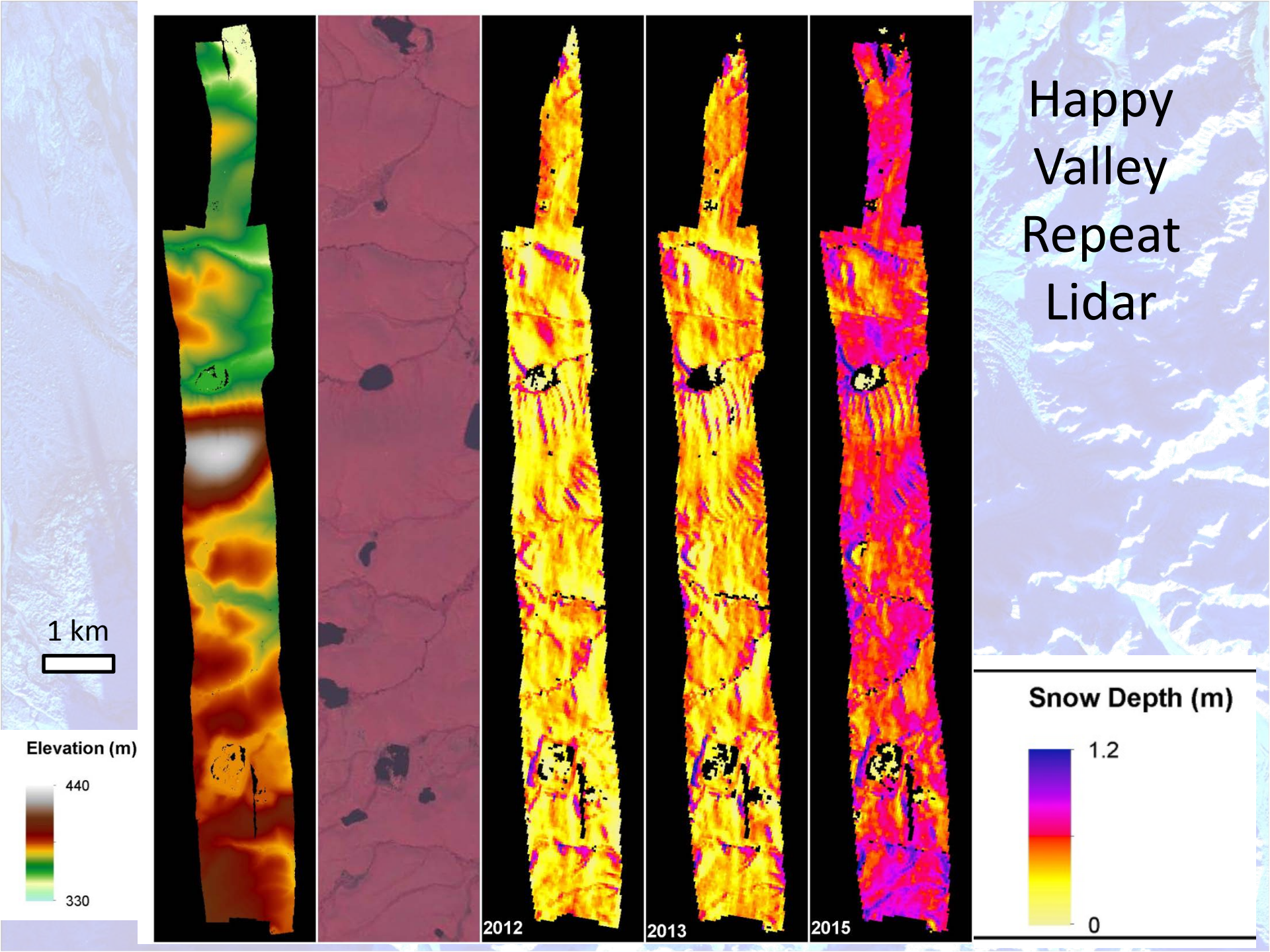
Liston and Sturm, 1998
Liston et al., 2007

Remote Sensing of Snow Depth

- Measured by DEM differencing
  - Also requires snow-free elevation model
  - Accuracies >> snow depth
- Lidar
  - Aerial or ground
- Structure from Motion
  - High-resolution aerial / drone photography

Happy Valley Repeat Lidar Location

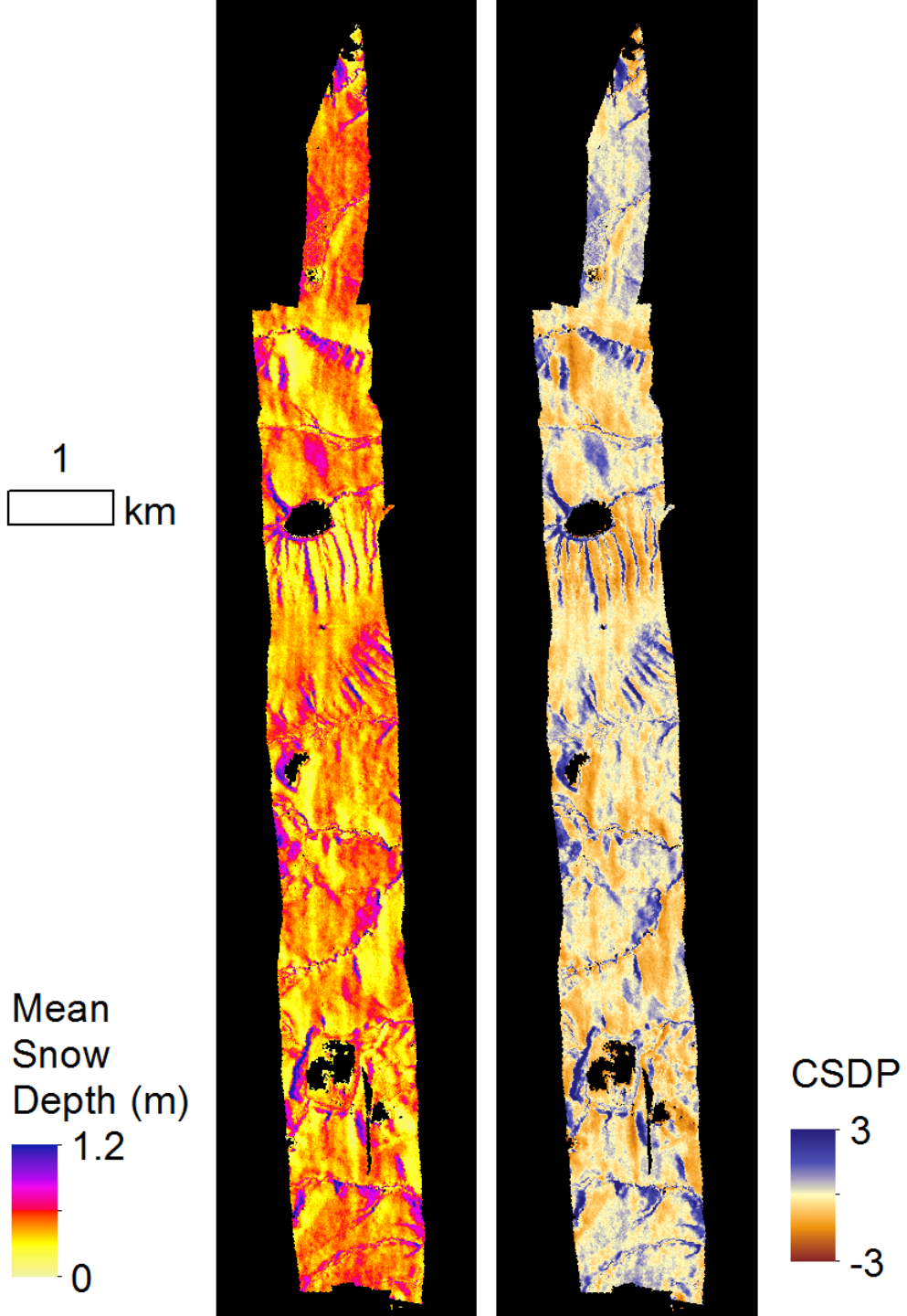
Happy Valley Repeat Lidar

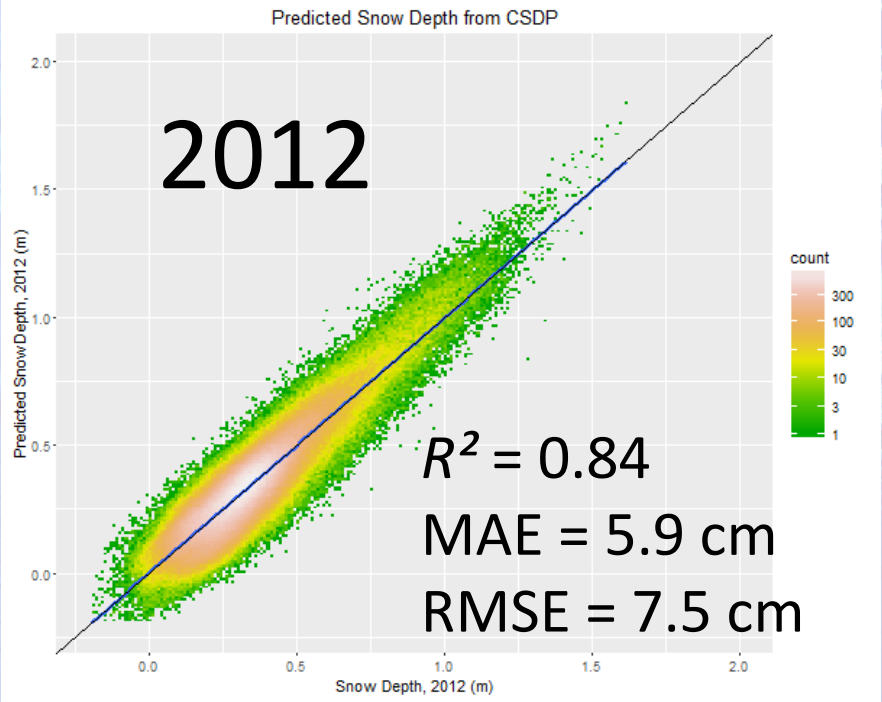


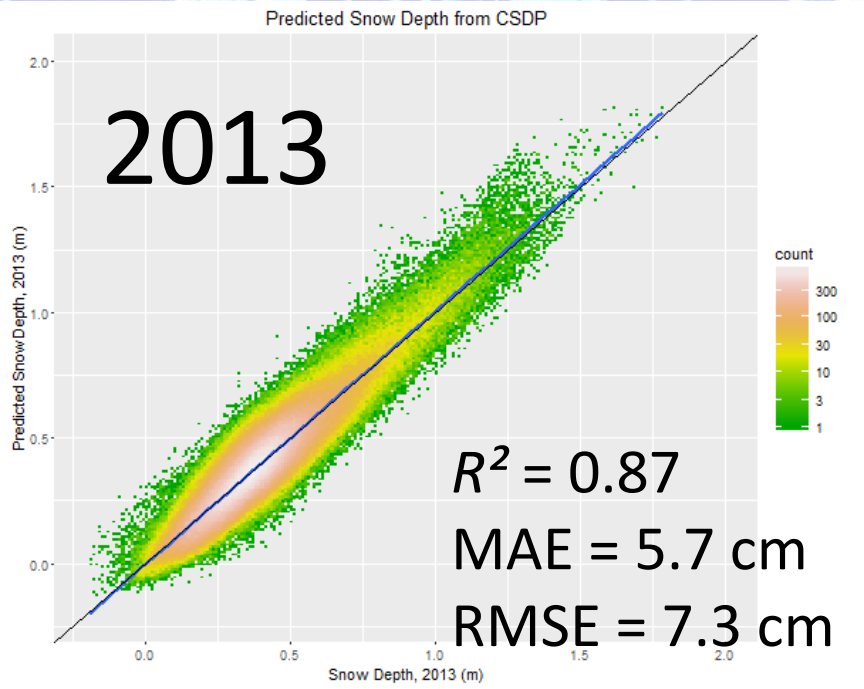
Happy Valley Snow Depths Summary

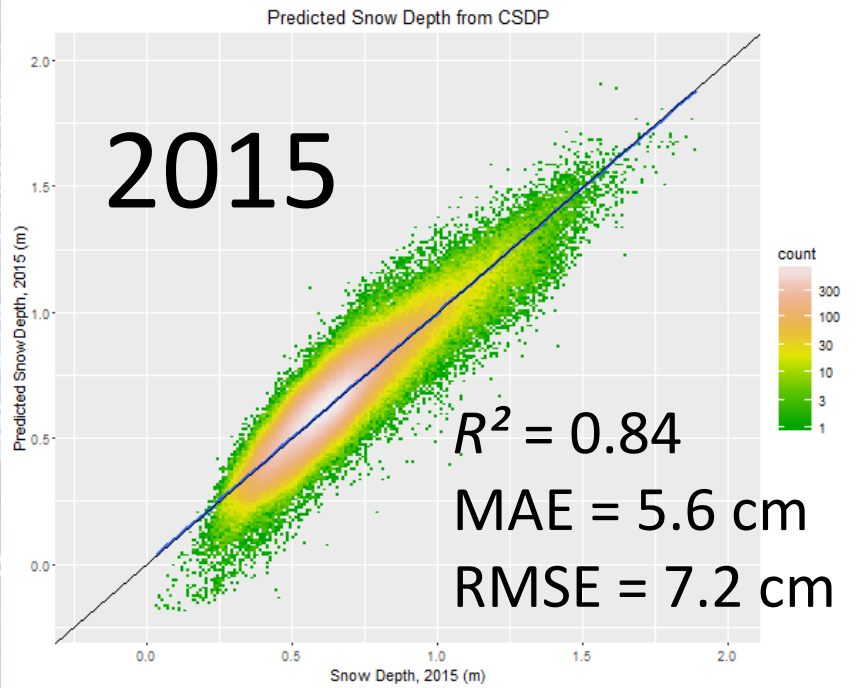
Year	Mean Snow Depth (m)	SD Snow Depth (m)
2012	0.3397	0.1916
2013	0.3990	0.2079
2015	0.6365	0.1881

Happy Valley Repeat Lidar: Climatological Snow Distribution Pattern (CSDP)




Predicted Snow Depth from CSDP
2012
R^2 = 0.84
MAE = 5.9 cm
RMSE = 7.5 cm
Predicted Snow Depth, 2012 (m)
Snow Depth, 2012 (m)
count
300
100
30
10
3
1
0.0
0.5
1.0
1.5
2.0


Predicted Snow Depth from CSDP
2013
R^2 = 0.87
MAE = 5.7 cm
RMSE = 7.3 cm
Predicted Snow Depth, 2013 (m)
Snow Depth, 2013 (m)
count
300
100
30
10
3
1
0.0
0.5
1.0
1.5
2.0


Predicted Snow Depth from CSDP
2015
R^2 = 0.84
MAE = 5.6 cm
RMSE = 7.2 cm
Predicted Snow Depth, 2015 (m)
Snow Depth, 2015 (m)
count
300
100
30
10
3
1
0.0
0.5
1.0
1.5
2.0

Characterizing Snow Persistence Patterns

- Where a consistent Climatological Snow Distribution Pattern (CSDP) occurs, it can be applied to predict snow distribution on the landscape with relatively few, stratified snow depth measurements
- How to map a CSDP over large areas without intensive repeat lidar?

Remote Sensing of Snow Persistence

- How to map a CSDP over large areas without intensive repeat lidar?
  - Snow covered area depletion
  - Snow cover as a function of date

Snow-Covered Area

- Visible to Infrared wavelengths
- Snow brighter than most other materials in visible wavelengths
  - Except clouds
- Snow dark in “short-wave” infrared
  - Normalized Difference Snow Index
- Infrared information helps in snow / cloud discrimination

Snow Cover Algorithms

- Normalized Difference Snow Index (NDSI):

$$\frac{VIS - SWIR}{VIS + SWIR}$$

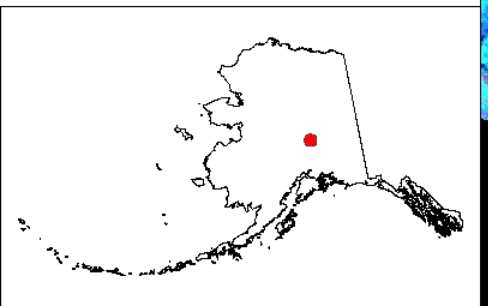
- Binary SnowMap (Presence/Absence)
  - NDSI Threshold > 0.4 = Snow
  - Also minimum values for visible and NIR reflectance must be exceeded

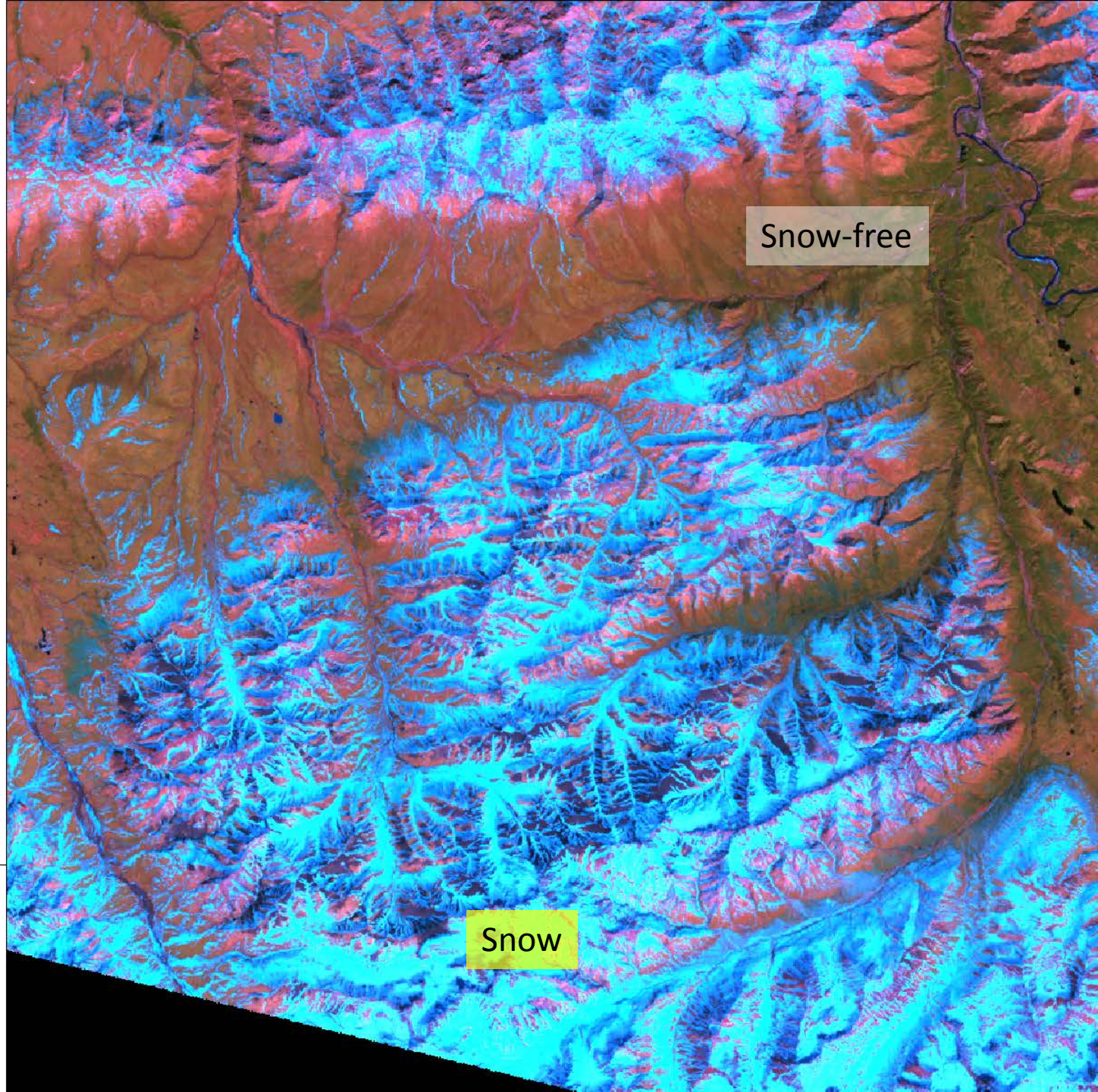
Denali National Park and Preserve Entrance

Landsat 5 TM 24 May 1998

- Snow-free
- Snow
- Cloud
- No Data

5 Km





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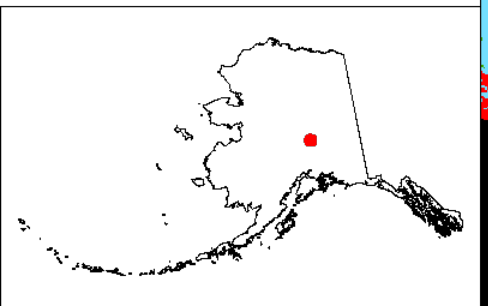
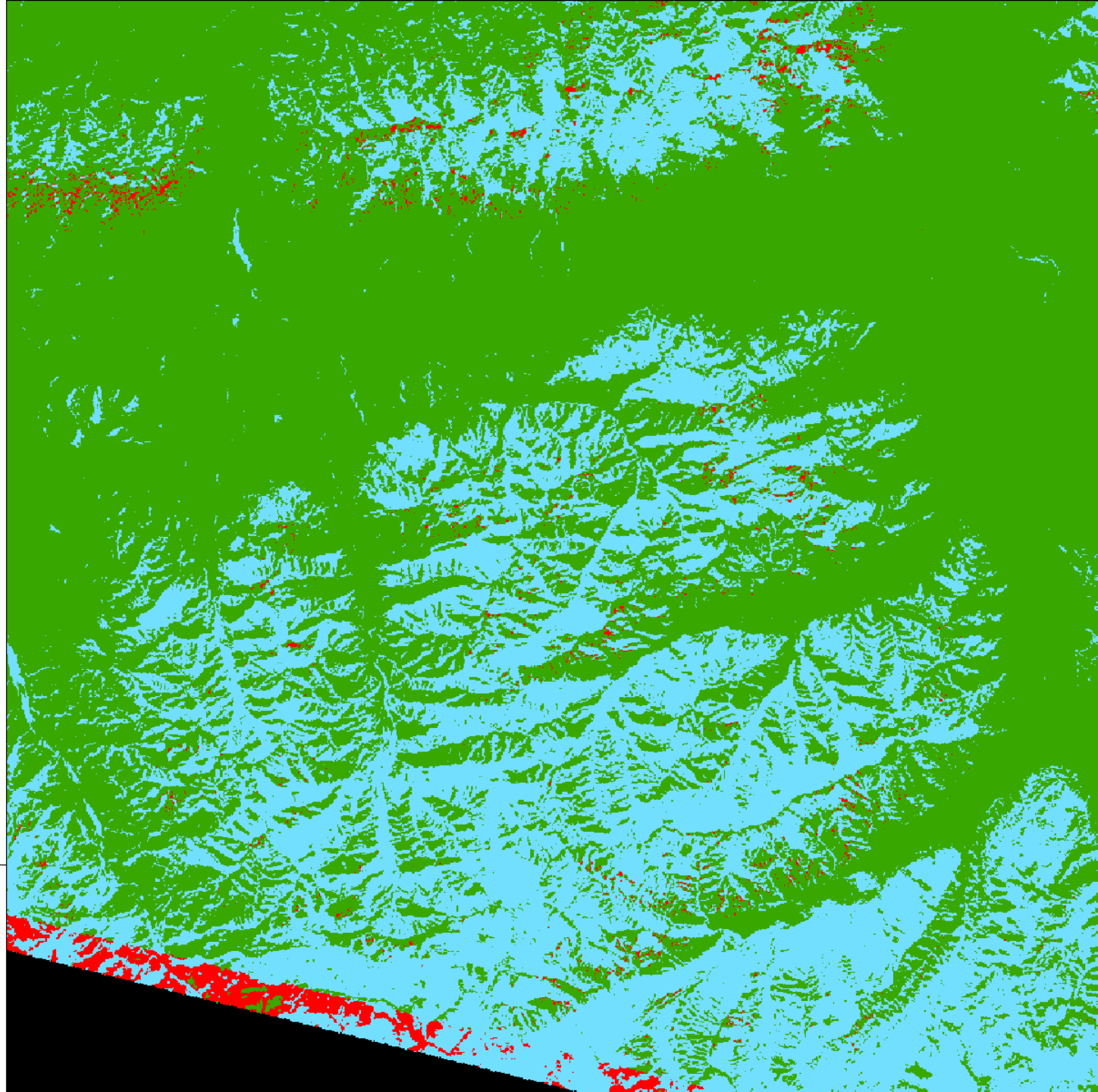
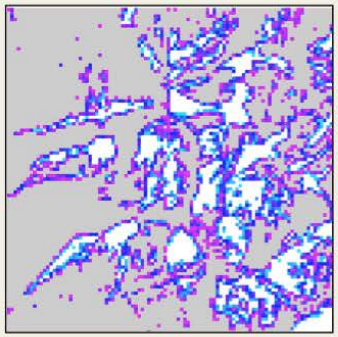
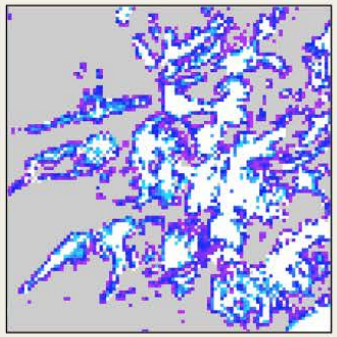


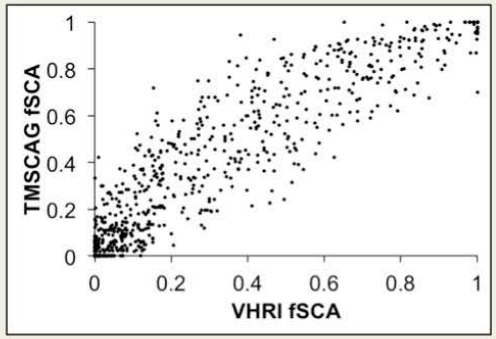


Landsat Fractional Snow Covered Area (fSCA) Product Validation from Very High Resolution Imagery (VHRI)

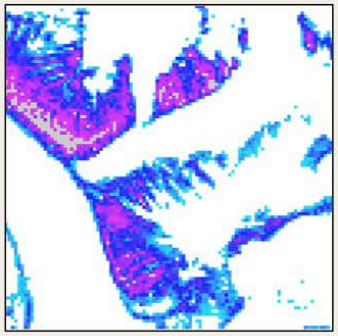
High Res Imagery | **30 m fSCA from VHRI** | **30 m fSCA from Landsat** | **VHRI vs Landsat Comparison**

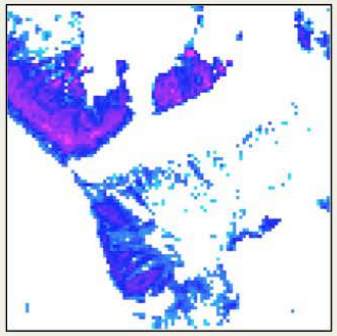


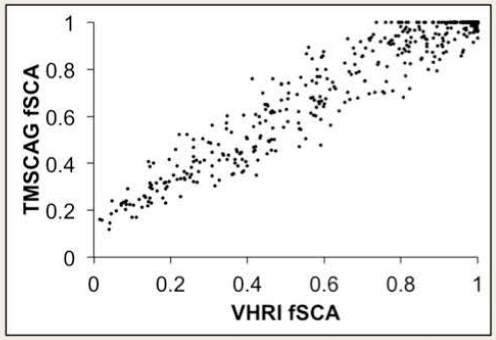




Southern Andes, Chile January 1, 2015 Soar Elevation Angle: 47° RMSE: 0.14







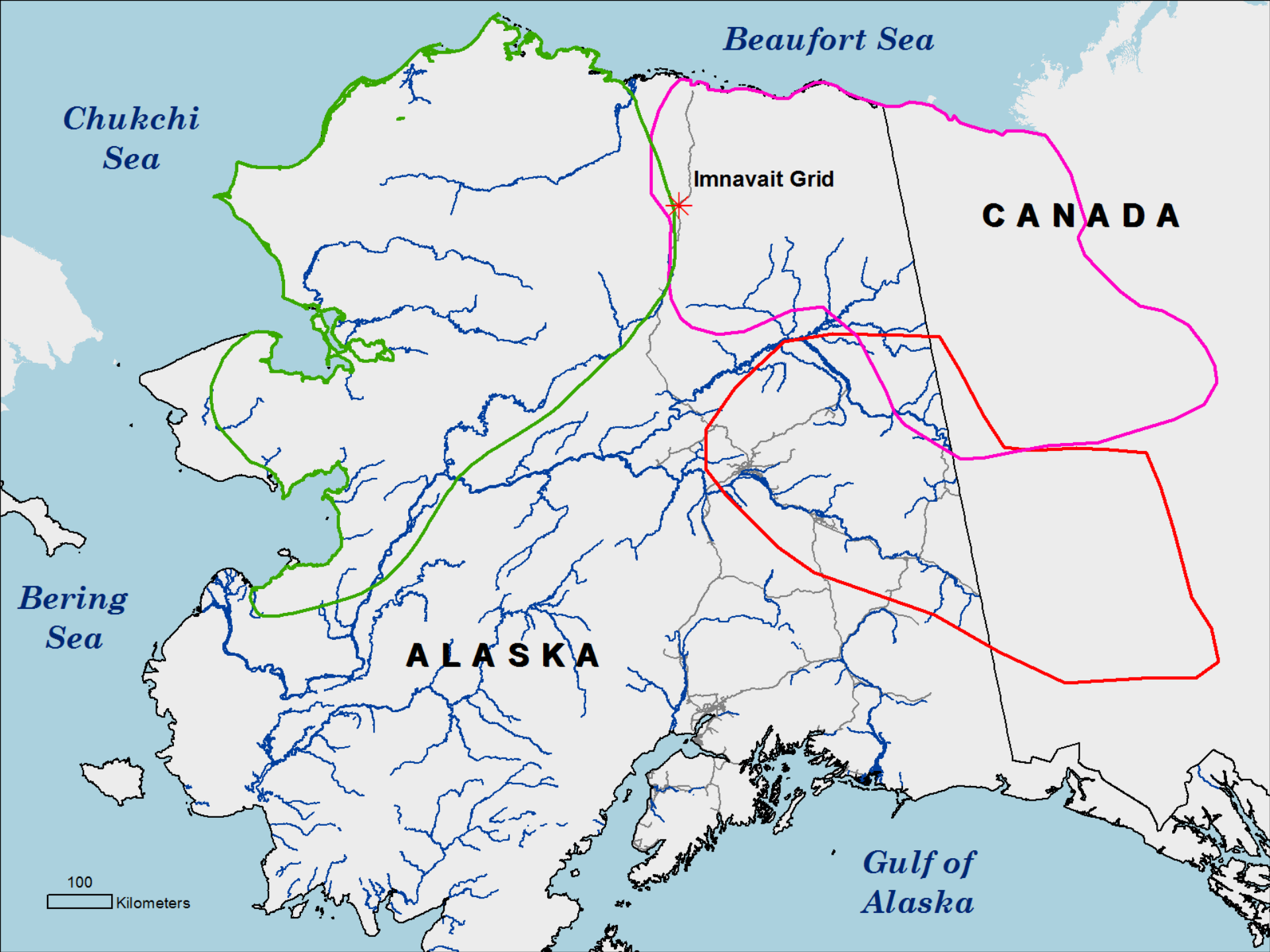
Mount Everest Region, Nepal May 1, 2015 Solar Elevation Angle: 66° RMSE: 0.08

Snow Cover Fraction

0 **0.5** **1.0**

0 **1.5 km**

Each validation subset is 3 x 3 km and contains 10,000 Landsat pixels.


Beaufort Sea
Chukchi Sea
Imnavait Grid
CANADA
Bering Sea
ALASKA
Gulf of Alaska
100
Kilometers

Snow Persistence Patterns from Remote Sensing

- Annual, Coarse Resolution (500 m+) maps of daily or weekly snow cover are available
- These data are unsuitable for many applications
  - Mapping snow drifts and snowbeds
  - Highly variable snow cover across short distances
    - Mountainous terrain
    - Areas where wind dominates snow distribution
  - Lake- and pond-rich landscapes
    - Different time-scale for snow and lake ice melt

Snow Persistence Patterns from the Landsat Archive (1999–present)

- 30+ years of Landsat imagery (back to 1985)
  - Imagery acquired at peak snow cover in late winter and early spring.
  - Imagery acquired during various stages of snowmelt during spring and into summer.
  - Hundreds of images with information about snow cover for any location of interest

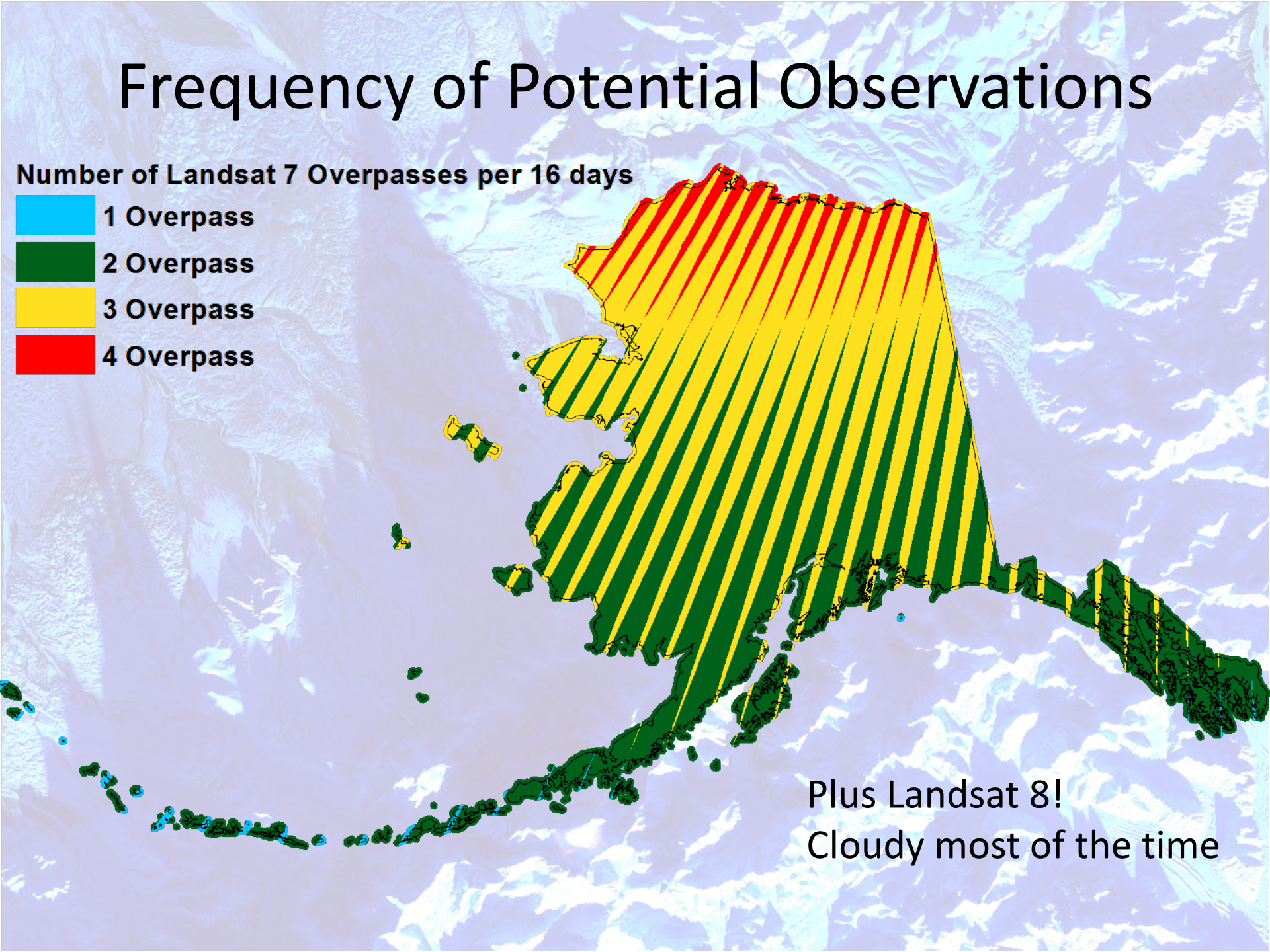
Landsat TM, ETM+, OLI Availability

- Landsat 4: Thematic Mapper (1982–1993)
  - Mostly 1992
- Landsat 5: Thematic Mapper (1984–present)
  - Mostly 1985, 1986, 2005–2011
- Landsat 7: Enhanced Thematic Mapper +
  - 1999–present, gaps after May 2003
- Landsat 8: Operational Land Imager
  - 2013–present

Return Interval for Alaska

- Return interval is the number of days between acquisitions.
- The return interval is nominally 16 days for Landsat.
- Orbits converge towards pole, resulting in higher frequency of potential observations in Alaska, especially further north.

Frequency of Potential Observations



Plus Landsat 8!
Cloudy most of the time

Snow Persistence Patterns from the Landsat Archive (1999–present)

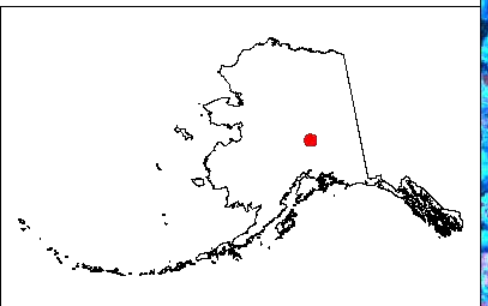
- SnowMap algorithm to map presence or absence of snow for each image in the time series
  - Modified for mountain shadows and tree canopy effect
- In combination with Landsat Surface Reflectance fmask:
  - Snow-covered land or water
  - Snow-free land
  - Snow-free water
  - Cloud (unknown)
  - Image gap or edge (unknown)

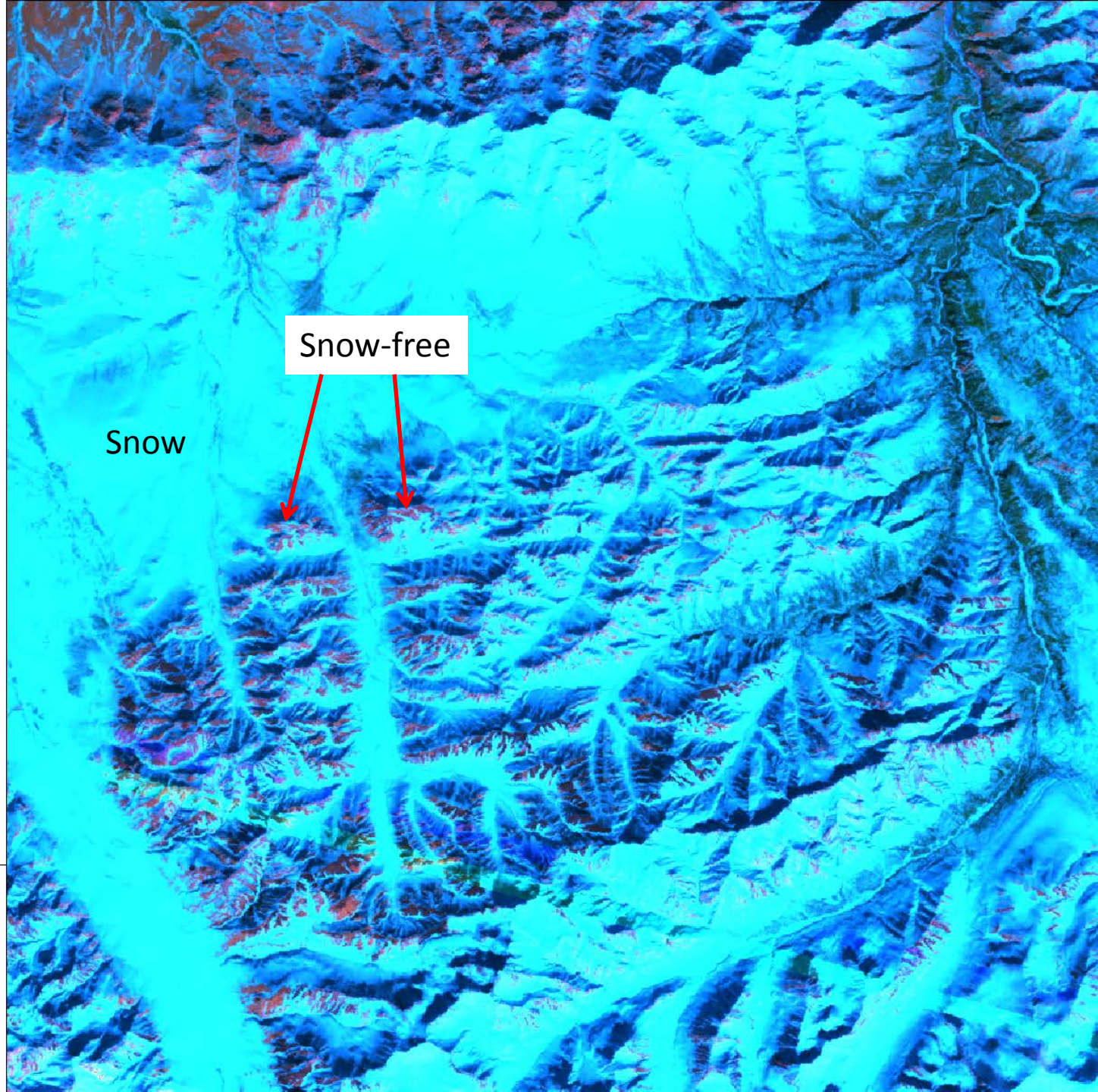
Denali National Park and Preserve Entrance

Landsat 7 ETM+ 10 April 2000

- Snow-free
- Snow
- Cloud
- No Data

5 Km





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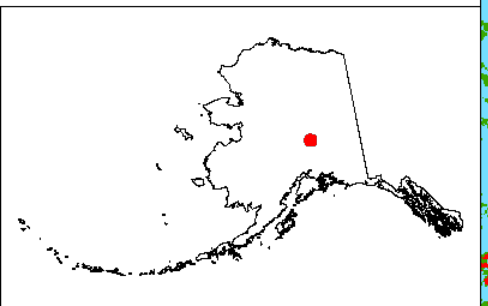

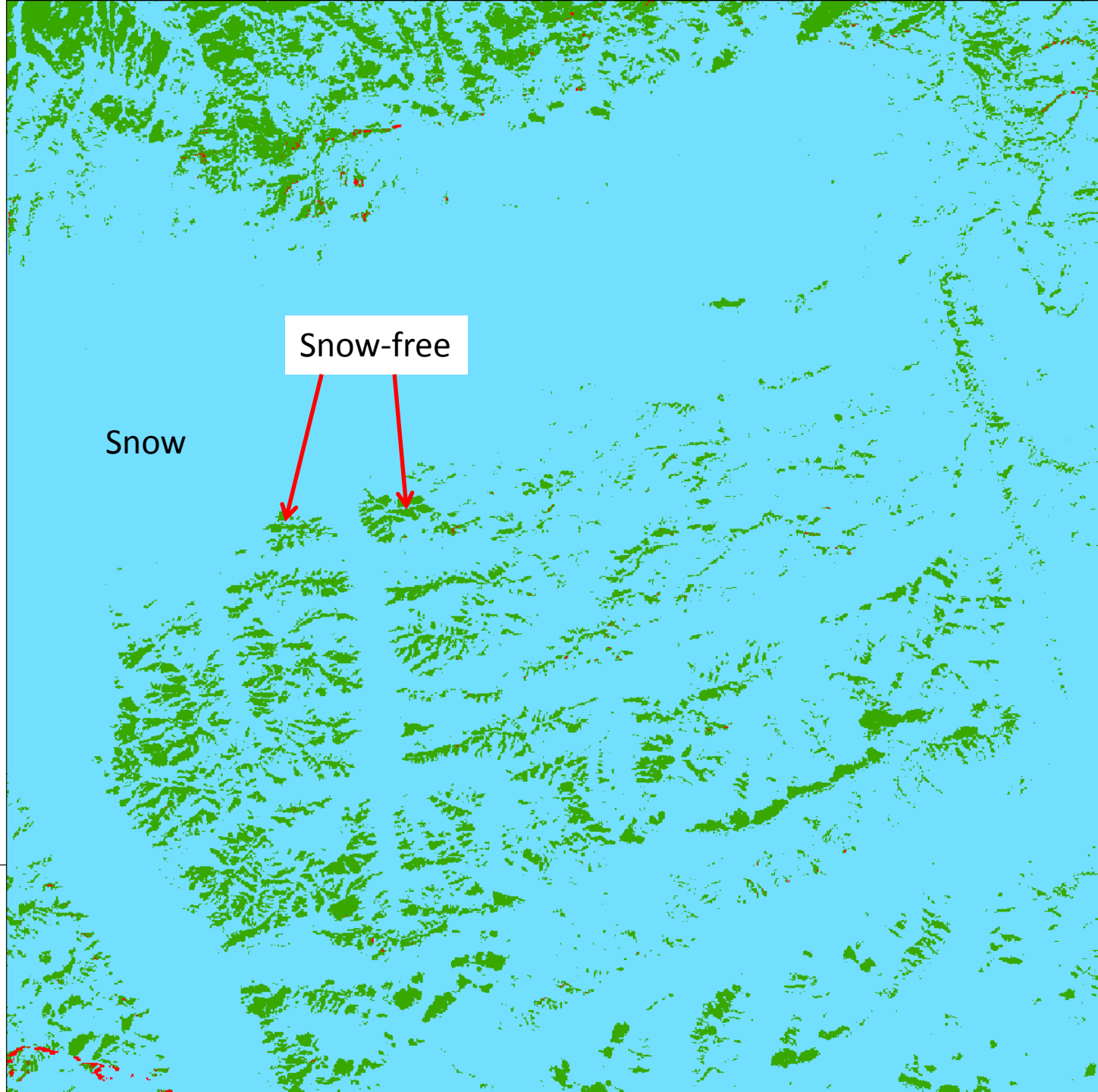

Denali National Park and Preserve Entrance

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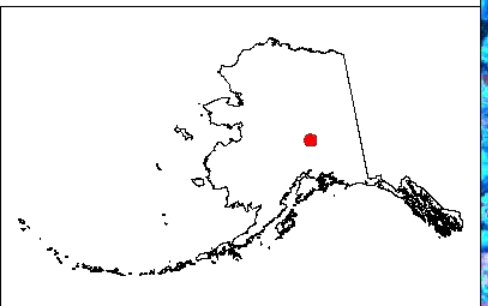
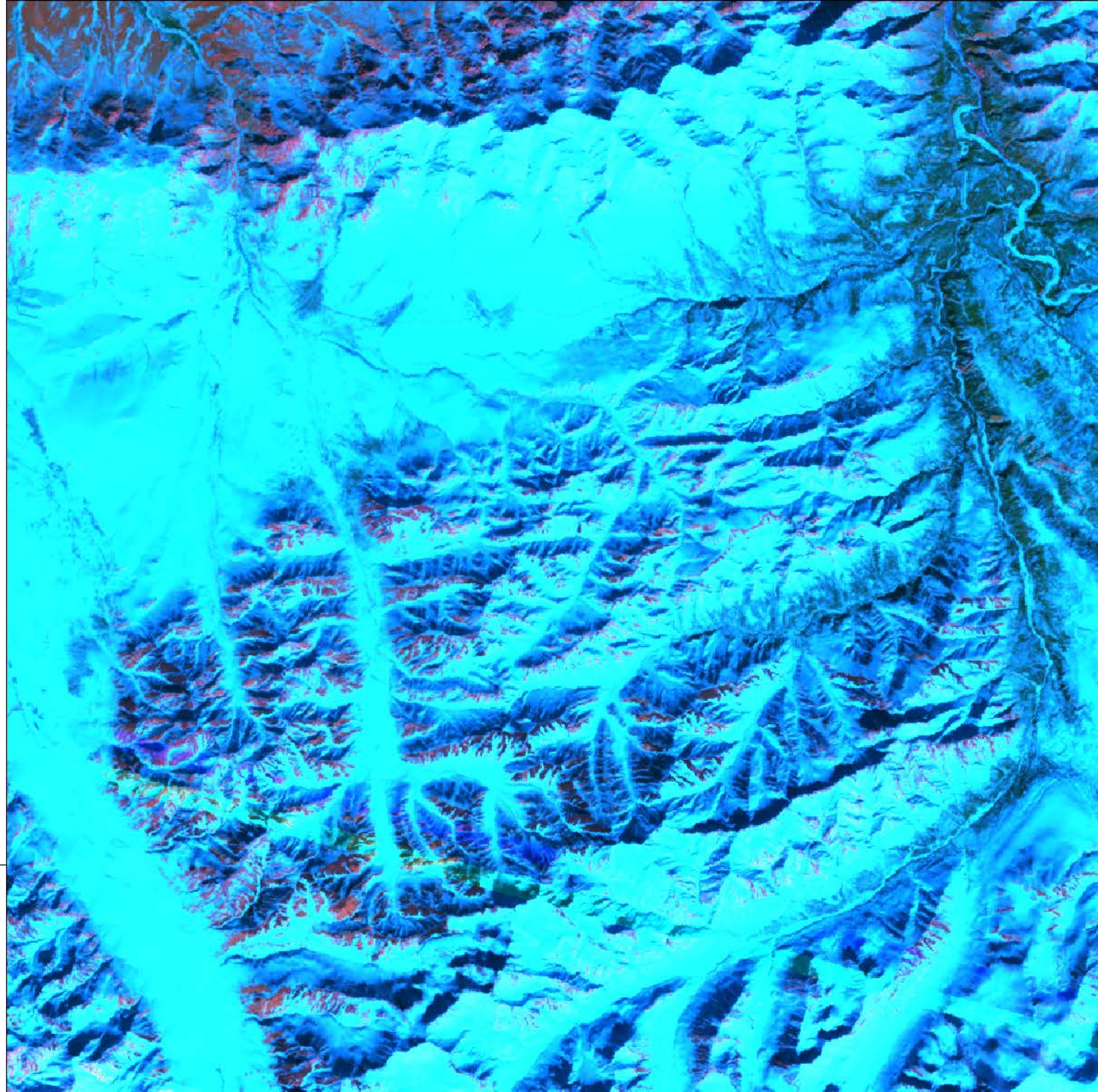
- No Data

5 Km



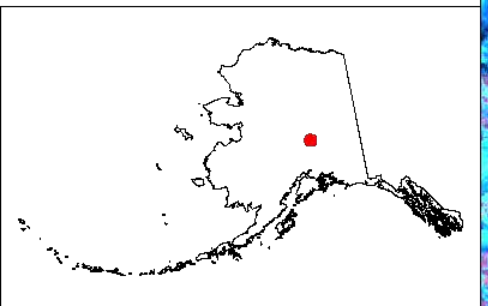


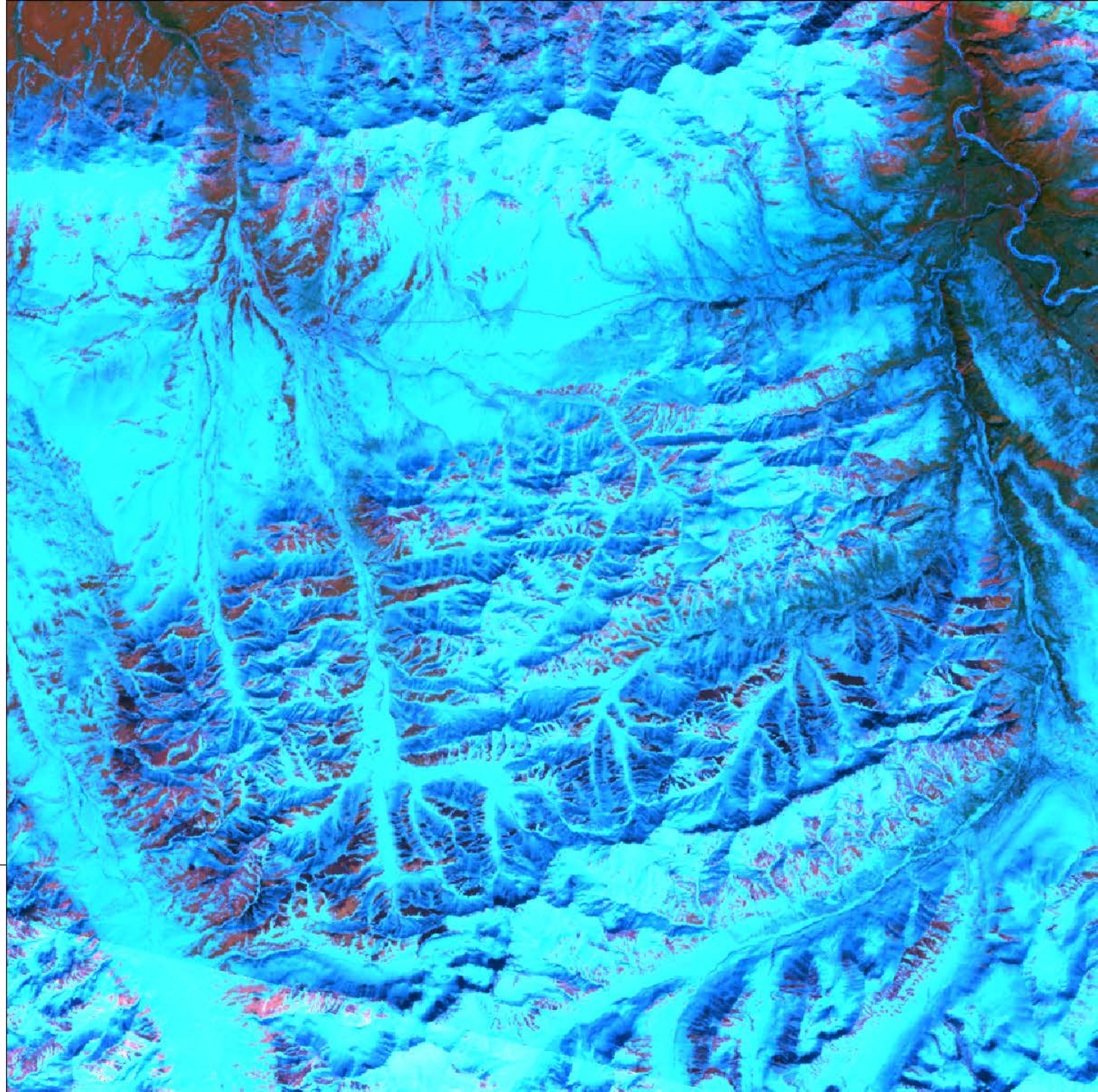
Denali National Park and Preserve Entrance

Landsat 7 ETM+ 5 May 2000

- Snow-free
- Snow
- Cloud
- No Data

5 Km



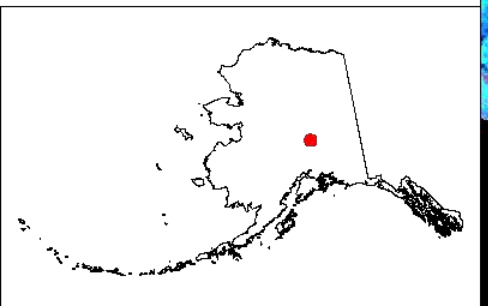


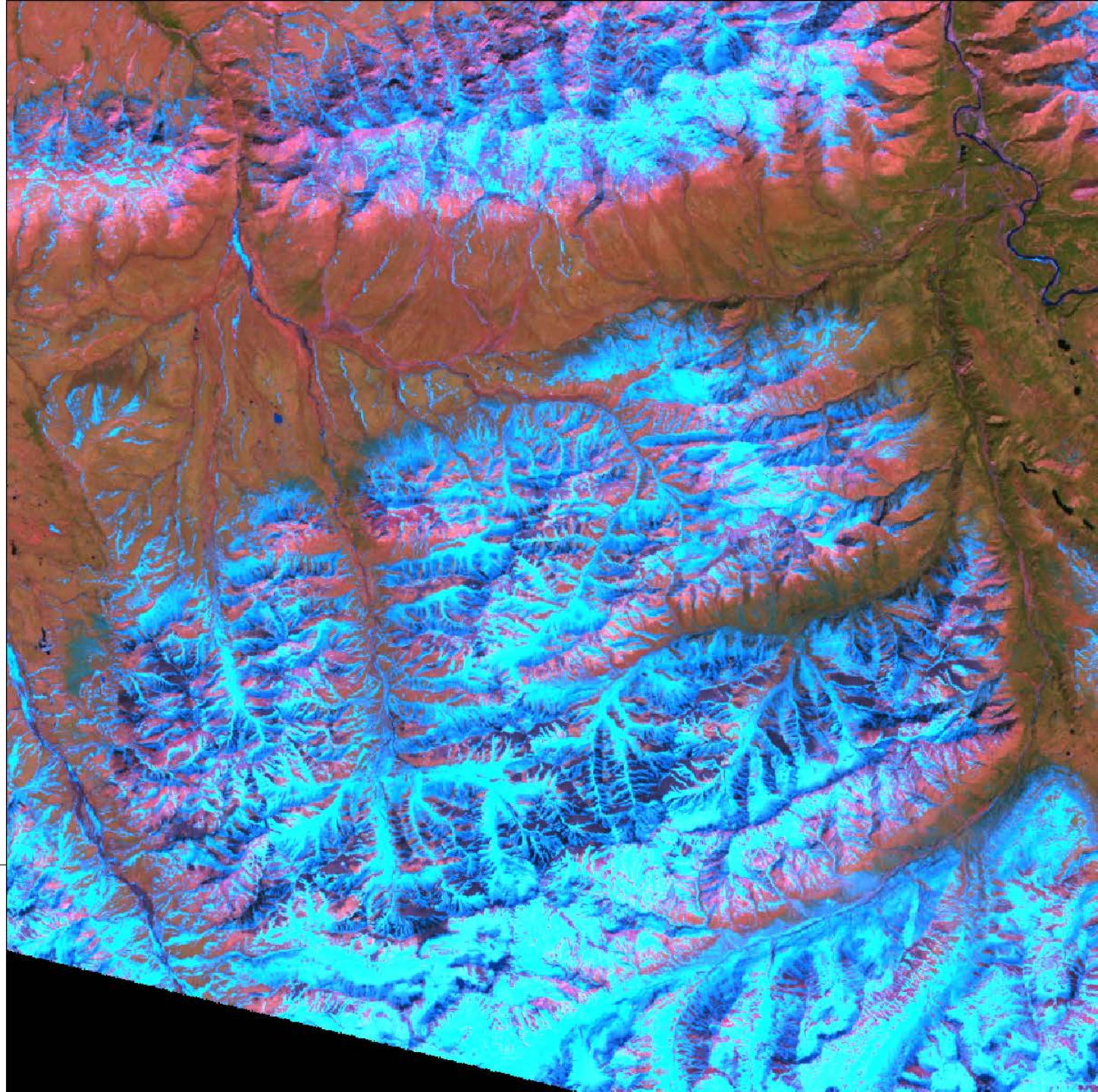
Denali National Park and Preserve Entrance

Landsat 5
TM
24 May 1998

- Snow-free
- Snow
- Cloud
- No Data

5 Km



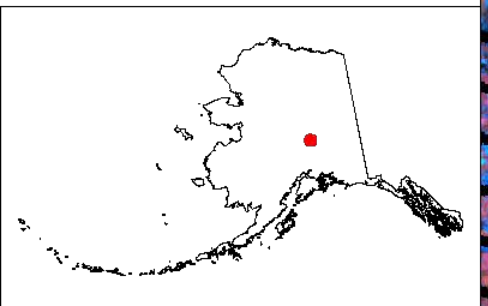


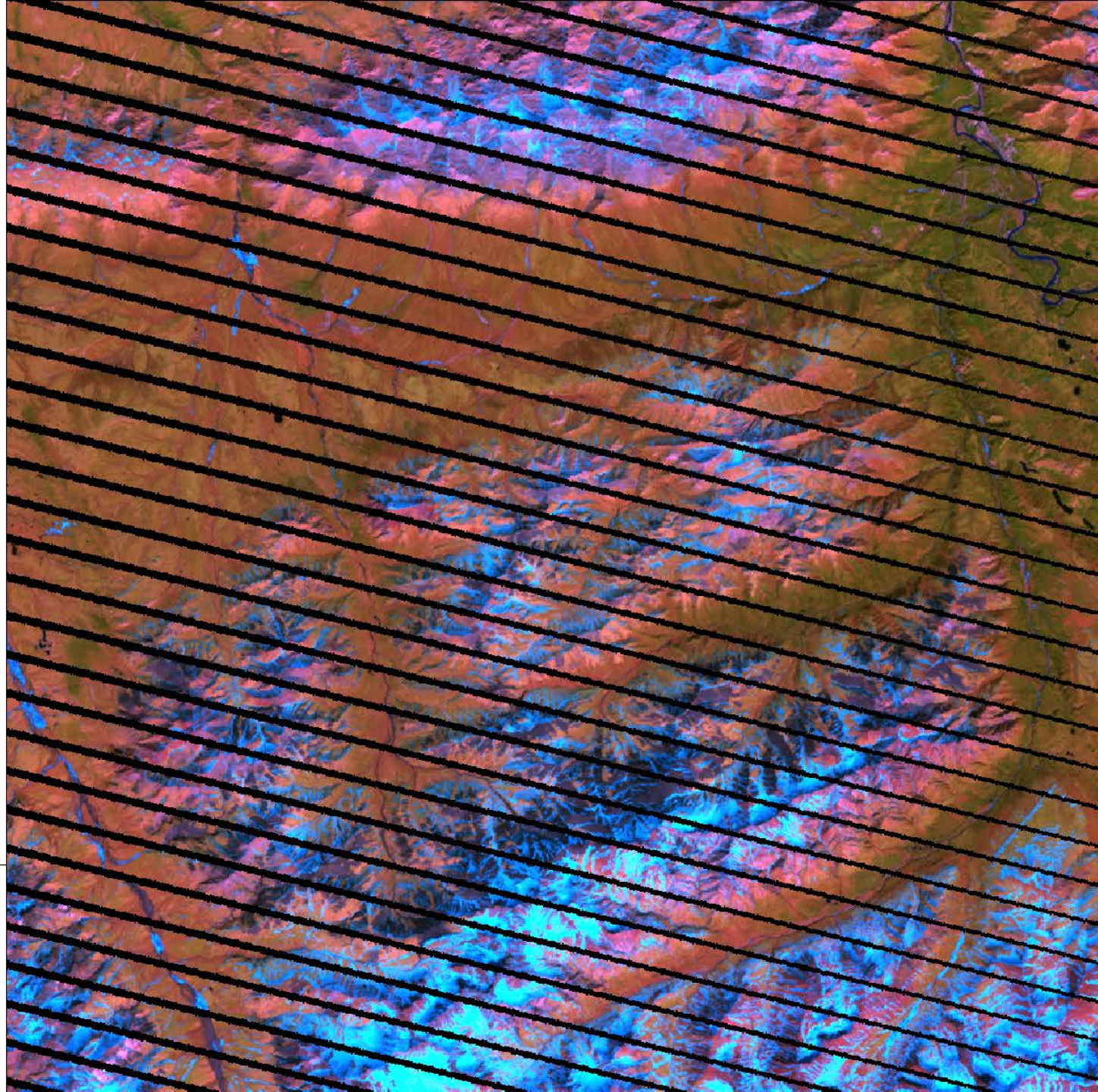
Denali National Park and Preserve Entrance

Landsat 7 ETM+ 25 May 2007

- Snow-free
- Snow
- Cloud
- No Data

5 Km



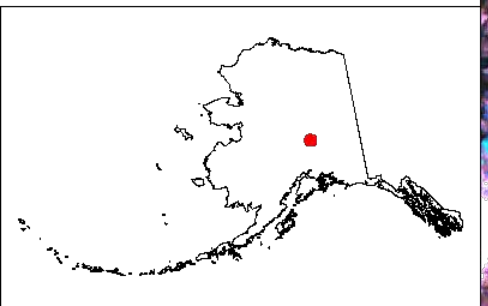


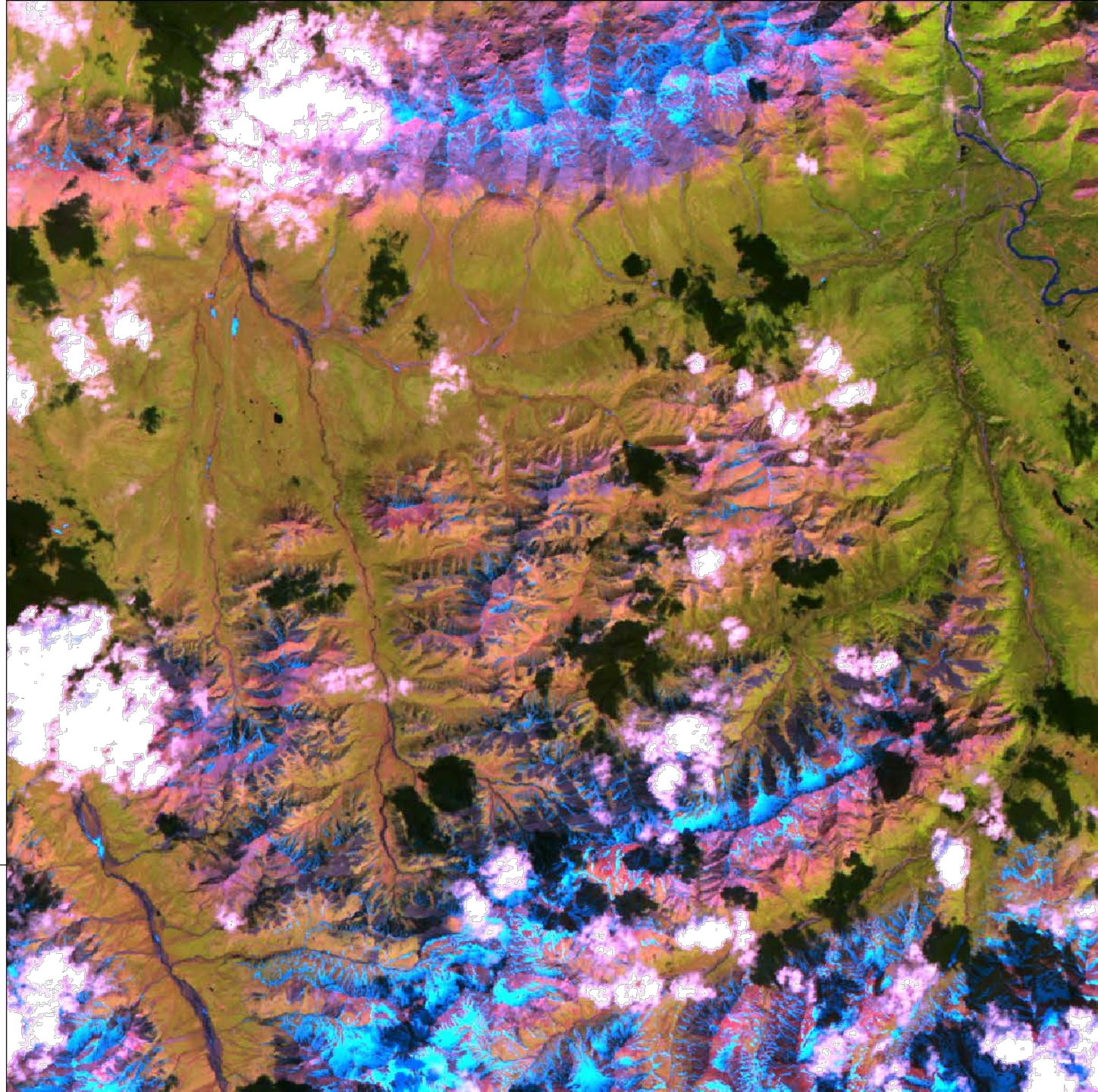
Denali National Park and Preserve Entrance

Landsat 5 TM 15 June 1986

- Snow-free
- Snow
- Cloud
- No Data

5 Km



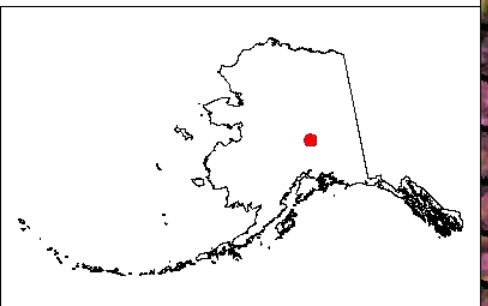


Denali National Park and Preserve Entrance

Landsat 7 ETM+ 8 July 2009

- Snow-free
- Snow
- Cloud
- No Data

5 Km

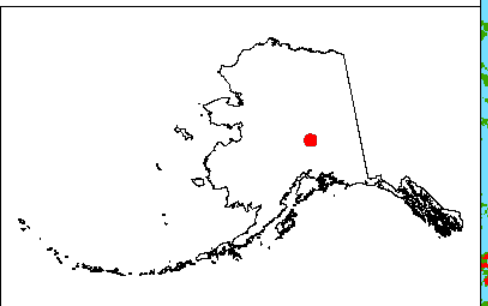


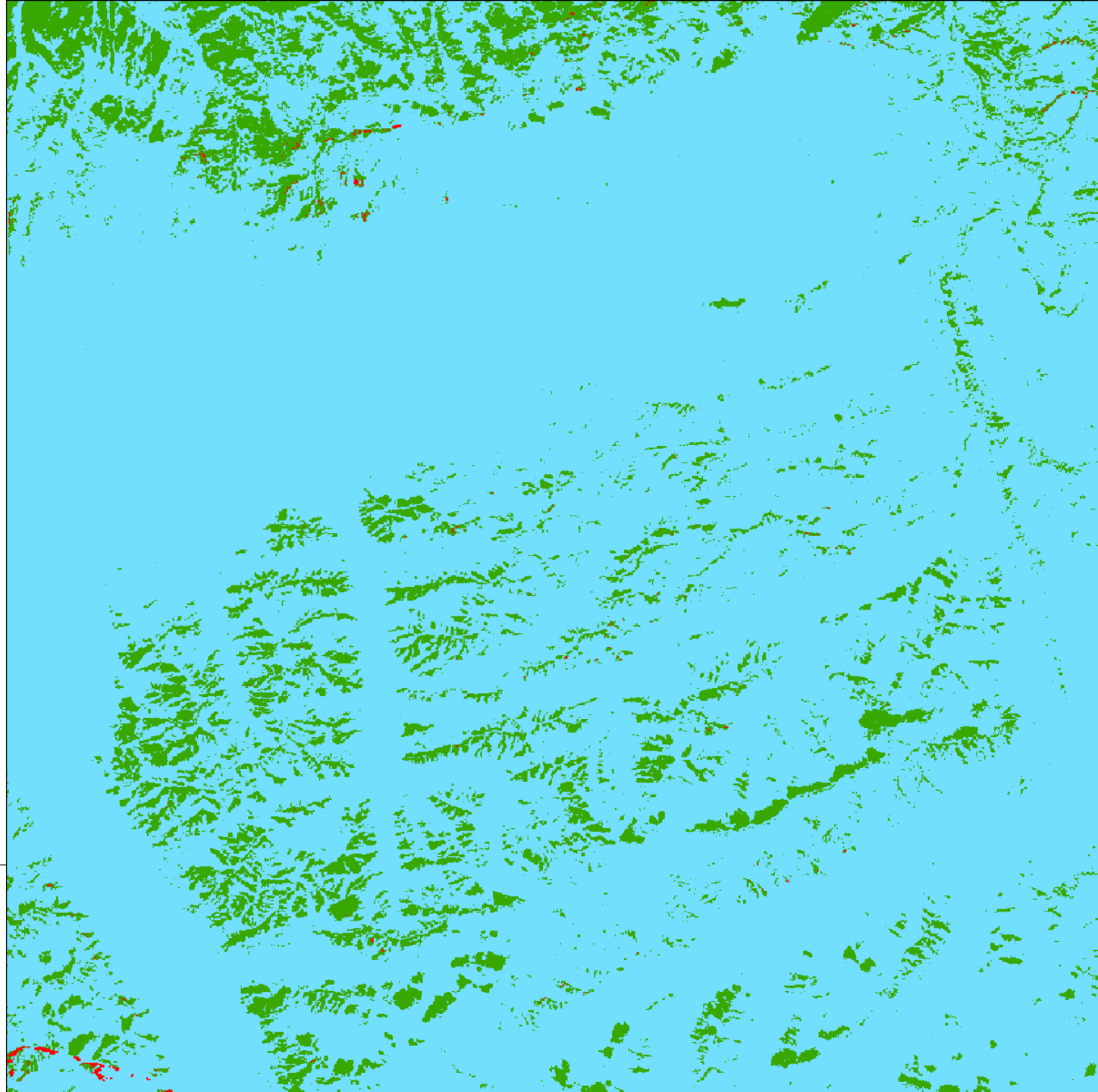
Denali National Park and Preserve Entrance

Landsat 7 ETM+ 10 April 2000

- Snow-free
- Snow
- Cloud
- No Data

5 Km



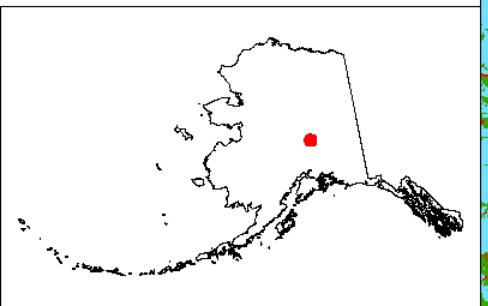


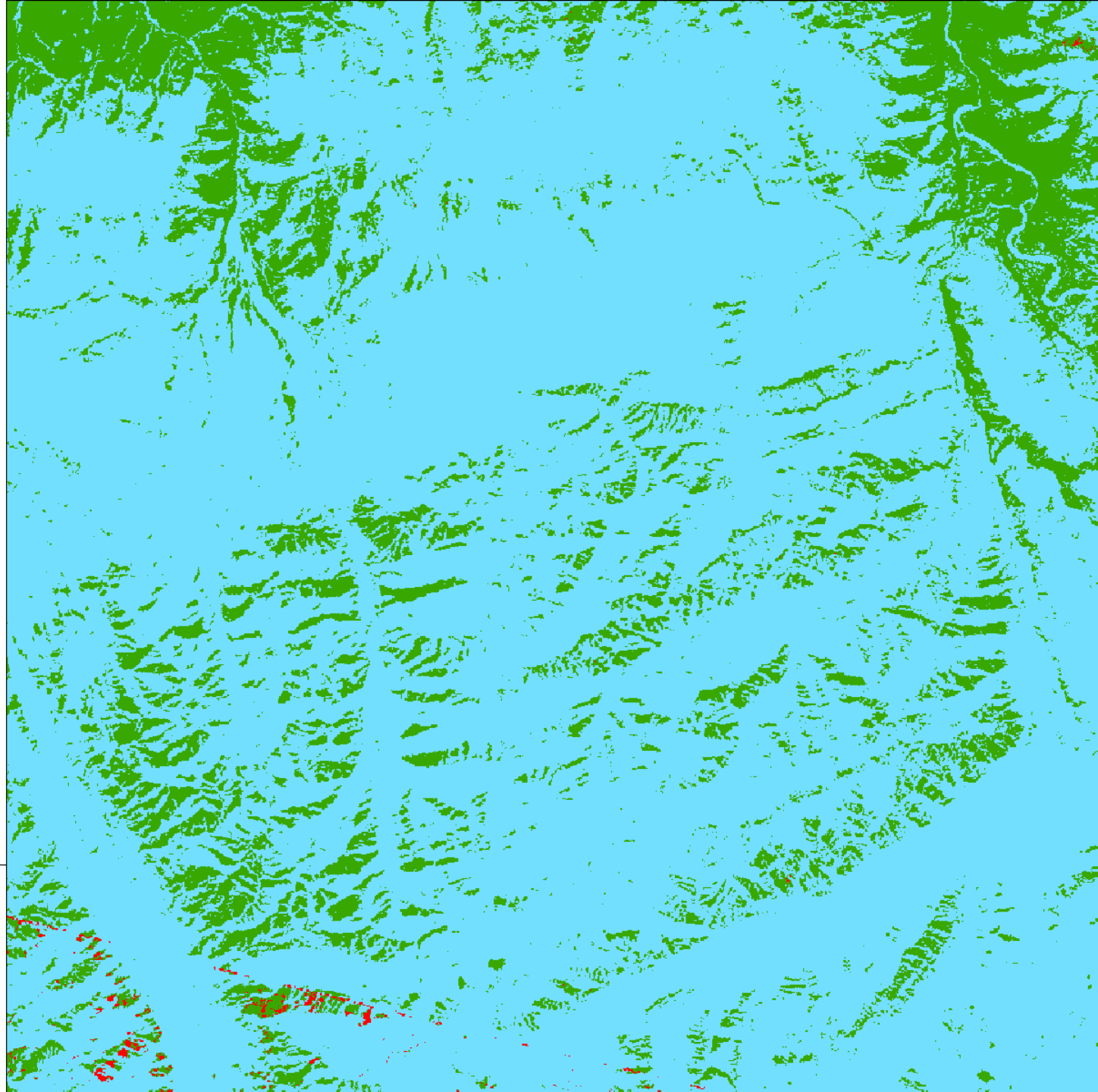
Denali National Park and Preserve Entrance

Landsat 7 ETM+ 5 May 2000

- Snow-free
- Snow
- Cloud
- No Data

5 Km





Denali National Park and Preserve Entrance

Landsat 5 TM 24 May 1998

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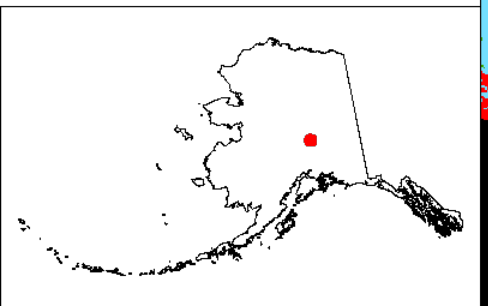
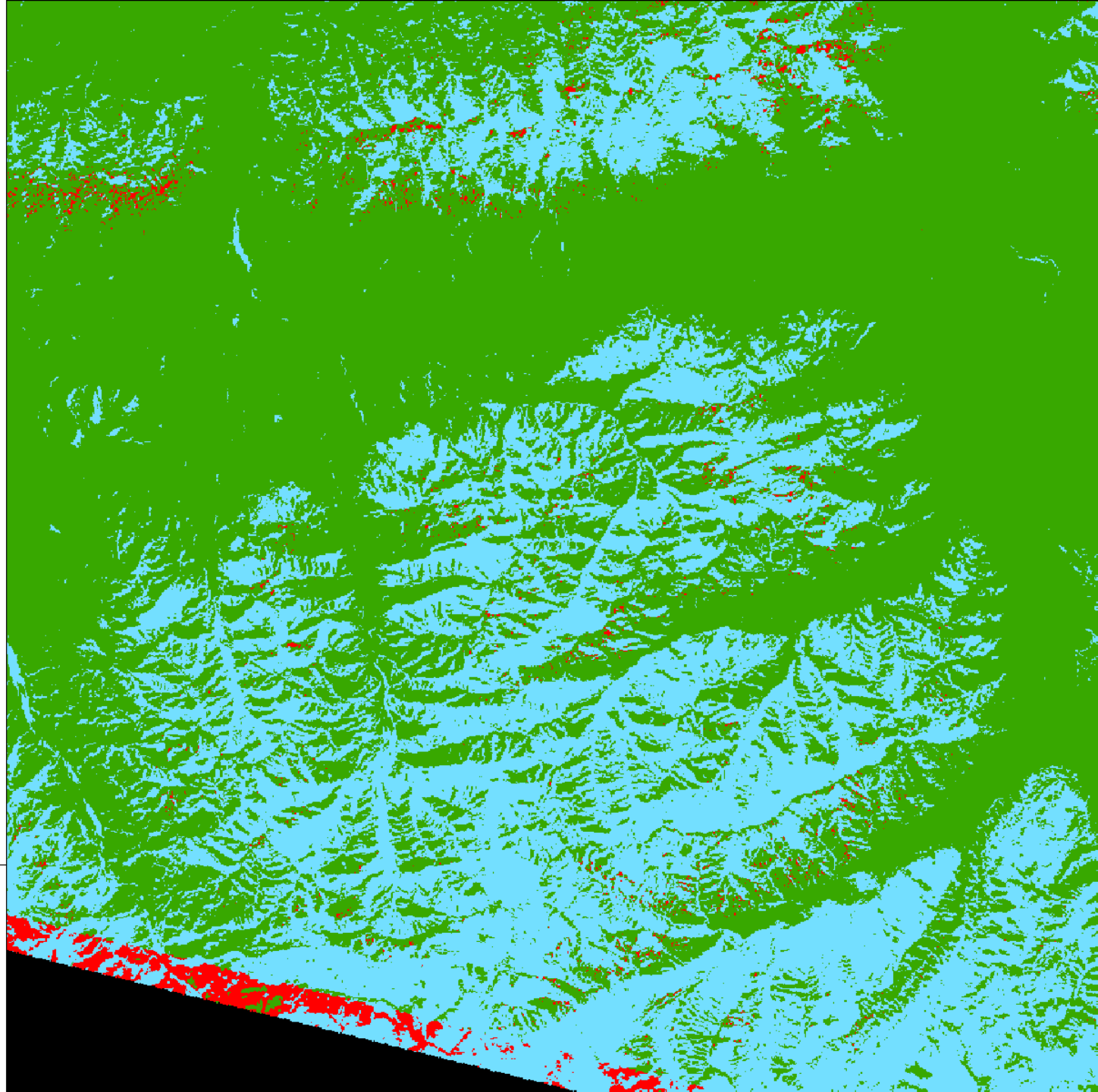
- Snow
- Cloud
- No Data

5 Km



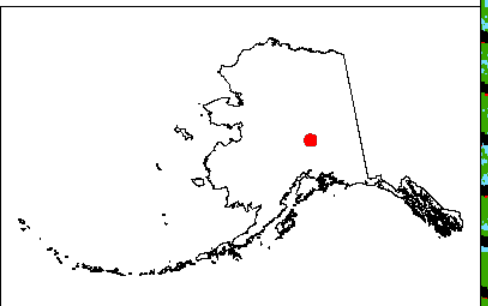


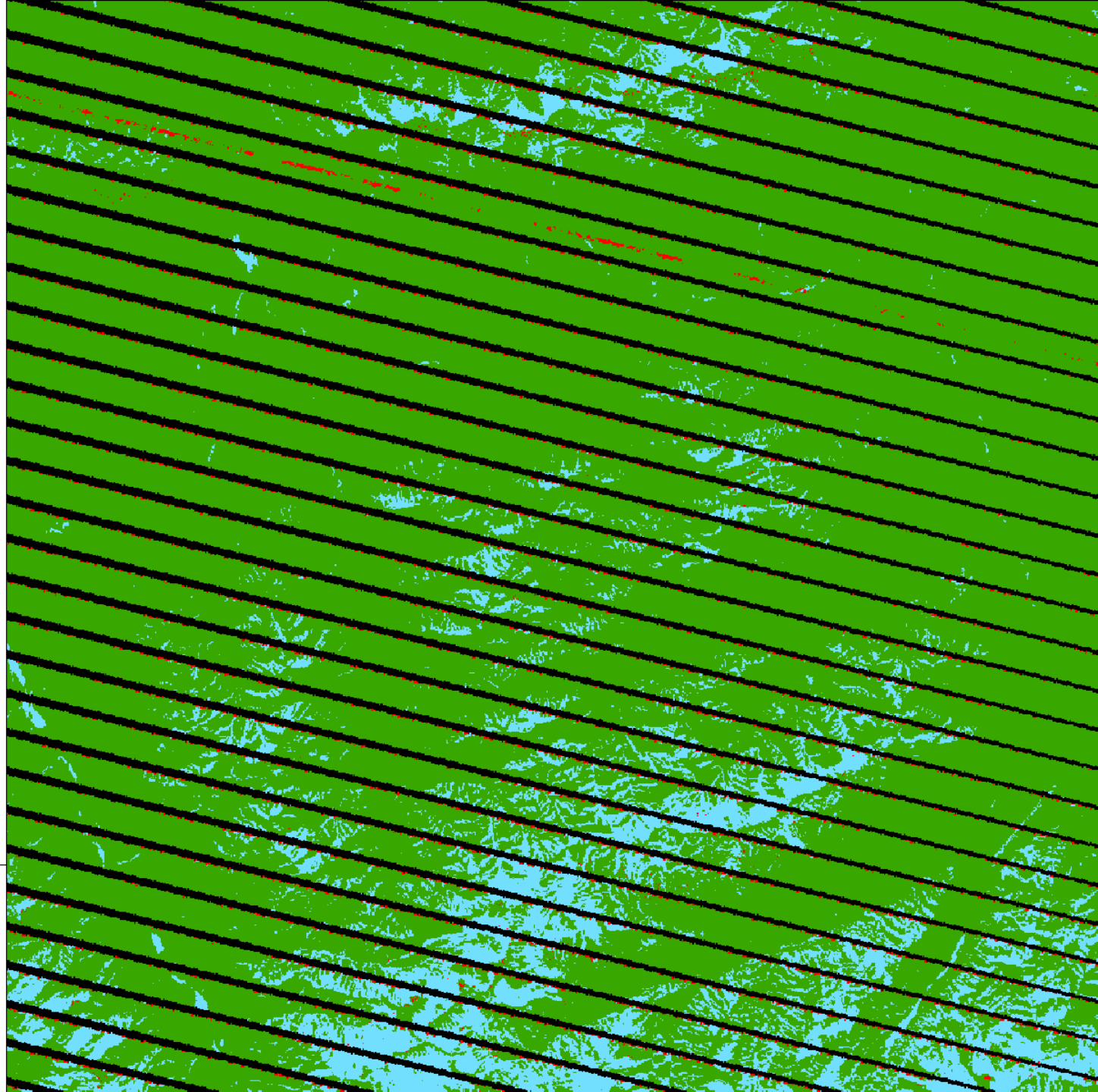
Denali National Park and Preserve Entrance

Landsat 7 ETM+ 25 May 2007

- Snow-free
- Snow
- Cloud
- No Data

5 Km



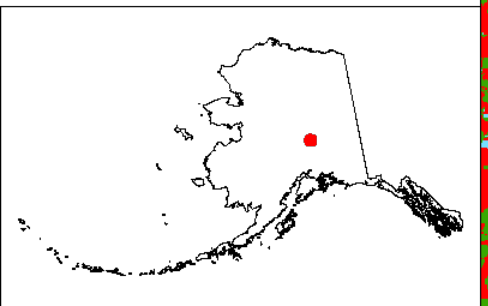


Denali National Park and Preserve Entrance

Landsat 5 TM 15 June 1986

- Snow-free
- Snow
- Cloud
- No Data

5 Km

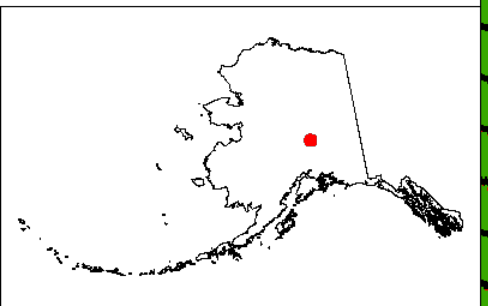


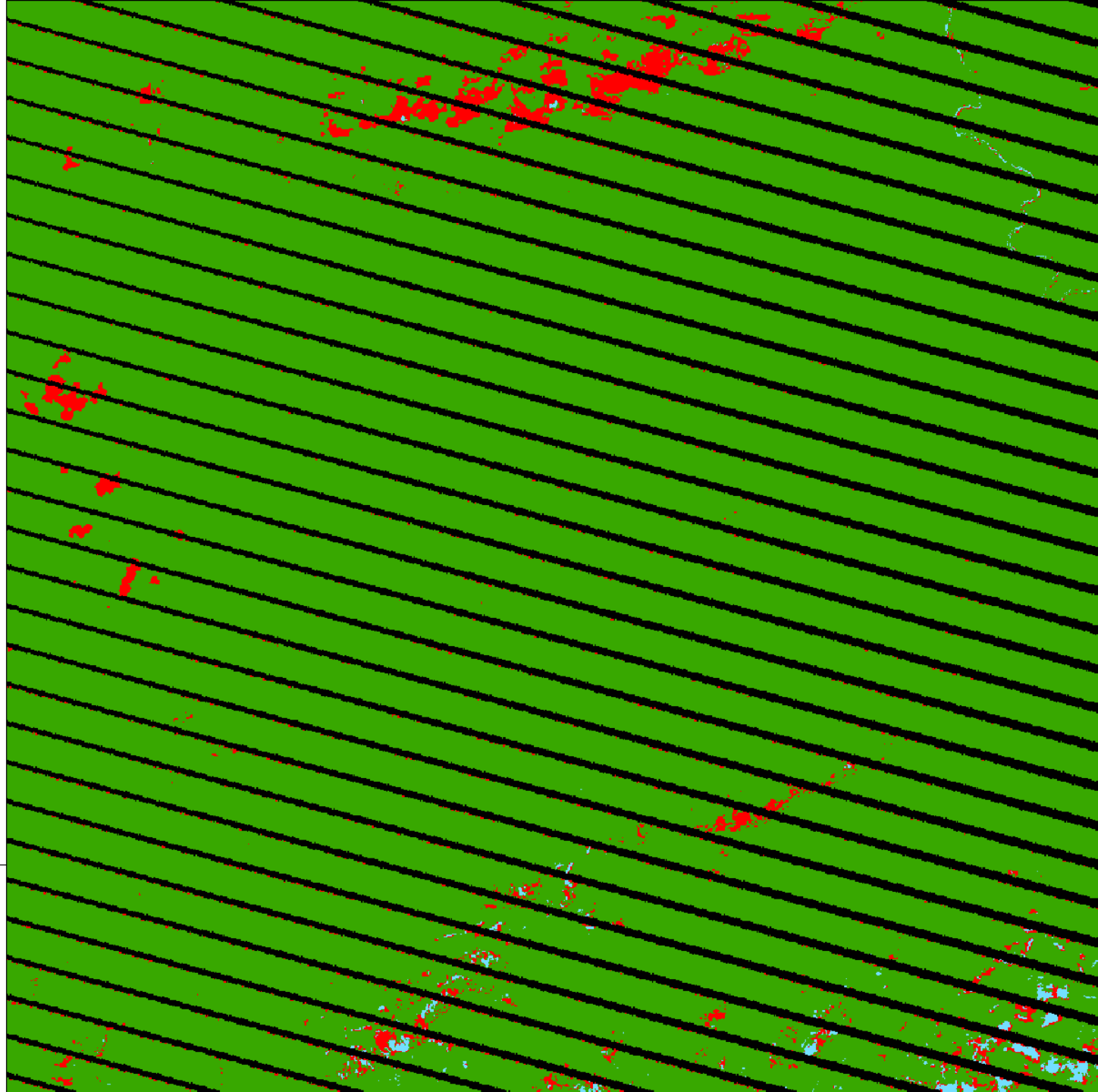
Denali National Park and Preserve Entrance

Landsat 7 ETM+ 8 July 2009

- Snow-free
- Snow
- Cloud
- No Data

5 Km





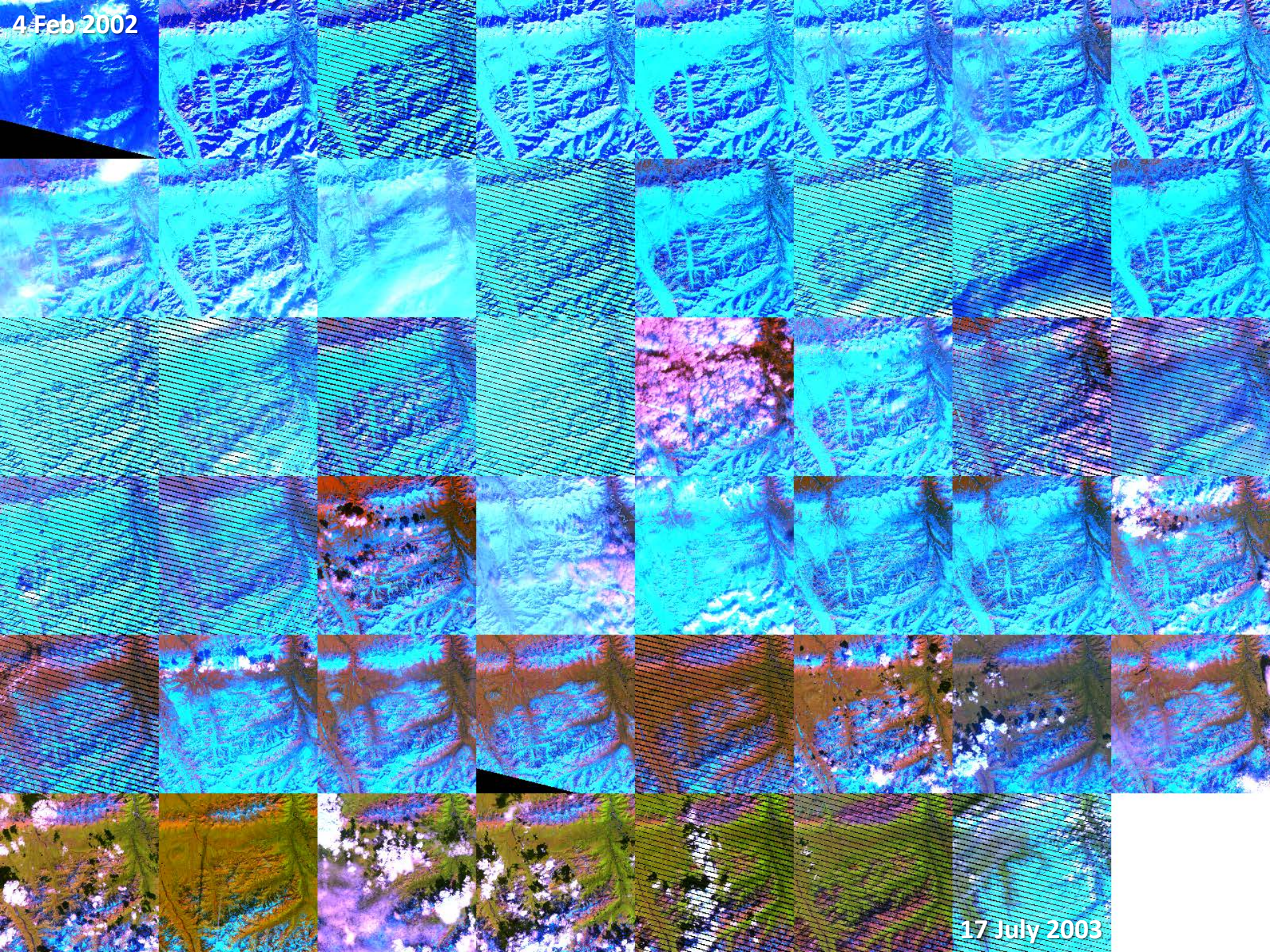
Simplified data table for one pixel

Scene	Day of Year	Snow State
Landsat 7, 10 April 2000	101	Snow
Landsat 7, 5 May 2000	126	Snow
Landsat 5, 24 May 1998	144	Snow
Landsat 7, 27 May 2007	147	Snow-free
Landsat 5, 15 June 1986	166	Cloud
Landsat 7, 8 July 2009	189	Snow-free

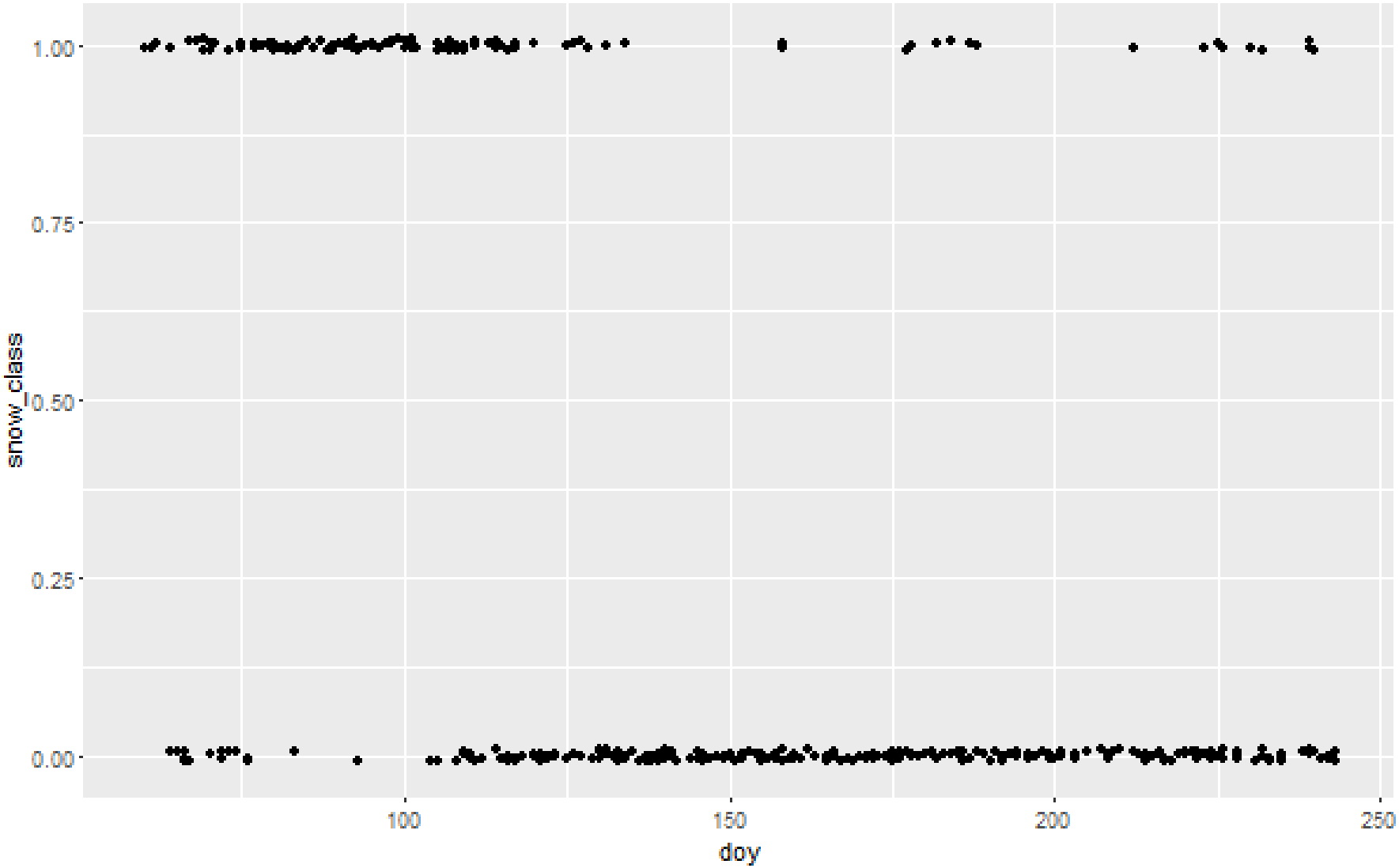
Simplified results for one pixel

Scene	Day of Year	Snow State
Landsat 7, 10 April 2000	101	Snow
Landsat 7, 5 May 2000	126	Snow
Landsat 5, 24 May 1998	144	Snow
Landsat 7, 27 May 2007	147	Snow-free
Landsat 5, 15 June 1986	166	Cloud
Landsat 7, 8 July 2009	189	Snow-free

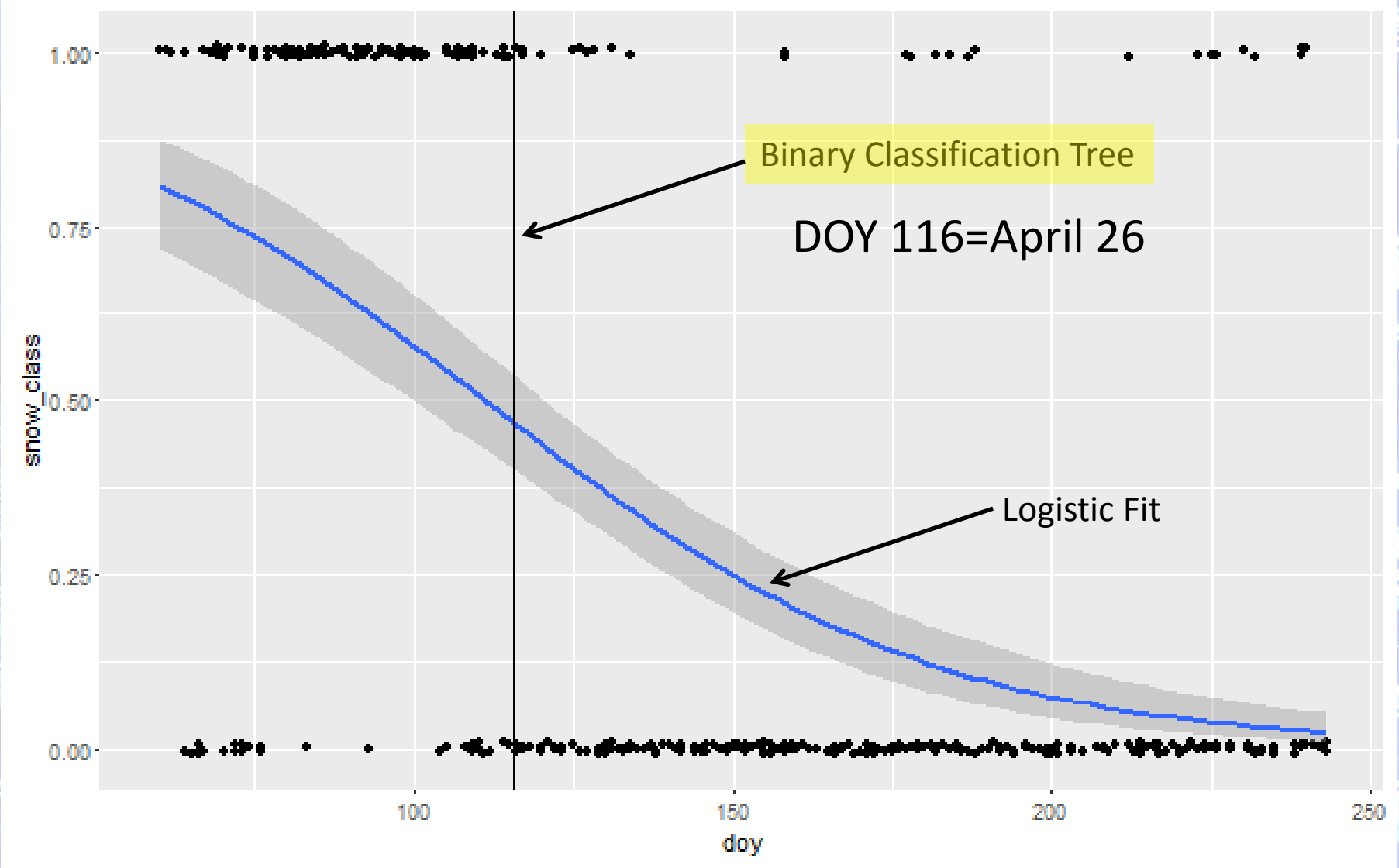
Binary Classification Tree returns
Typical Snowmelt Date ~ 25 May

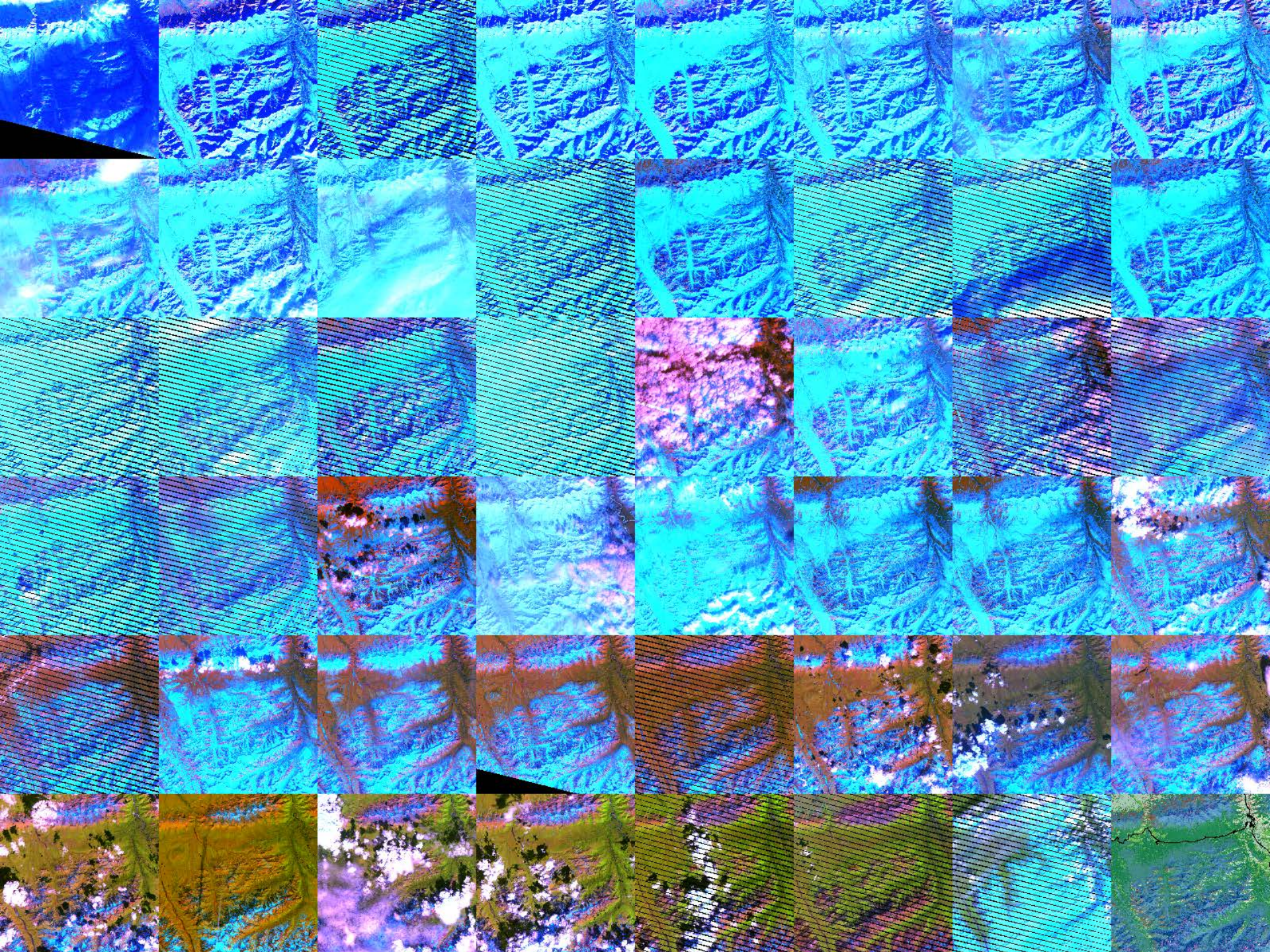

4 Feb 2002
17 July 2003

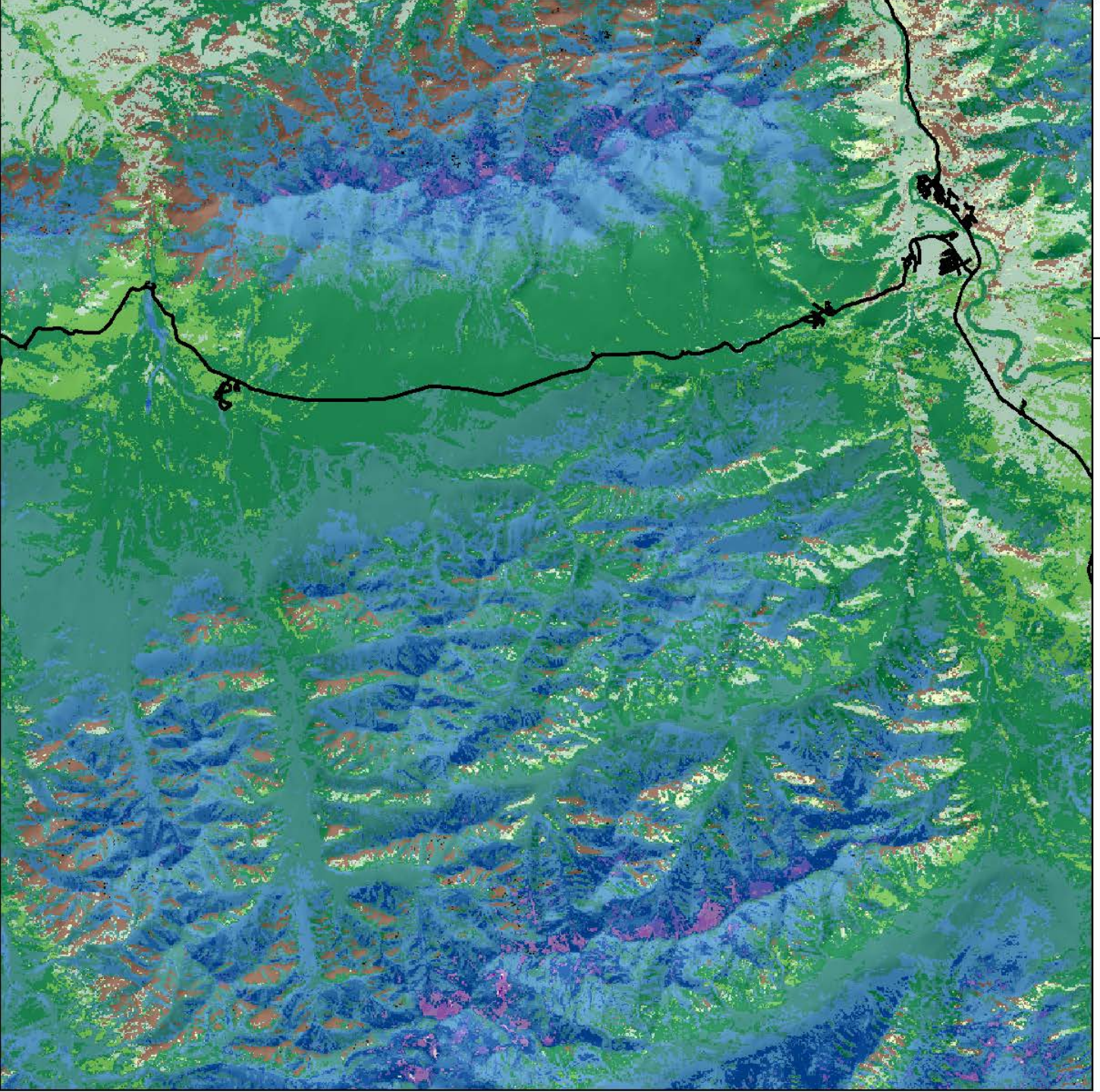
Snow Time Series, 1999–2015

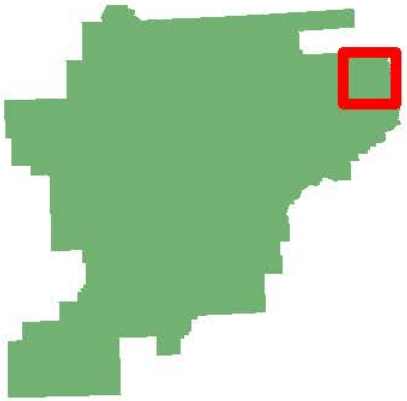


Snow Time Series, 1999–2015







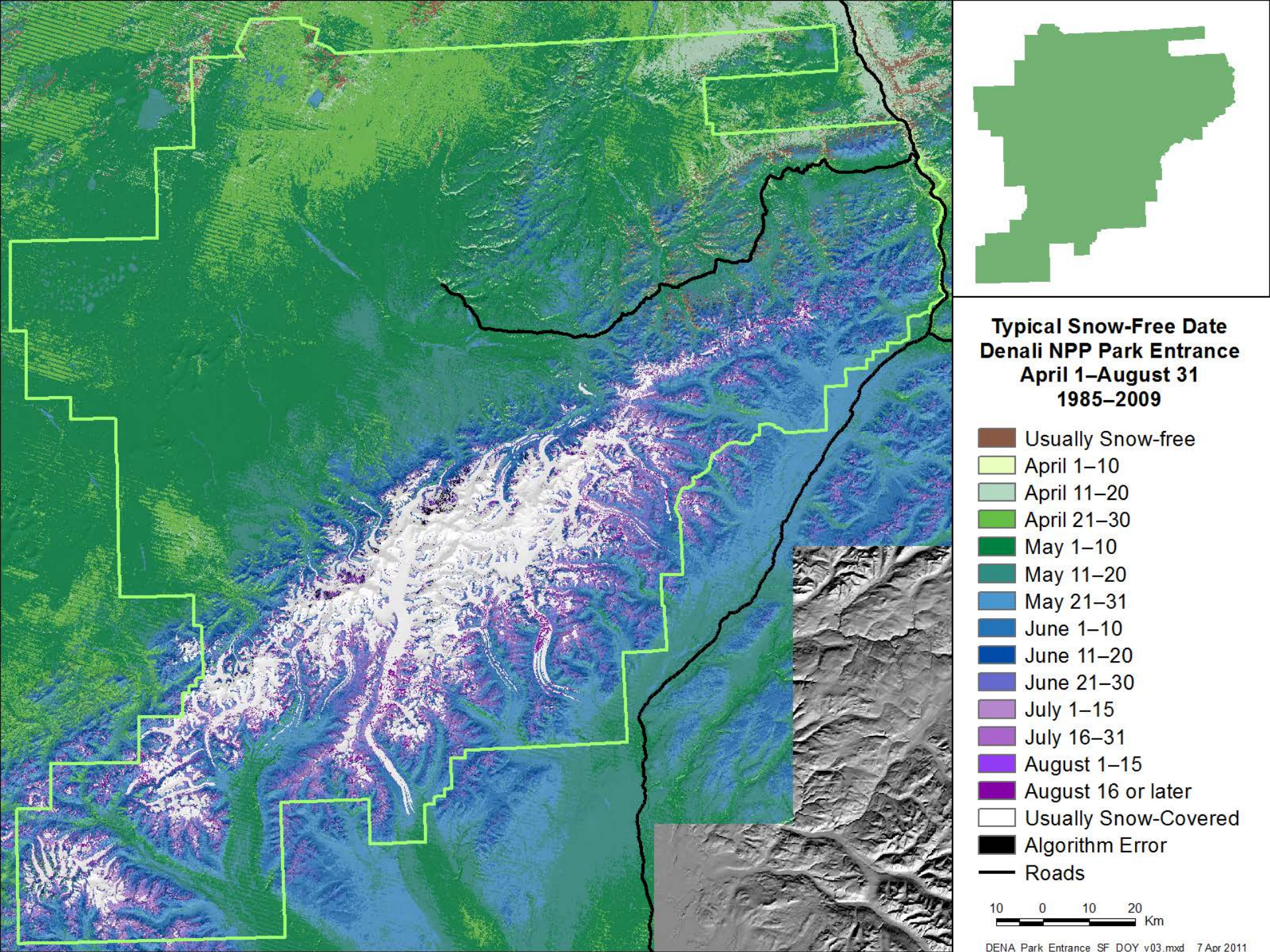


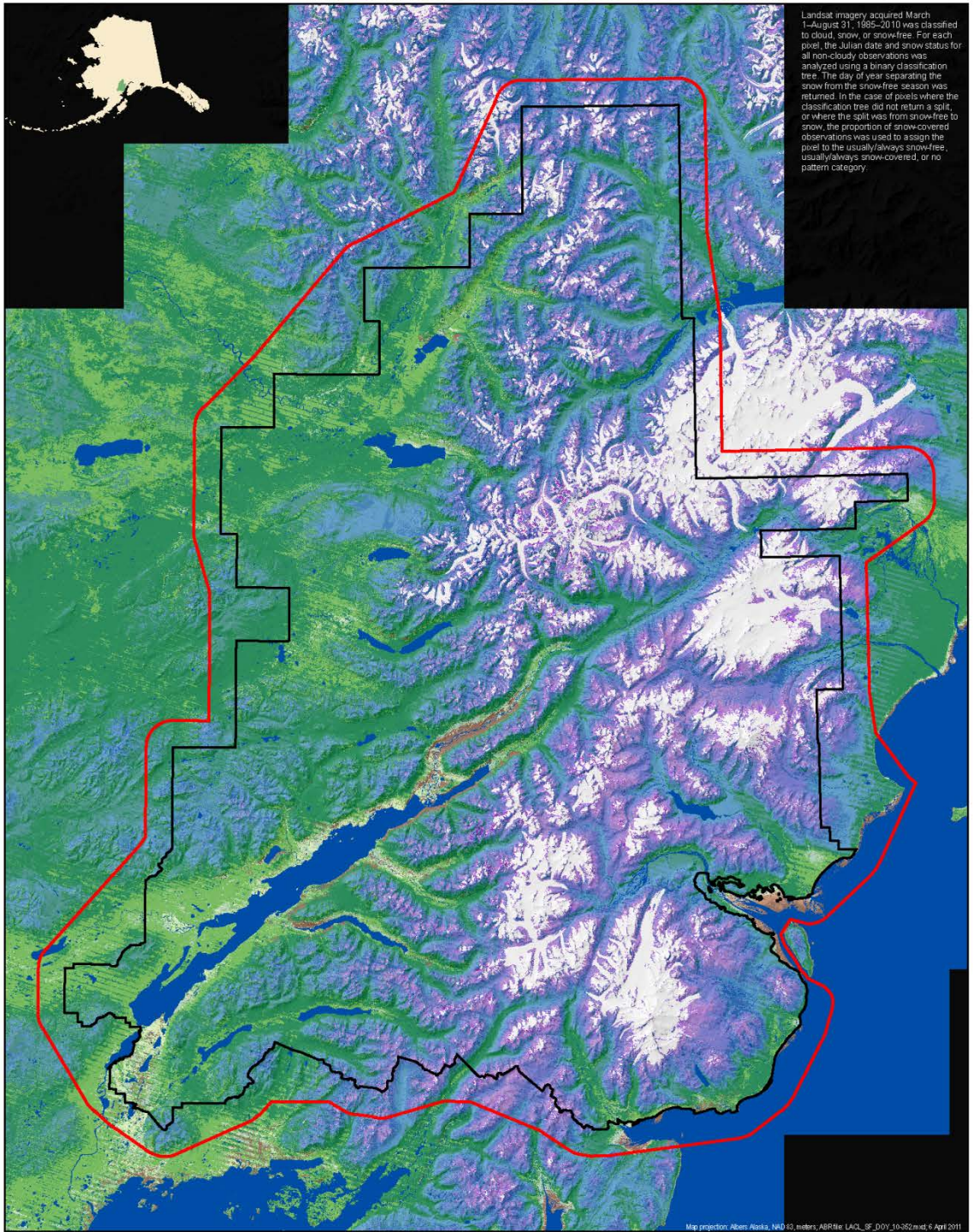
Typical Snow-Free Date
Denali NPP Park Entrance
April 1–August 31
1985–2009

- Usually Snow-free
- April 1–10
- April 11–20
- April 21–30
- May 1–10
- May 11–20
- May 21–31
- June 1–10
- June 11–20
- June 21–30
- July 1–15
- July 16–31
- August 1–15
- August 16 or later
- Usually Snow-Covered
- Algorithm Error
- Roads

2 0 2 4 Km

DENA_Park_Entrance_SF_DOY_v03.mxd 7 Apr 2011


Typical Snow-Free Date
Denali NPP Park Entrance
April 1–August 31
1985–2009
Usually Snow-free
April 1–10
April 11–20
April 21–30
May 1–10
May 11–20
May 21–31
June 1–10
June 11–20
June 21–30
July 1–15
July 16–31
August 1–15
August 16 or later
Usually Snow-Covered
Algorithm Error
Roads
10 0 10 20
Km
DENA Park Entrance SF DOY v03.mxd 7 Apr 2011



Lake Clark National Park and Preserve

Figure 3. Typical Snow-free Day of Year, Lake Clark National Park and Preserve

No Pattern	April 21–30	July 1–15
Usually or Always Snow-free	May 1–10	July 16–31
March 1–10	May 11–20	August 1–15
March 11–20	May 21–31	August 16–31
March 21–31	June 1–10	Usually or Always Snow
April 1–10	June 11–20	Park Boundary
April 11–20	June 21–30	LACL Soils Study Area

Landscape-scale soils mapping study.

Snow cover duration affects soil temperature and growing season length.

Lake Clark National Park and Preserve

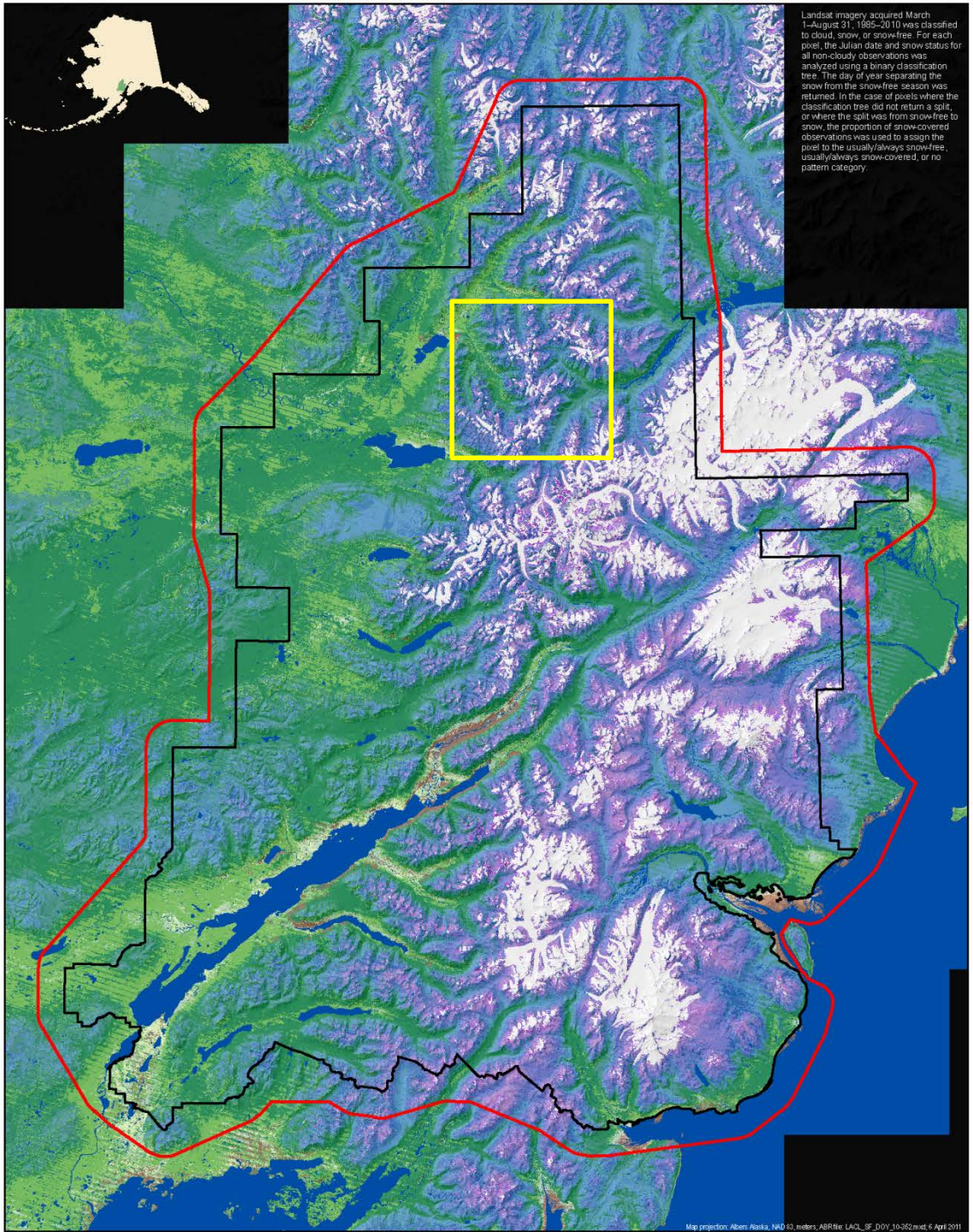


Figure 3. Typical Snow-free Day of Year, Lake Clark National Park and Preserve

No Pattern	April 21–30	July 1–15
Usually or Always Snow-free	May 1–10	July 16–31
March 1–10	May 11–20	August 1–15
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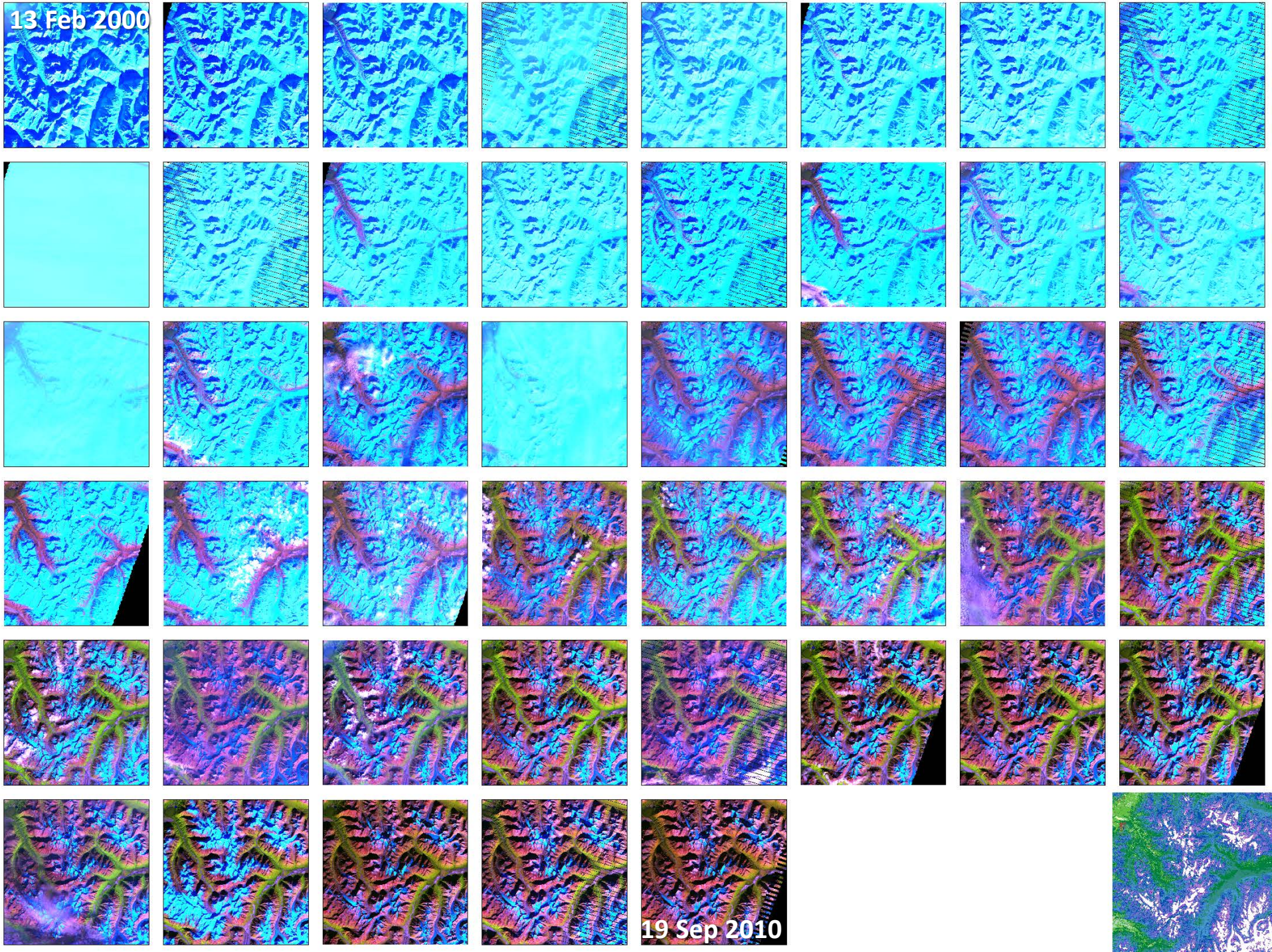
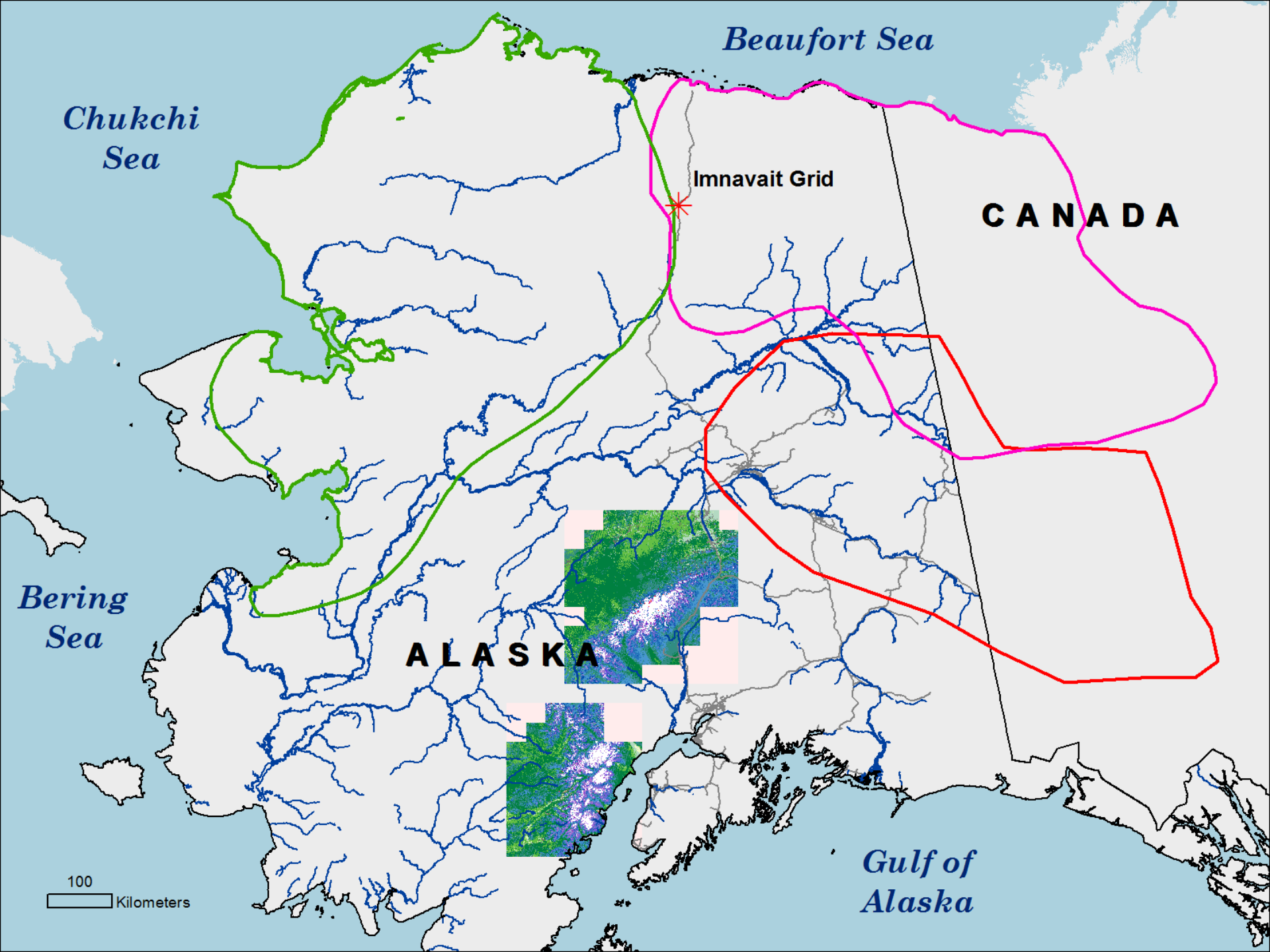
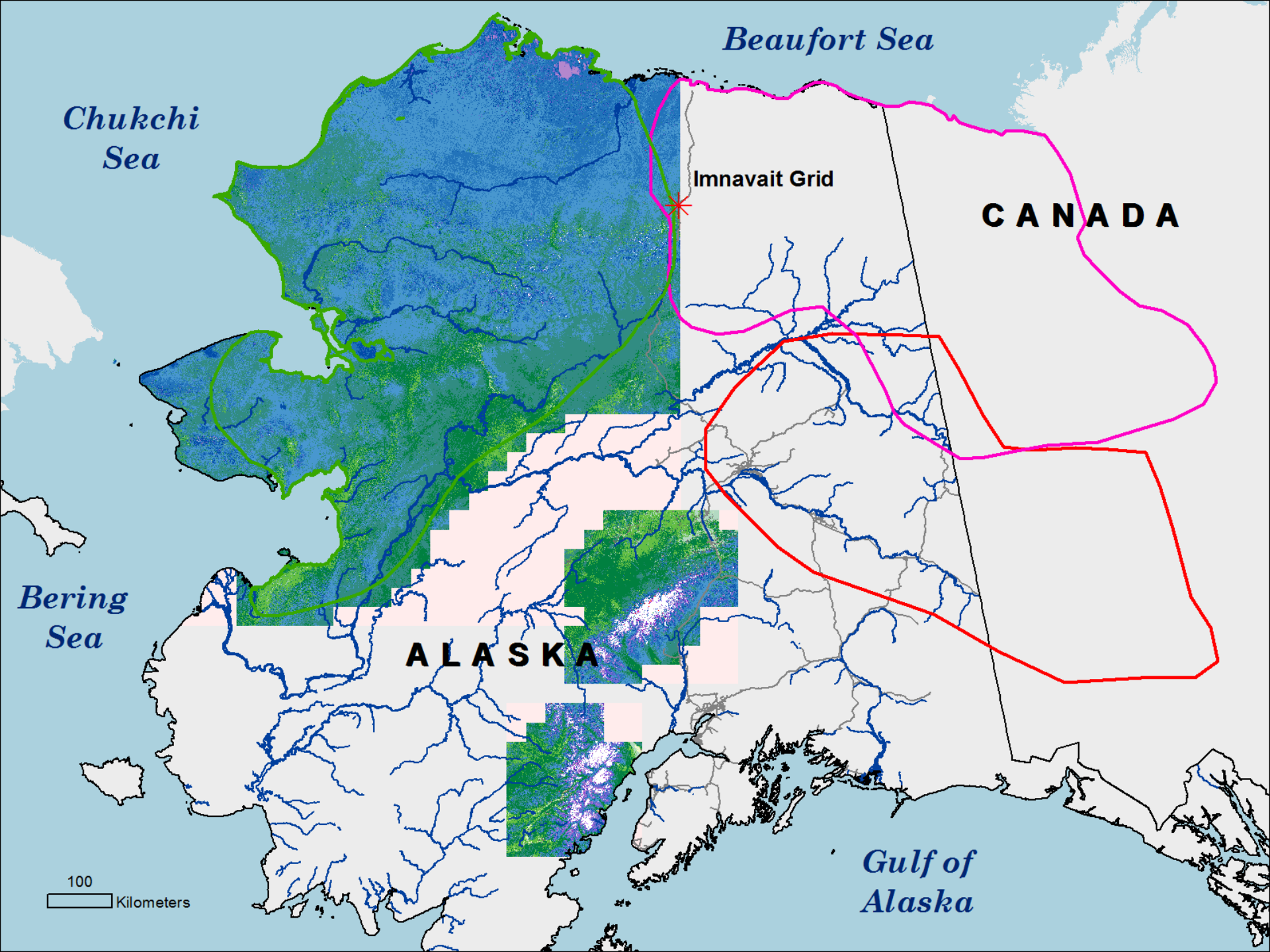
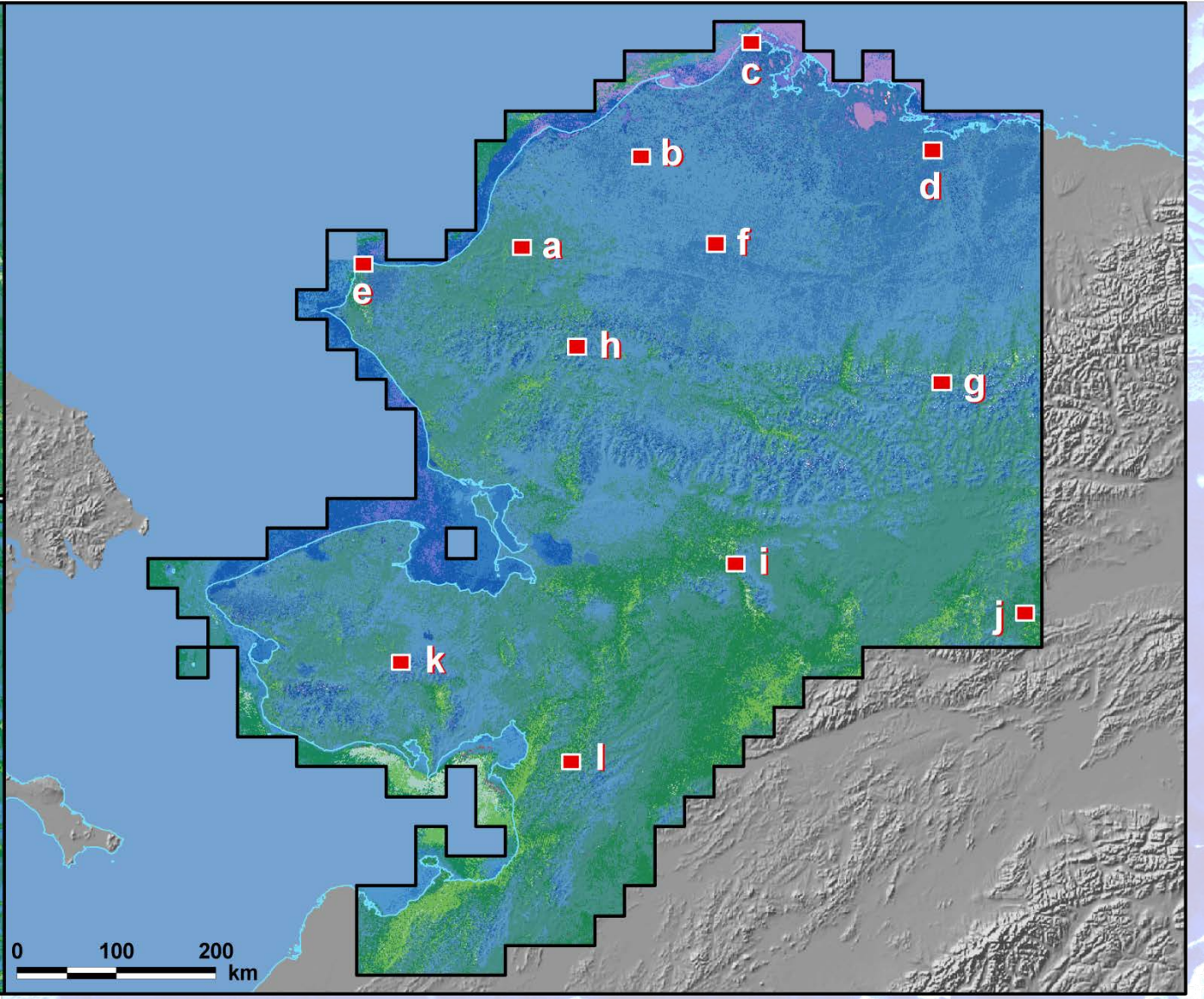
March 21–31	June 1–10	Usually or Always Snow
April 1–10	June 11–20	Park Boundary
April 11–20	June 21–30	LACL Soils Study Area


13 Feb 2000
19 Sep 2010


Beaufort Sea
Chukchi Sea
Imnavait Grid
CANADA
Bering Sea
ALASKA
Gulf of Alaska
100
Kilometers

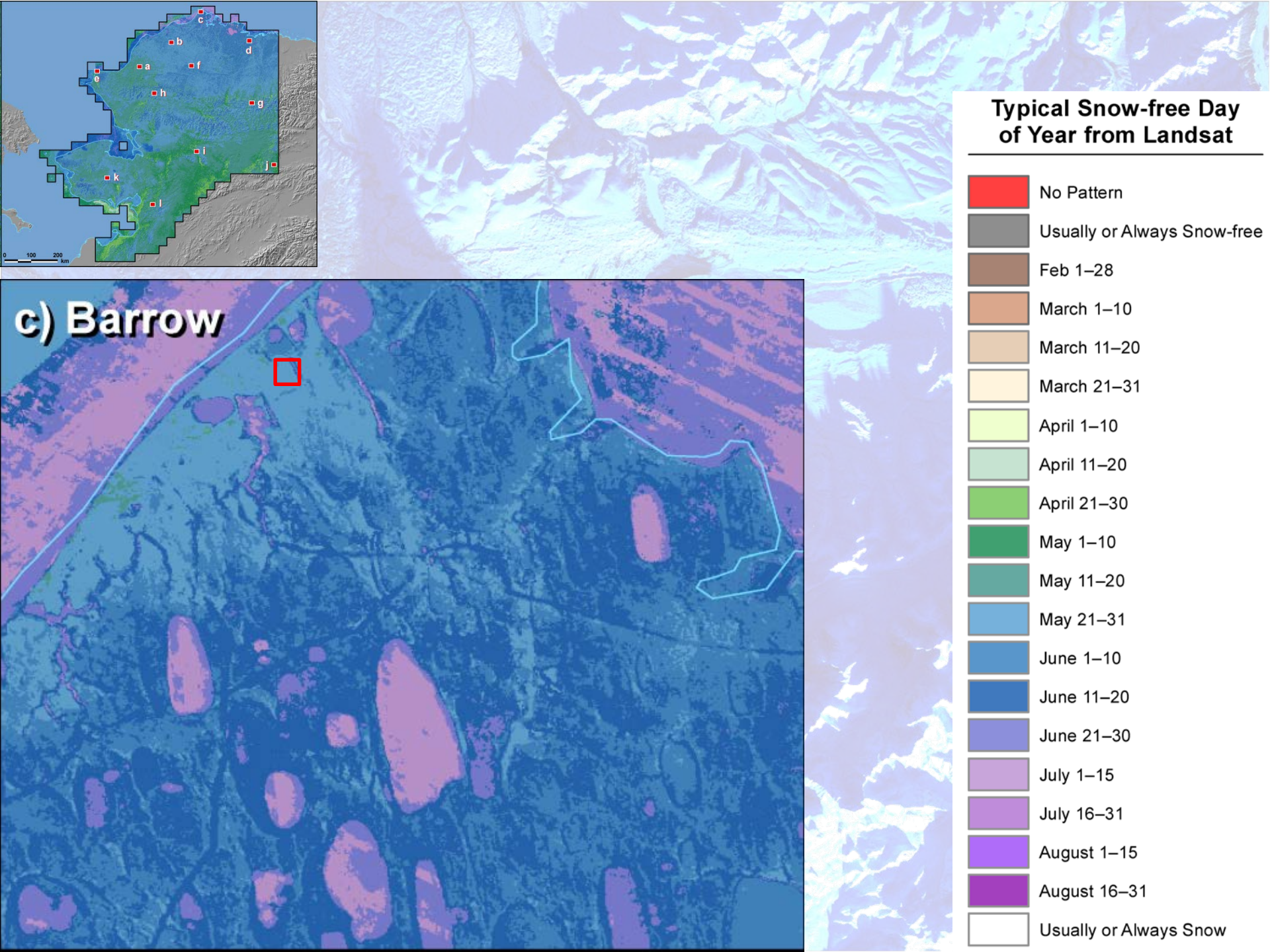

Beaufort Sea
Chukchi Sea
Imnavait Grid
CANADA
Bering Sea
ALASKA
Gulf of Alaska
100
Kilometers

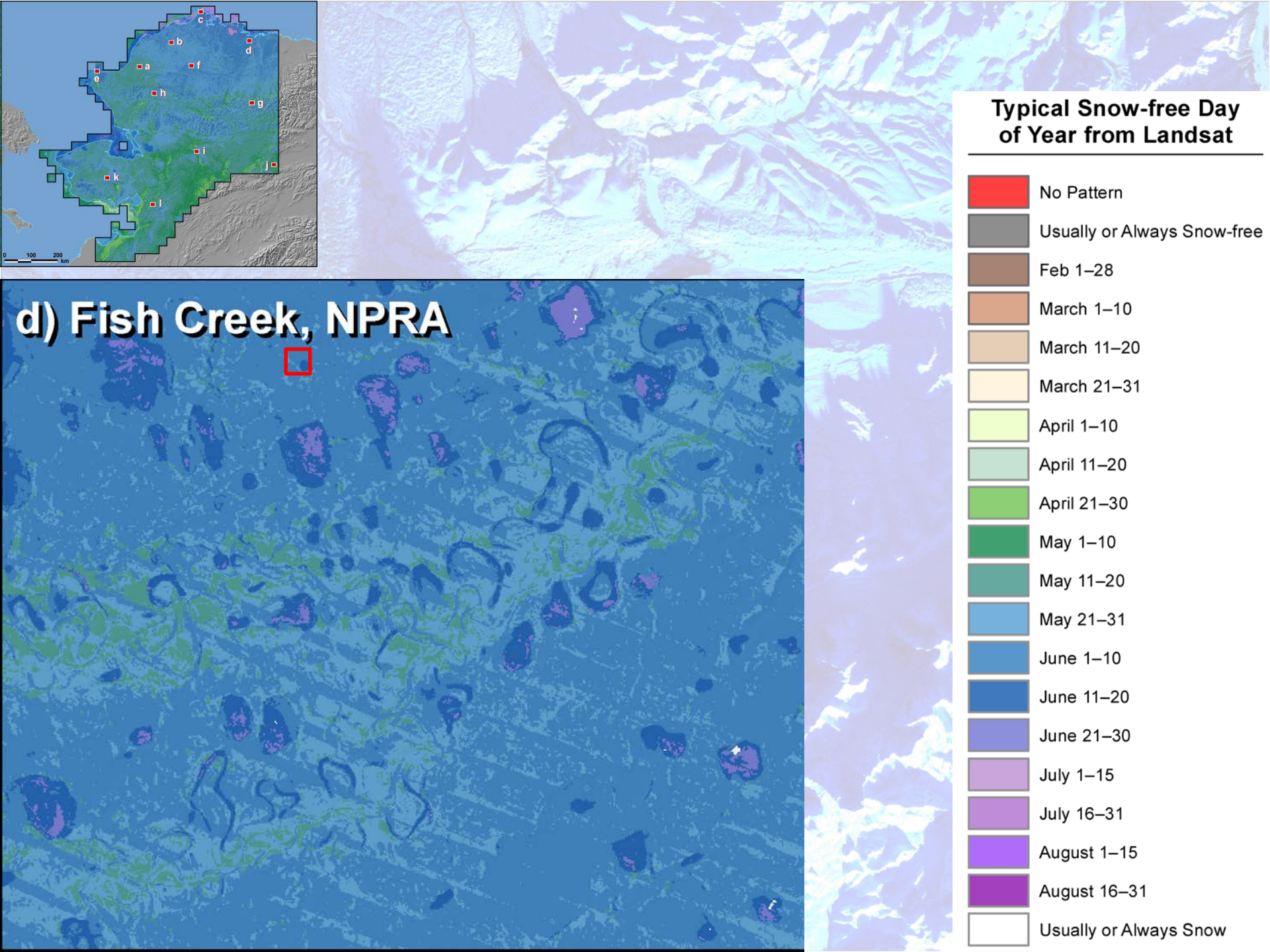


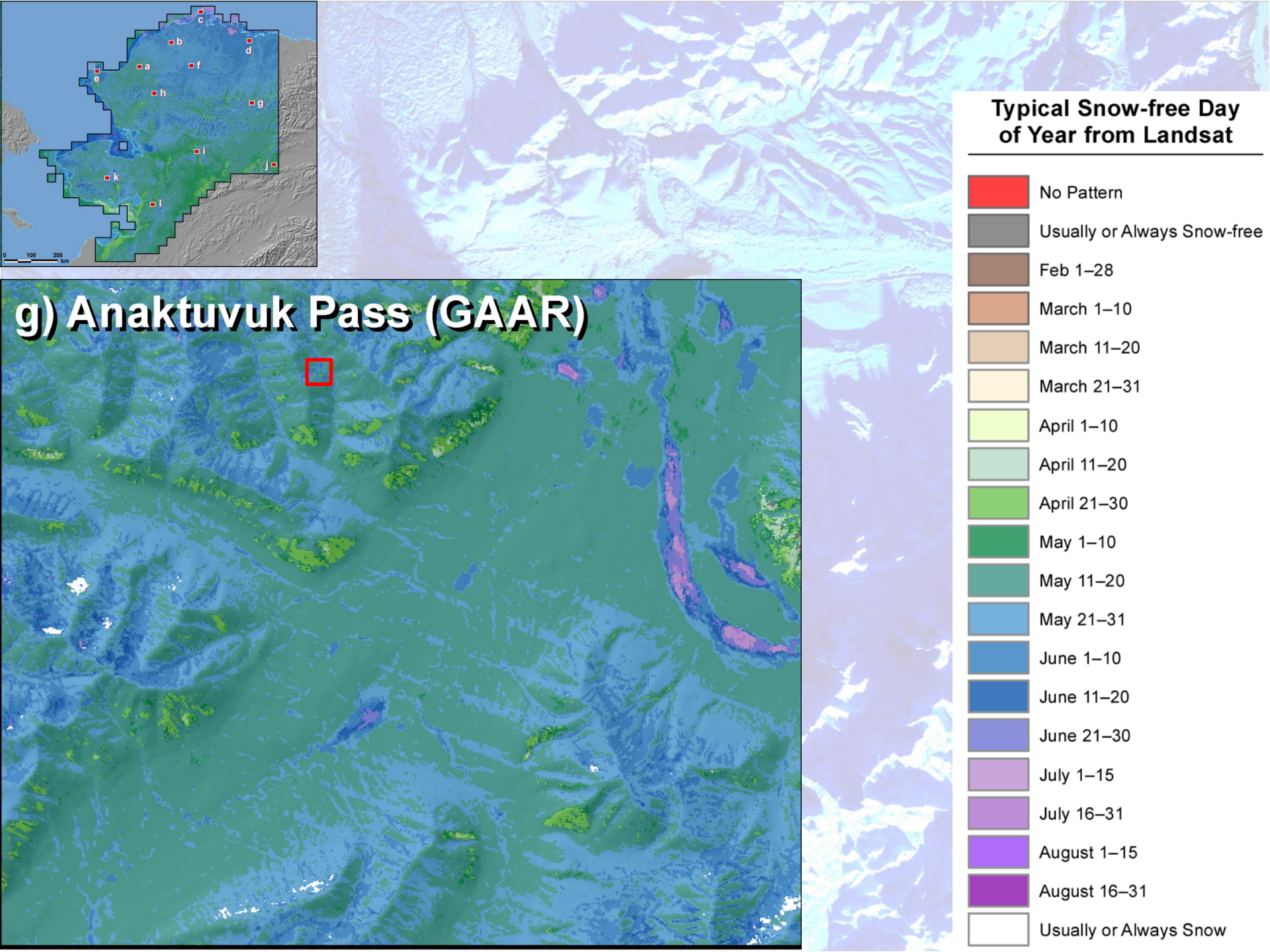
Typical Snow-free Day of Year from Landsat

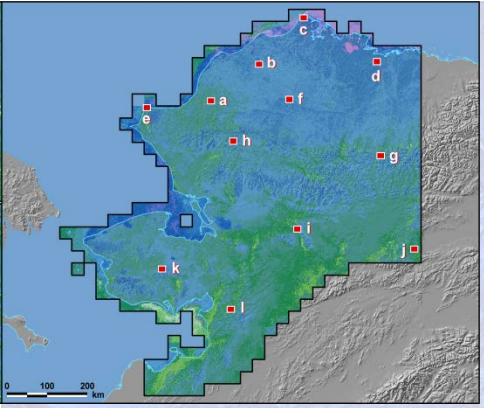
- No Pattern
- Usually or Always Snow-free
- Feb 1–28
- March 1–10
- March 11–20
- March 21–31
- April 1–10
- April 11–20
- April 21–30
- May 1–10
- May 11–20
- May 21–31
- June 1–10
- June 11–20
- June 21–30
- July 1–15
- July 16–31
- August 1–15
- August 16–31
- Usually or Always Snow

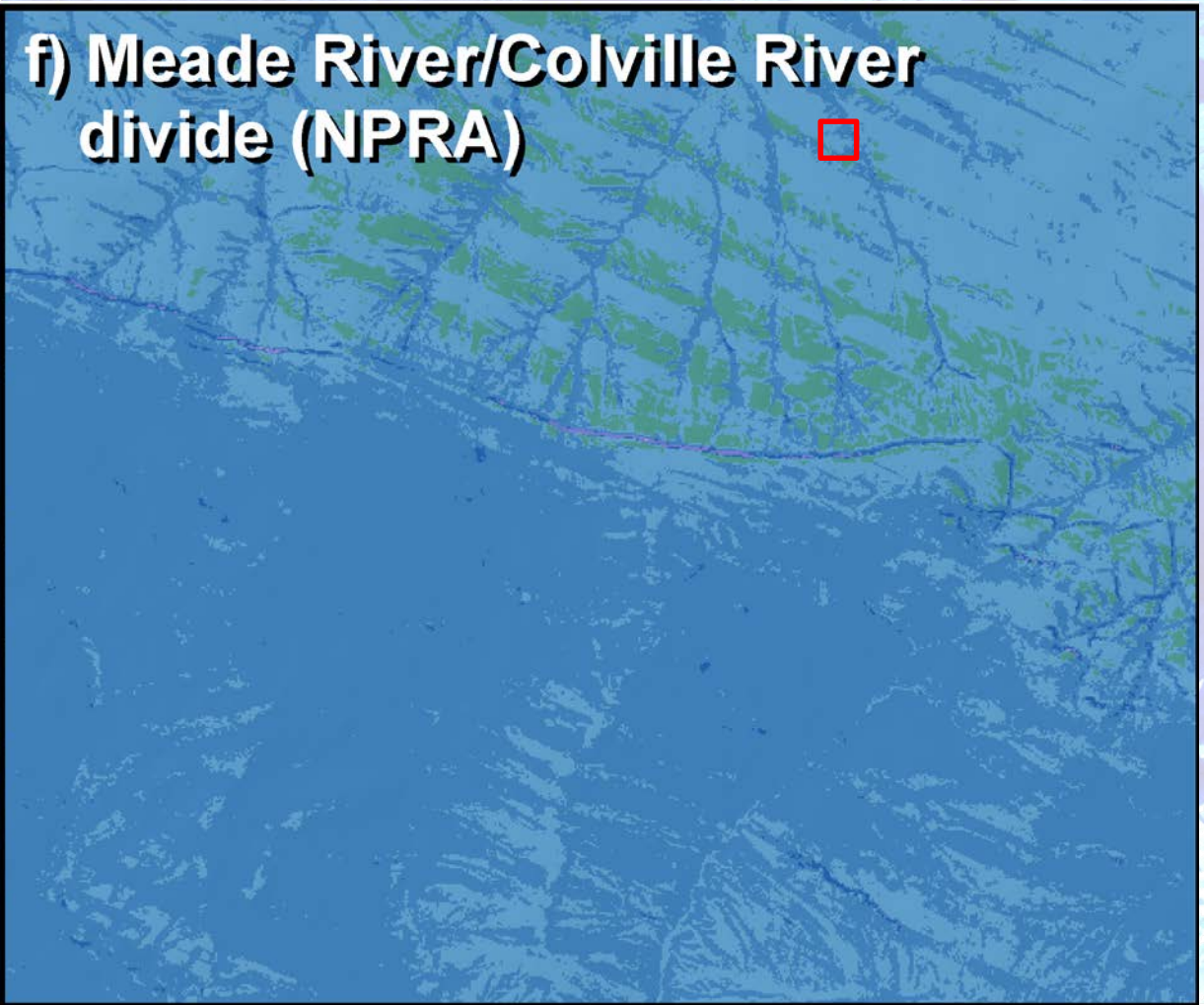
Macander, M. J., C. S. Swingley, K. Joly, M. K. Raynolds. 2015. Landsat-based snow persistence map for northwest Alaska. Remote Sensing of Environment.


c) Barrow
Typical Snow-free Day of Year from Landsat
No Pattern
Usually or Always Snow-free
Feb 1–28
March 1–10
March 11–20
March 21–31
April 1–10
April 11–20
April 21–30
May 1–10
May 11–20
May 21–31
June 1–10
June 11–20
June 21–30
July 1–15
July 16–31
August 1–15
August 16–31
Usually or Always Snow


c
b
d
a
f
e
h
g
i
j
k
l
0
100
200
km
d) Fish Creek, NPRA
Typical Snow-free Day of Year from Landsat
No Pattern
Usually or Always Snow-free
Feb 1–28
March 1–10
March 11–20
March 21–31
April 1–10
April 11–20
April 21–30
May 1–10
May 11–20
May 21–31
June 1–10
June 11–20
June 21–30
July 1–15
July 16–31
August 1–15
August 16–31
Usually or Always Snow

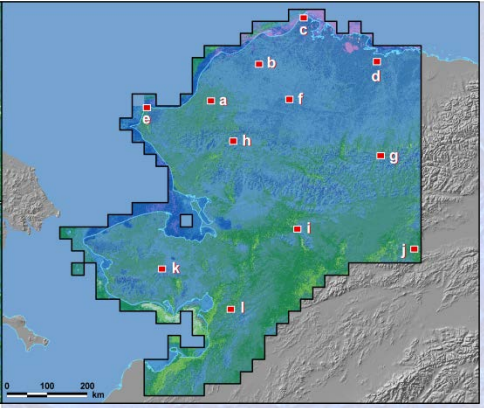

g) Anaktuvuk Pass (GAAR)
Typical Snow-free Day of Year from Landsat
No Pattern
Usually or Always Snow-free
Feb 1–28
March 1–10
March 11–20
March 21–31
April 1–10
April 11–20
April 21–30
May 1–10
May 11–20
May 21–31
June 1–10
June 11–20
June 21–30
July 1–15
July 16–31
August 1–15
August 16–31
Usually or Always Snow

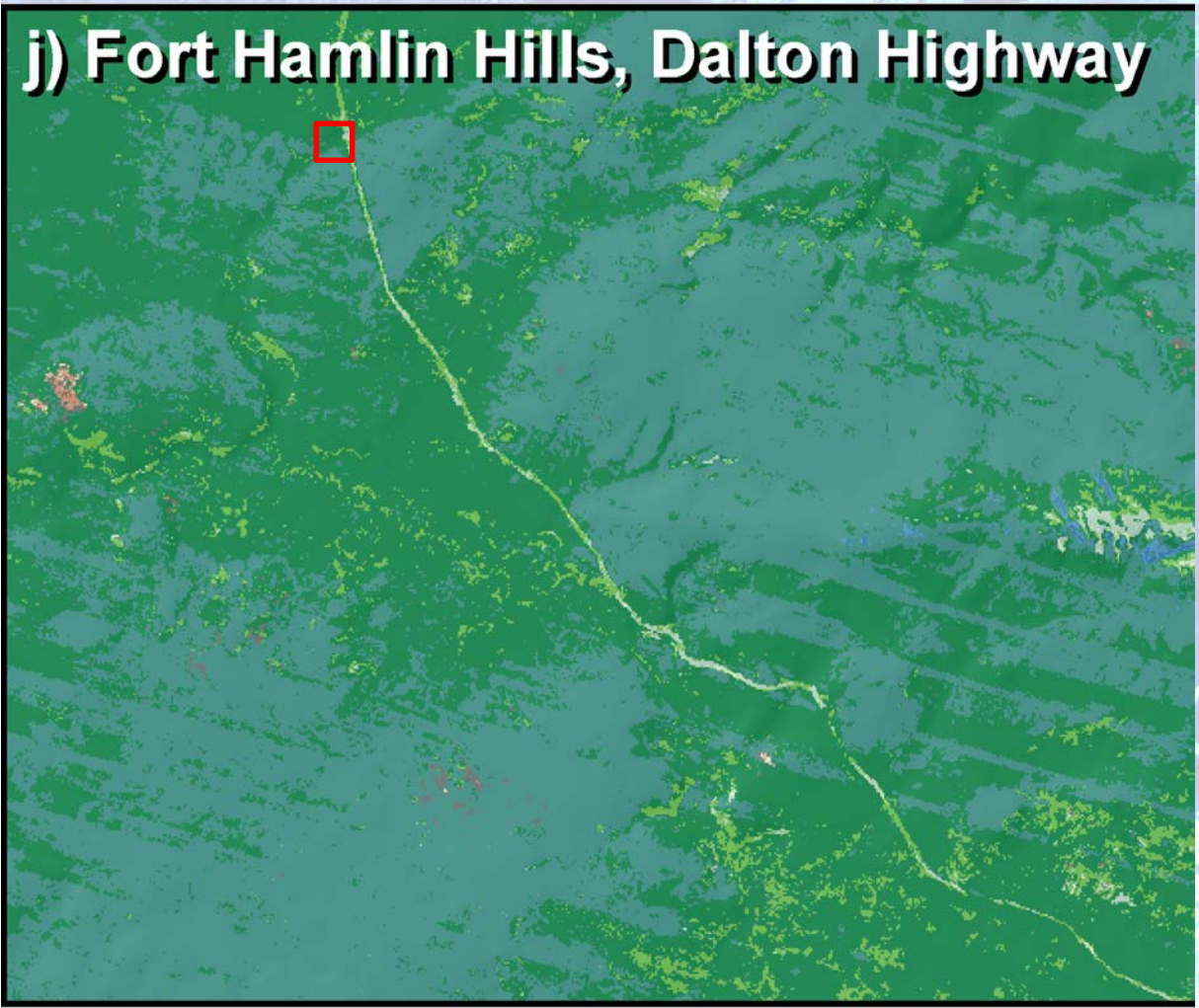




Typical Snow-free Day of Year from Landsat

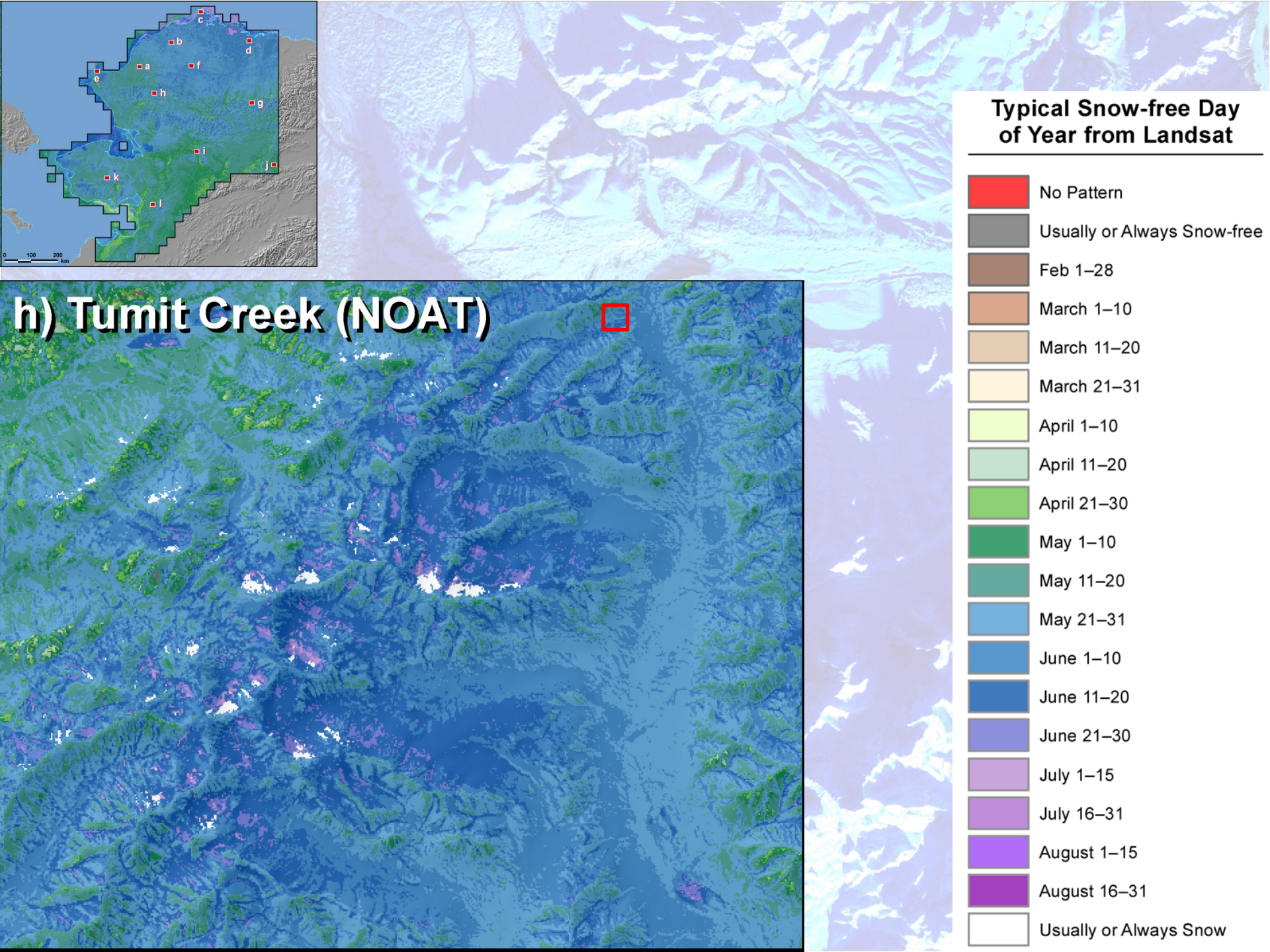
- No Pattern
- Usually or Always Snow-free
- Feb 1–28
- March 1–10
- March 11–20
- March 21–31
- April 1–10
- April 11–20
- April 21–30
- May 1–10
- May 11–20
- May 21–31
- June 1–10
- June 11–20
- June 21–30
- July 1–15
- July 16–31
- August 1–15
- August 16–31
- Usually or Always Snow

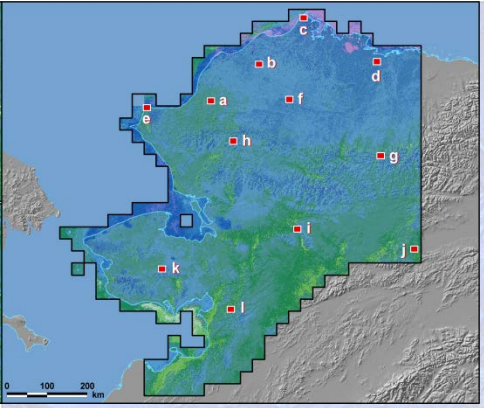


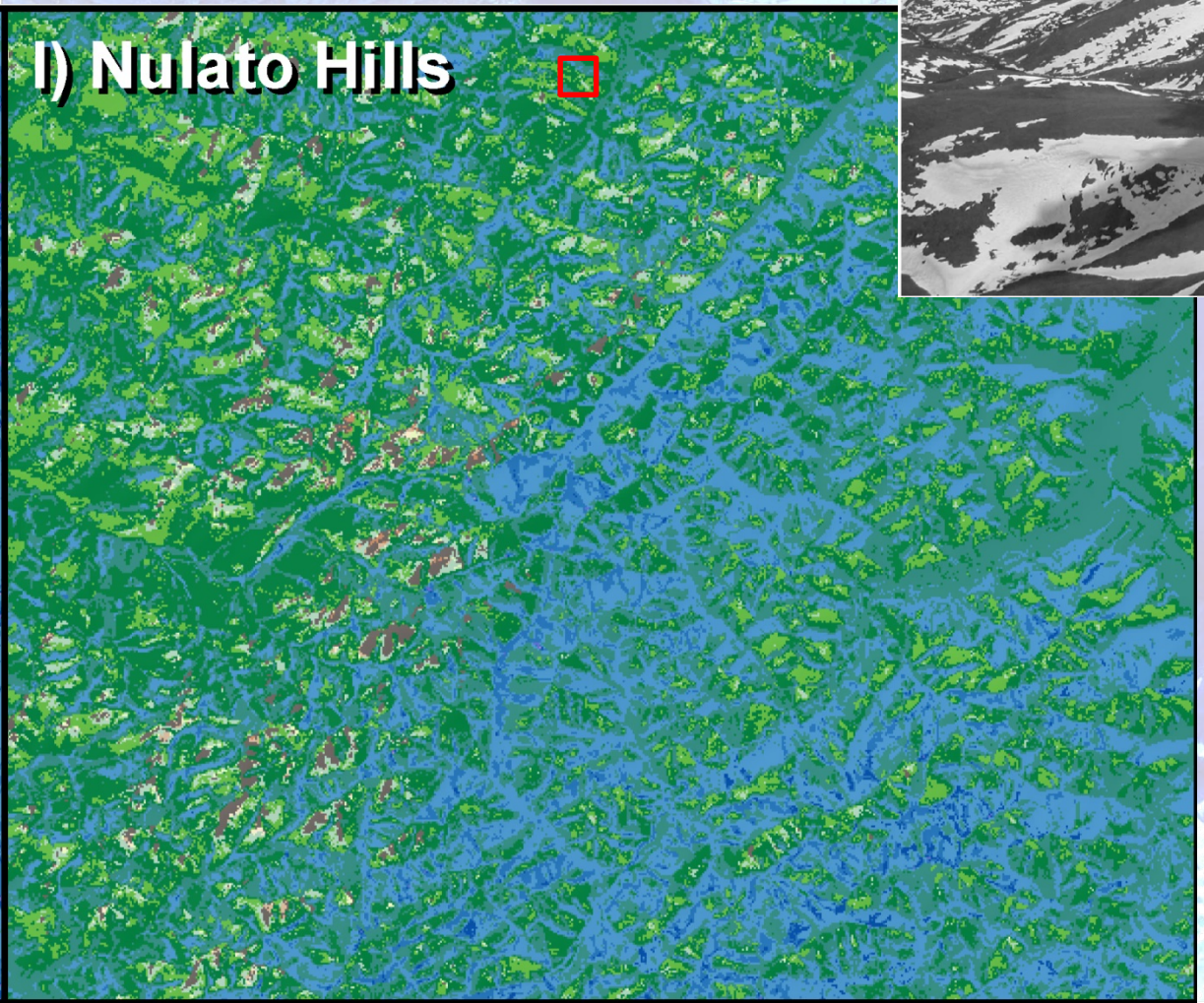


Typical Snow-free Day of Year from Landsat

- No Pattern
- Usually or Always Snow-free
- Feb 1–28
- March 1–10
- March 11–20
- March 21–31
- April 1–10
- April 11–20
- April 21–30
- May 1–10
- May 11–20
- May 21–31
- June 1–10
- June 11–20
- June 21–30
- July 1–15
- July 16–31
- August 1–15
- August 16–31
- Usually or Always Snow

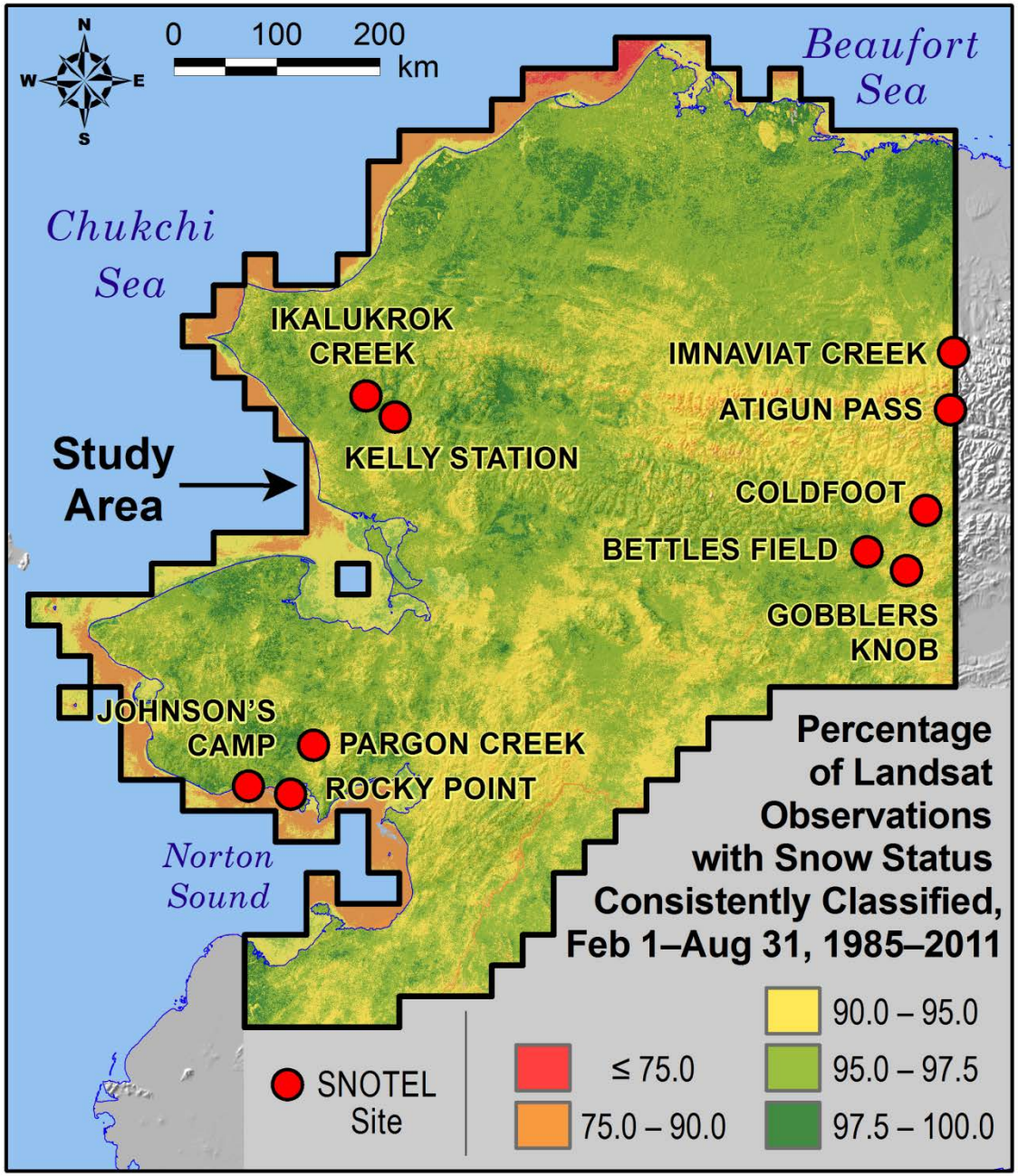

h) Tumit Creek (NOAT)
Typical Snow-free Day of Year from Landsat
No Pattern
Usually or Always Snow-free
Feb 1–28
March 1–10
March 11–20
March 21–31
April 1–10
April 11–20
April 21–30
May 1–10
May 11–20
May 21–31
June 1–10
June 11–20
June 21–30
July 1–15
July 16–31
August 1–15
August 16–31
Usually or Always Snow





- April 21–30
- May 1–10
- May 11–20
- May 21–31
- June 1–10
- June 11–20
- June 21–30
- July 1–15
- July 16–31
- August 1–15
- August 16–31
- Usually or Always Snow

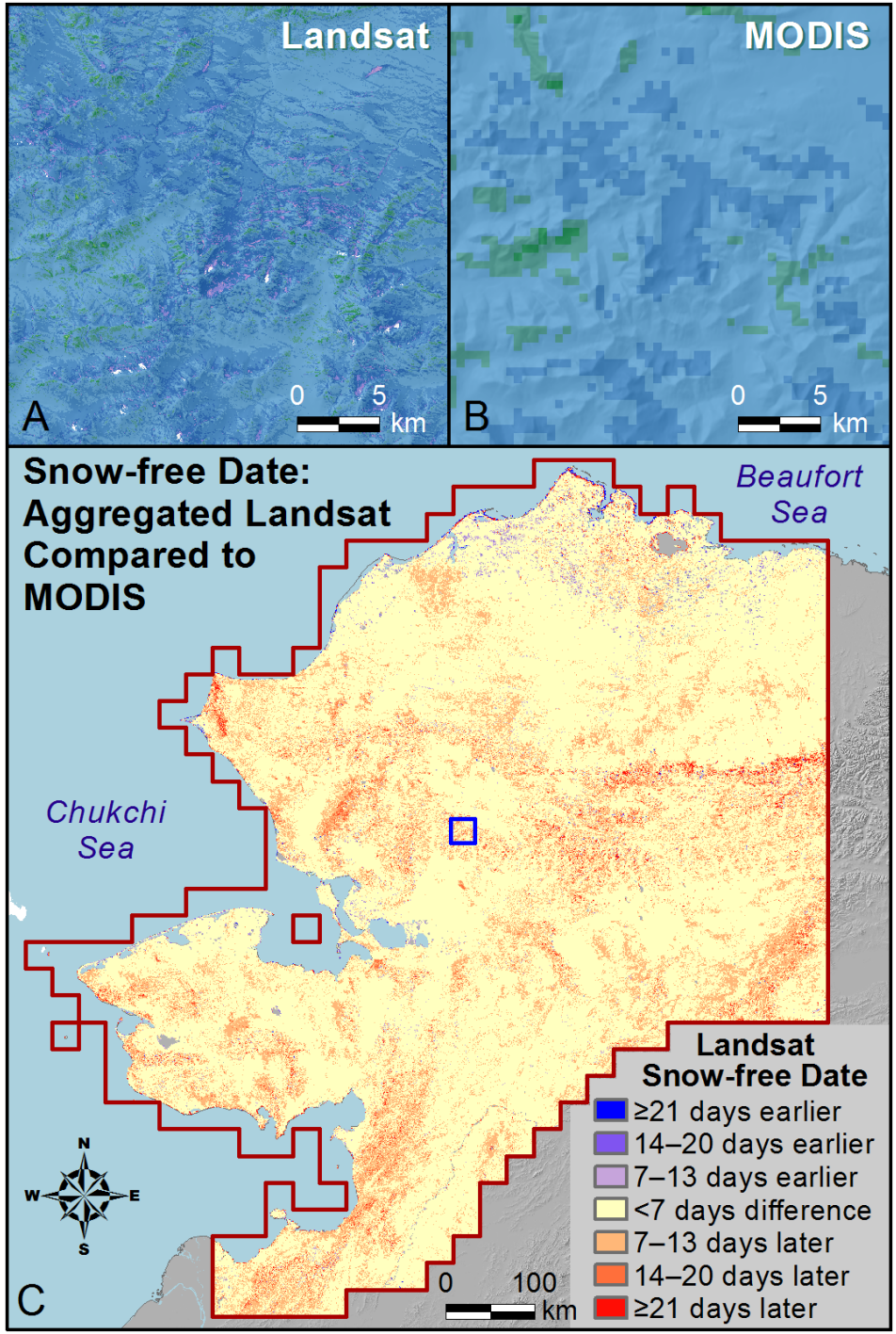
Validation:
Internal Consistency



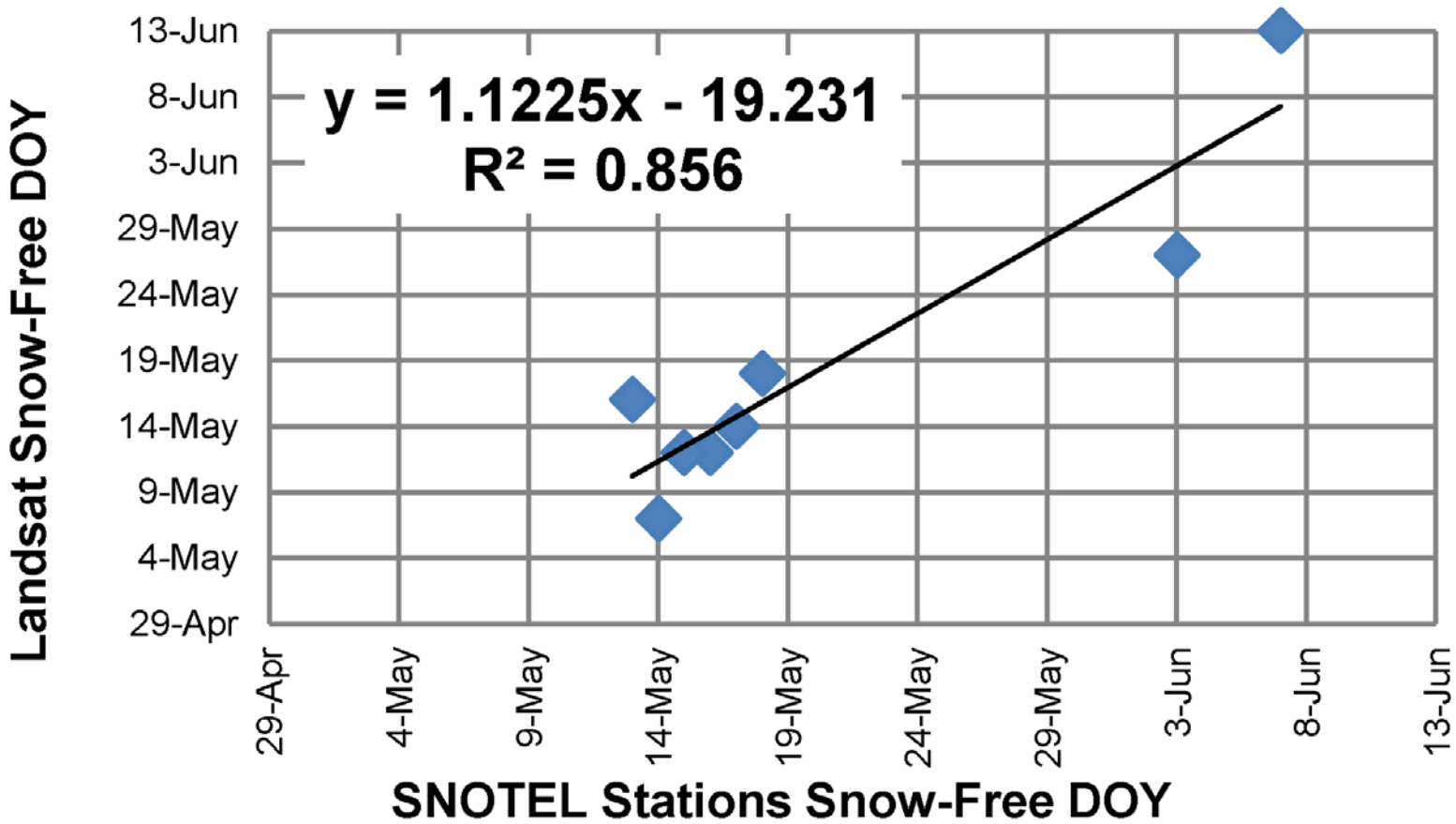
Validation:
Comparison to
MODIS Snow Metrics

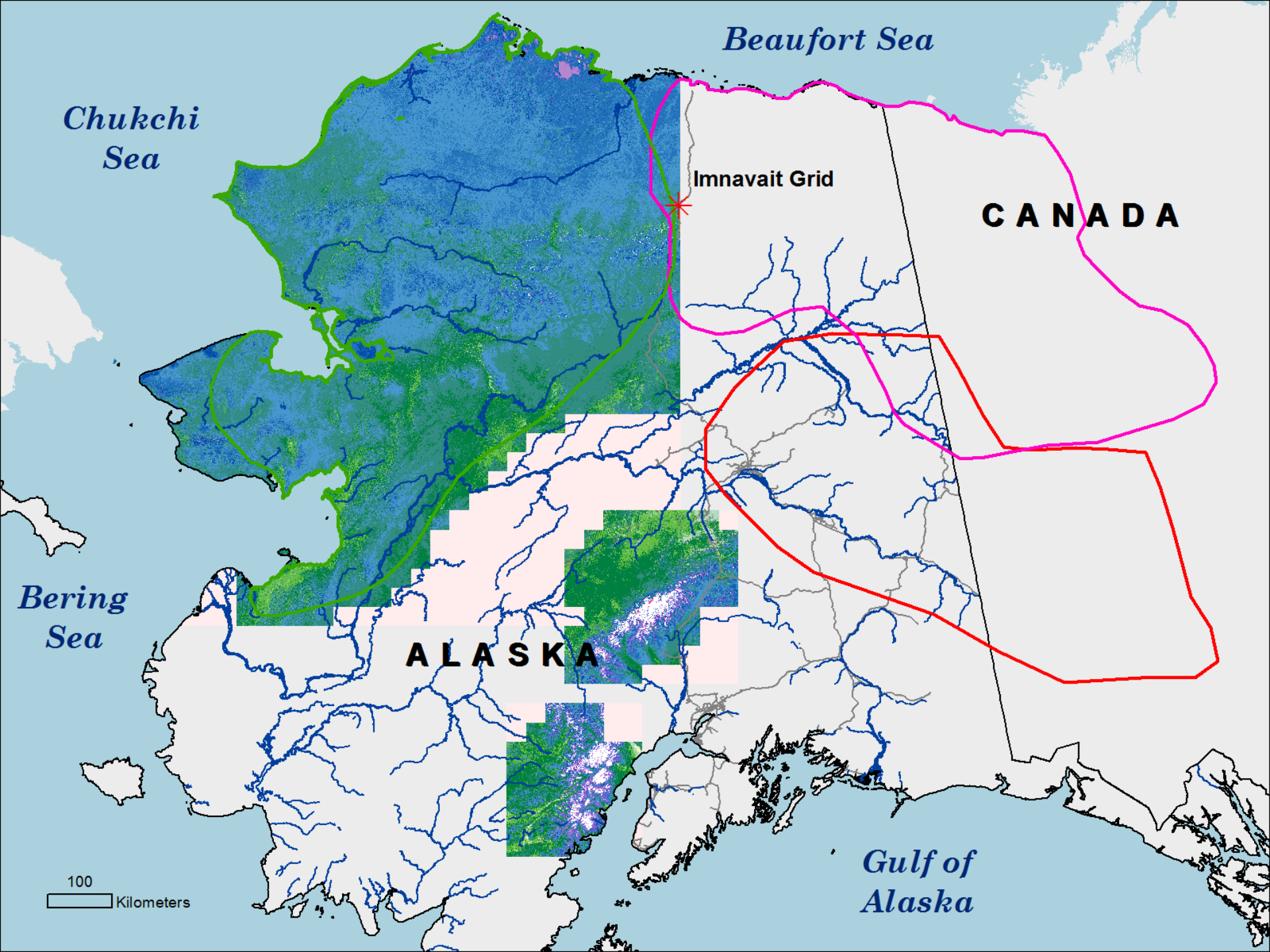
Mean Difference: 3.4 days (MODIS earlier)

Mean Absolute Difference: 4.2 days



Validation:
Comparison to SNOTEL




Beaufort Sea
Chukchi Sea
Imnavait Grid
CANADA
Bering Sea
ALASKA
Gulf of Alaska
100
Kilometers

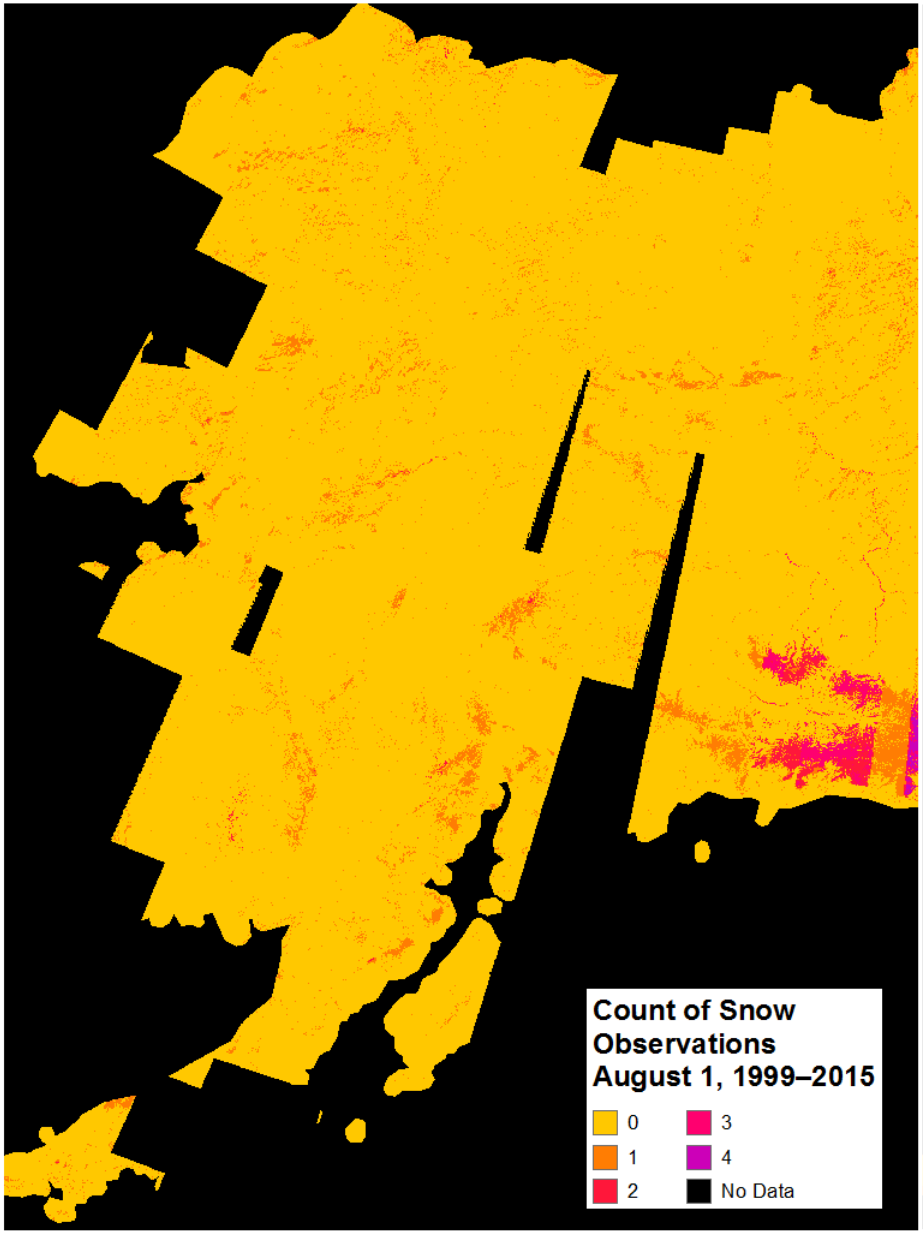
2012 vs. 2016

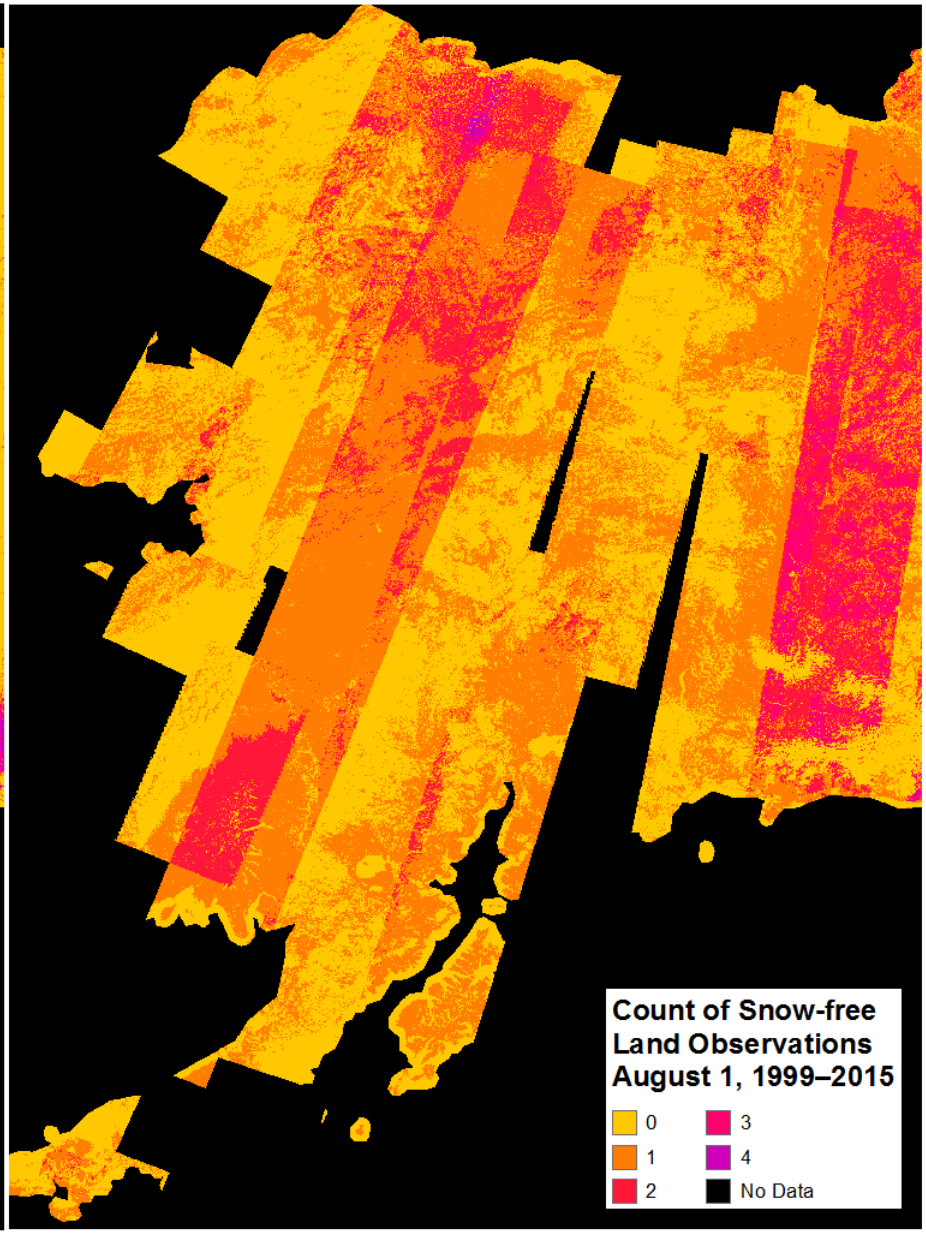
- 2012
  - Downloaded >10,000 Landsat scenes, performed image calibration, gridding, shadow modeling and snow mapping on our servers
  - Months of lead time
  - Data through 2011, also included sparse 1985-1998 scenes

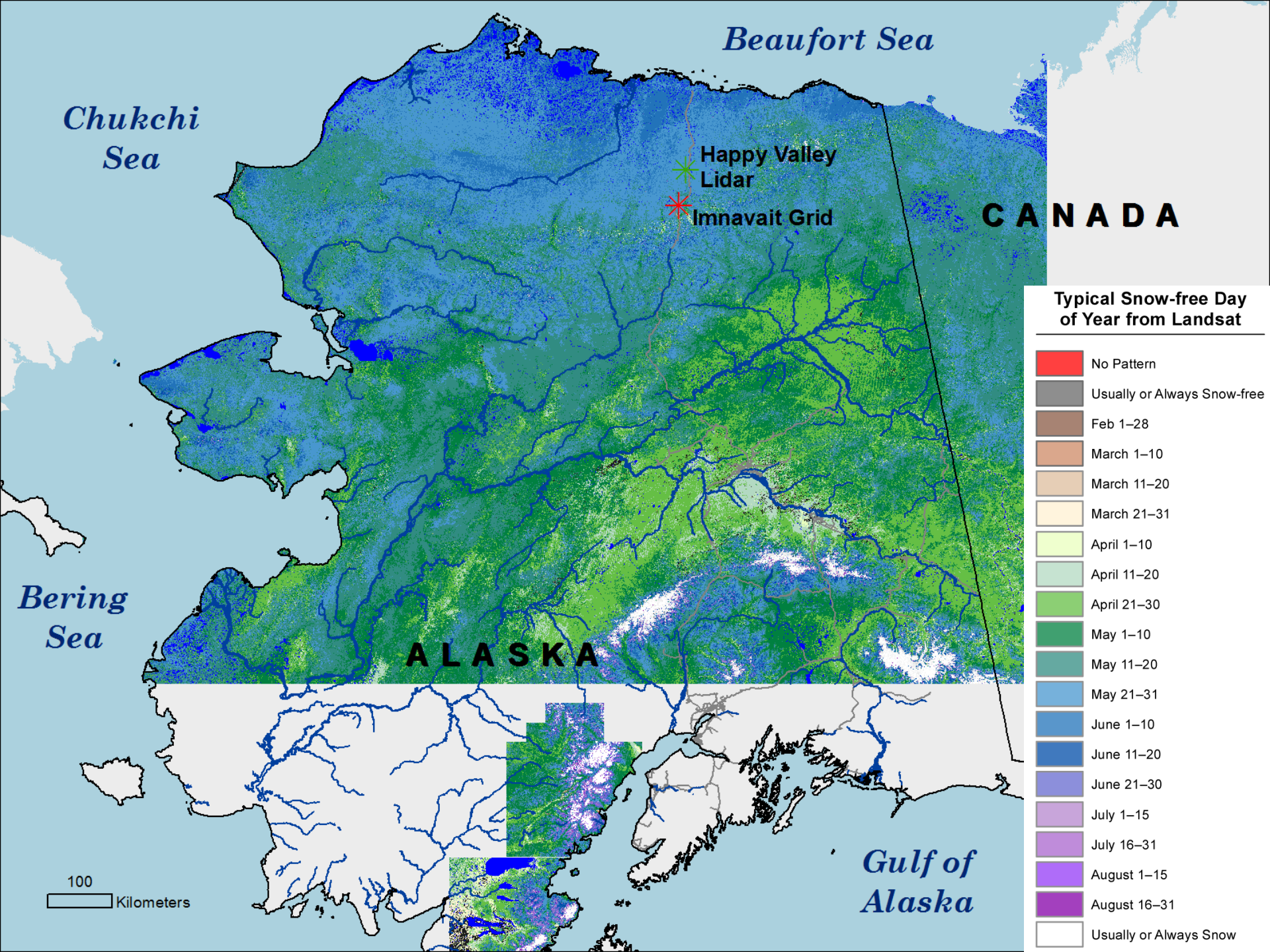
2012 vs. 2016

- 2016
  - Used Landsat imagery and FMASK stored in Google Earth Engine
  - Calculated Terrain Shadow on-the-fly (GDEM)
  - Applied Selkowitz decision tree to reduce false cloud detections (snow/cloud confusion)
  - Started analysis from 1999 to reduce bias from regime changes
  - Extracted summary data as counts of snow and snow-free land for each day of year, March 1–August 31

Summary Counts, August 1






Beaufort Sea
Chukchi Sea
Bering Sea
Gulf of Alaska
CANADA
ALASKA
Happy Valley Lidar
Imnavait Grid
100
Kilometers
Typical Snow-free Day of Year from Landsat
No Pattern
Usually or Always Snow-free
Feb 1–28
March 1–10
March 11–20
March 21–31
April 1–10
April 11–20
April 21–30
May 1–10
May 11–20
May 21–31
June 1–10
June 11–20
June 21–30
July 1–15
July 16–31
August 1–15
August 16–31
Usually or Always Snow

Applications of Snow Persistence Maps

- Snow depth affect plant ecology and wildlife in many ways
- Habitat may be physically unavailable until snow has melted
- Shallow snow and scoured areas experience early melt
  - Early green-up
  - Exposure to winter cold
  - Drier

Applications of Snow Persistence Maps

- Snow beds and snow drifts experience later melt
  - Delayed phenology throughout season
    - Newly emerged vegetation available later
    - Berries available later
  - Denning sites for polar bears, wolverines
  - Soils and vegetation feedback

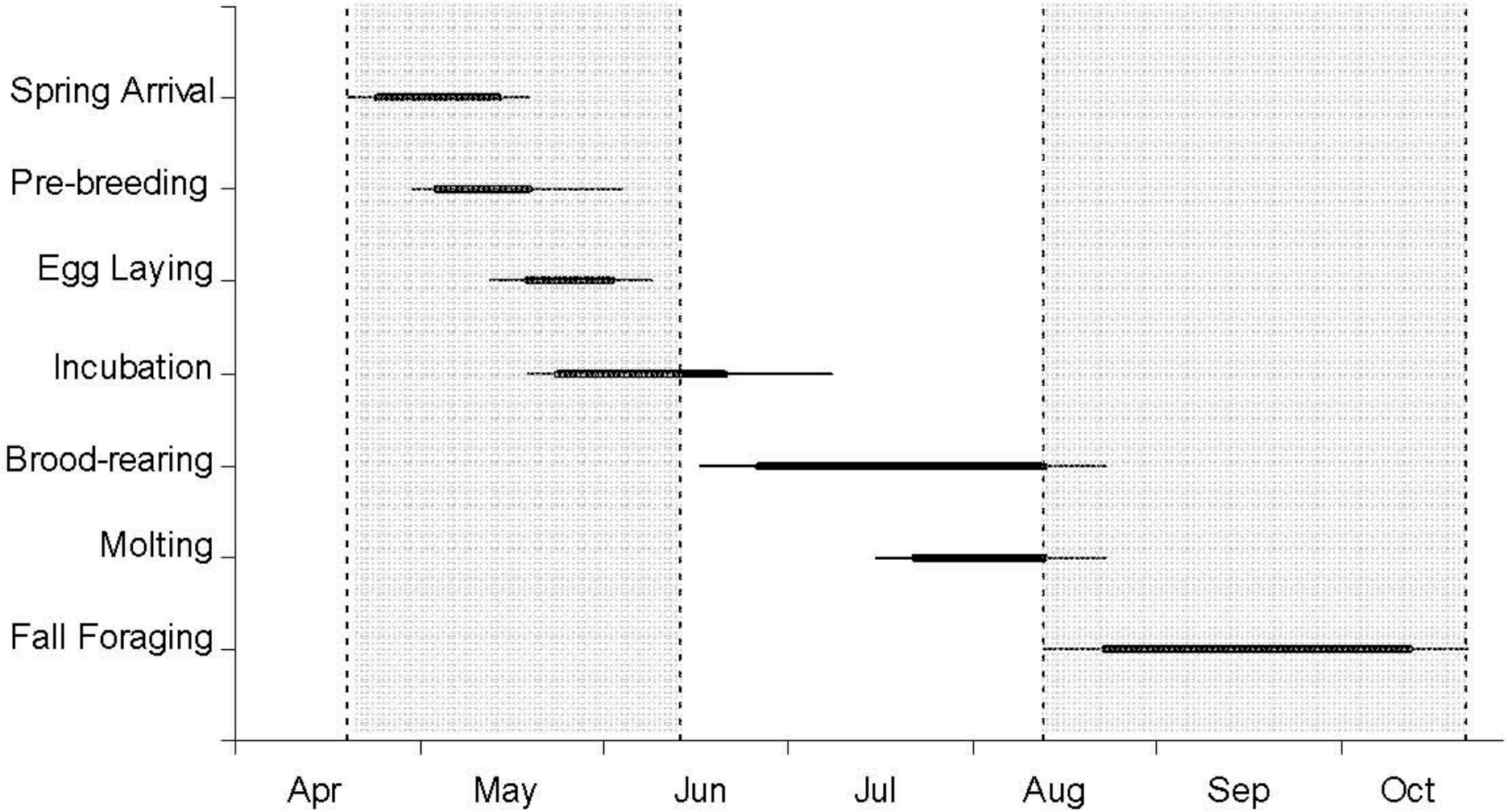
Some Applications of Snow Persistence Maps

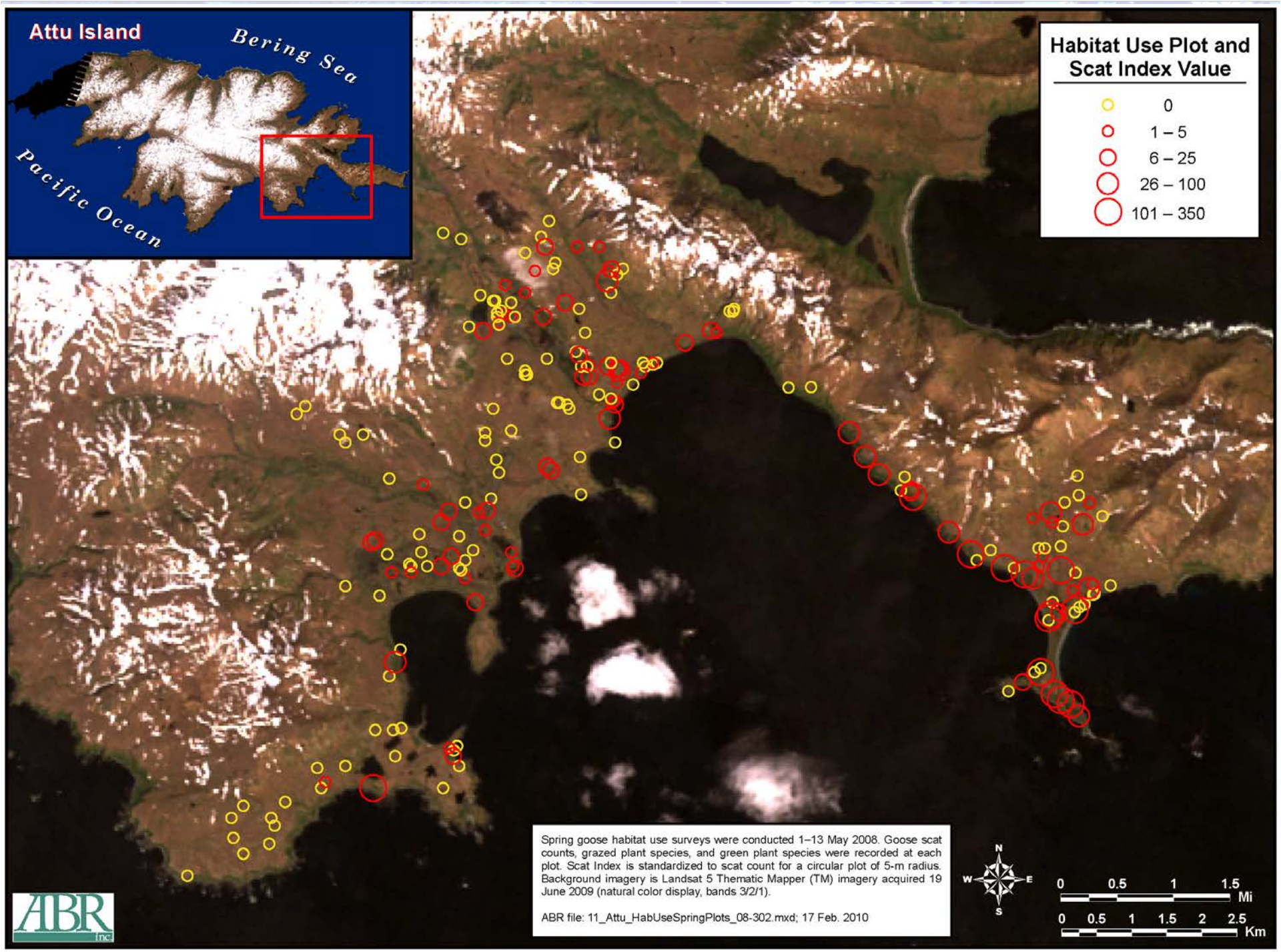
1. Contributing area to spring and summer streamflow in headwaters basins
2. Seasonal habitat availability (Landsat example for Aleutian Cackling Goose in Near Islands, Alaska)

Objective

- Assess the relative importance of Shemya's Cackling Goose habitats within the Near Island group.

Aleutian Cackling Goose life stages




Attu Island
Bering Sea
Pacific Ocean
Habitat Use Plot and Scat Index Value
0
1 – 5
6 – 25
26 – 100
101 – 350
Spring goose habitat use surveys were conducted 1–13 May 2008. Goose scat counts, grazed plant species, and green plant species were recorded at each plot. Scat Index is standardized to scat count for a circular plot of 5-m radius. Background imagery is Landsat 5 Thematic Mapper (TM) imagery acquired 19 June 2009 (natural color display, bands 3/2/1).
ABR file: 11_Attu_HabUseSpringPlots_08-302.mxd; 17 Feb. 2010
N
W
E
S
0 0.5 1 1.5 Mi
0 0.5 1 1.5 2 2.5 Km
ABR Inc.

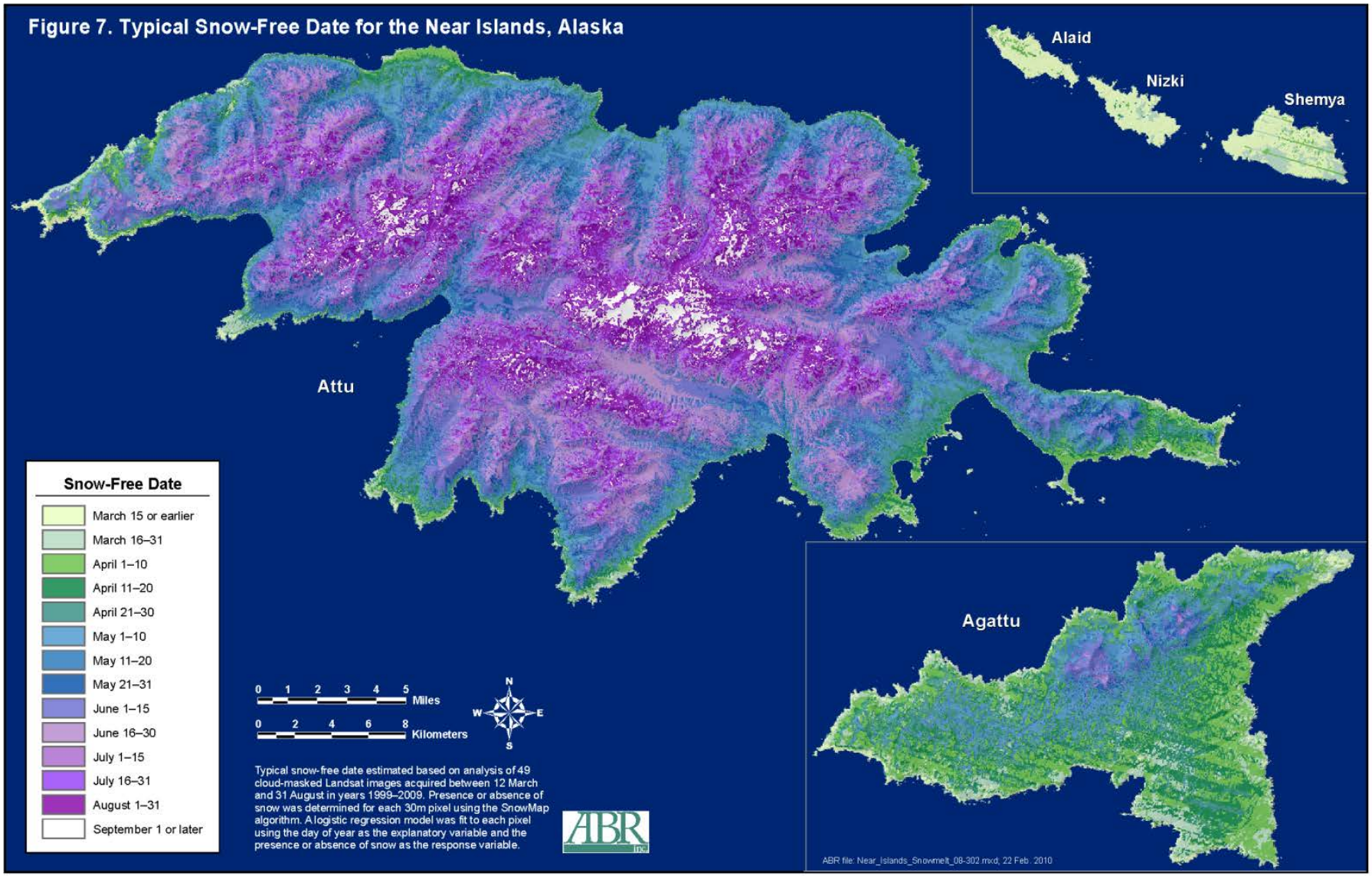
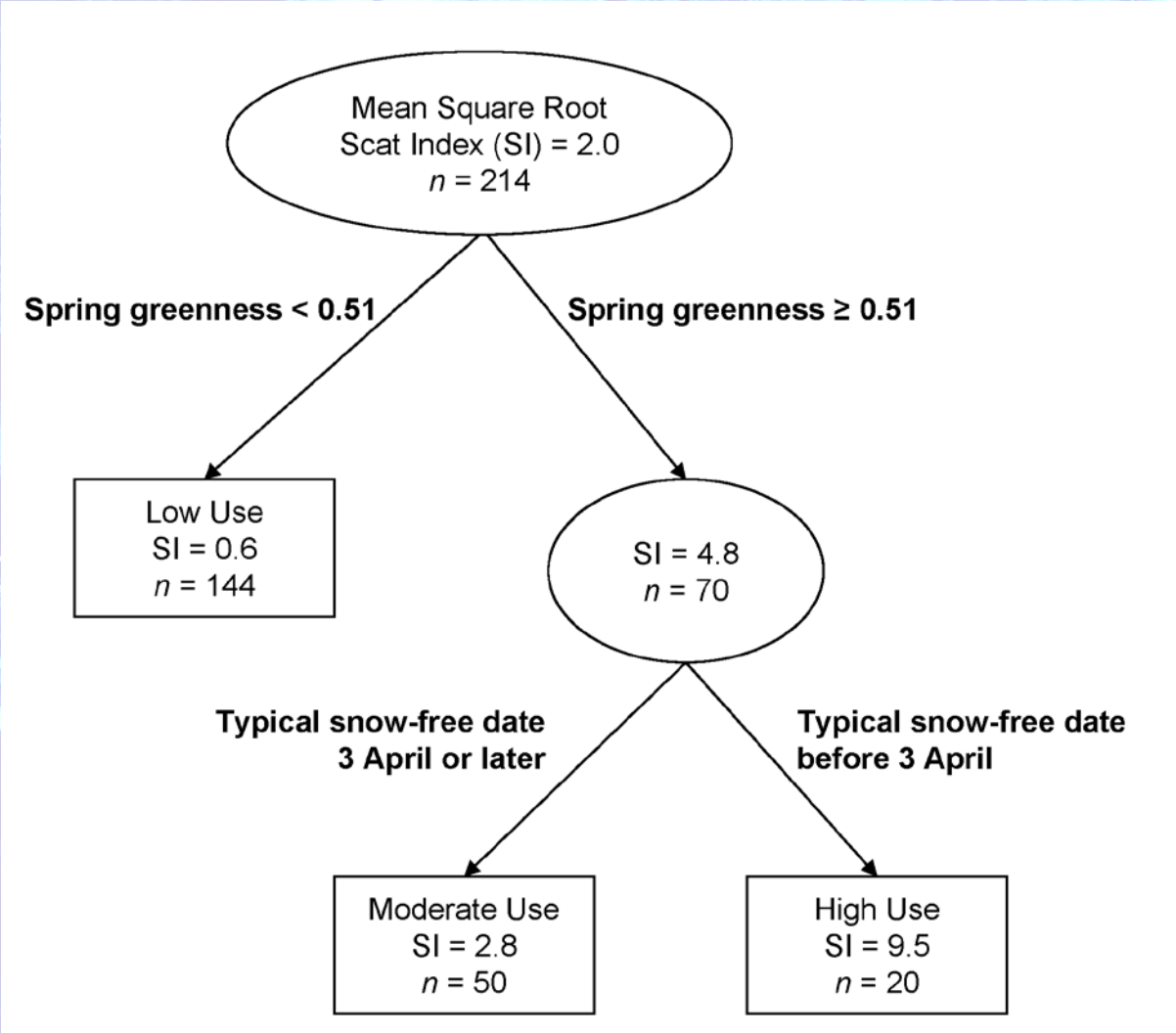


Figure 7. Typical Snow-Free Date for the Near Islands, Alaska
Alaid
Nizki
Shemya
Attu
Agattu
Snow-Free Date
March 15 or earlier
March 16–31
April 1–10
April 11–20
April 21–30
May 1–10
May 11–20
May 21–31
June 1–15
June 16–30
July 1–15
July 16–31
August 1–31
September 1 or later
0 1 2 3 4 5 Miles
0 2 4 6 8 Kilometers
N
W
E
S
Typical snow-free date estimated based on analysis of 49 cloud-masked Landsat images acquired between 12 March and 31 August in years 1999–2009. Presence or absence of snow was determined for each 30m pixel using the SnowMap algorithm. A logistic regression model was fit to each pixel using the day of year as the explanatory variable and the presence or absence of snow as the response variable.
ABR Inc.
ABR file: Near_Islands_Snowmelt_08-302.mxd; 22 Feb. 2010

Regression Tree Habitat Use Model



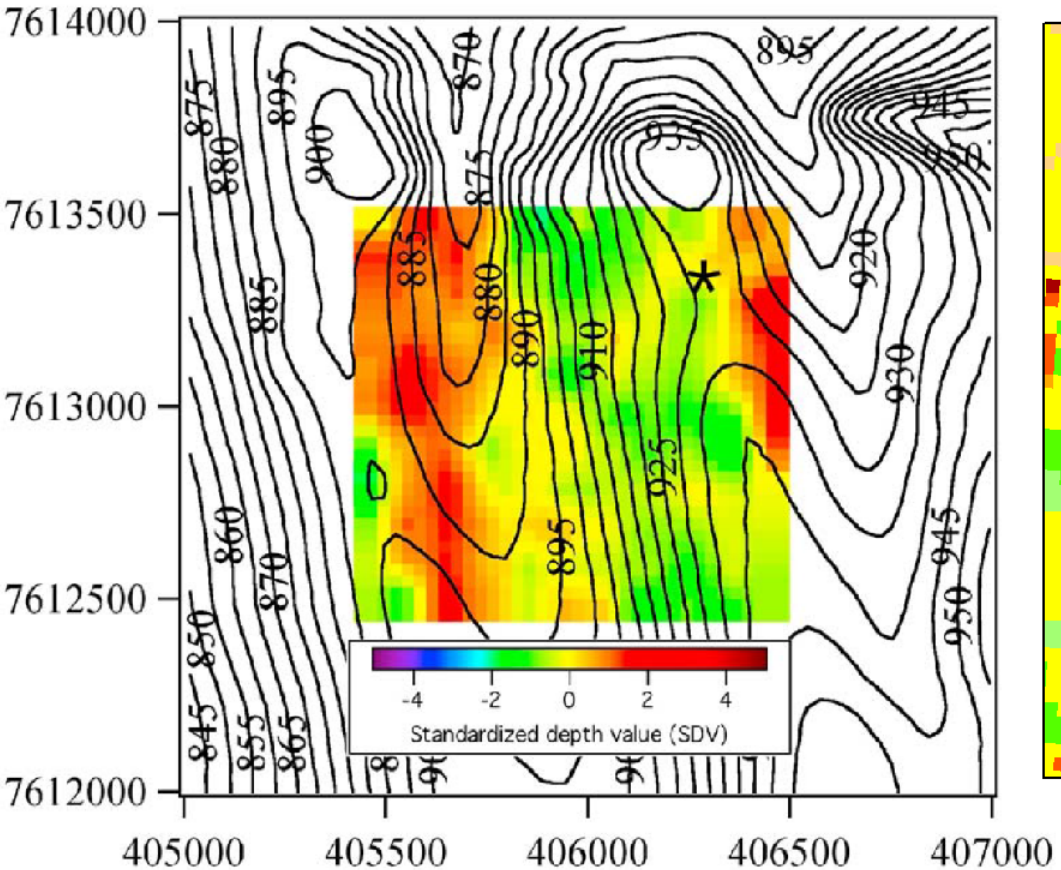
Aleutian Cackling Goose Conclusions

- In spring on Shemya, the primary determinant of goose habitat value appears to be the presence of preferred forage plants that green up early. The primary observed goose forage plant was the grass *Festuca rubra*.

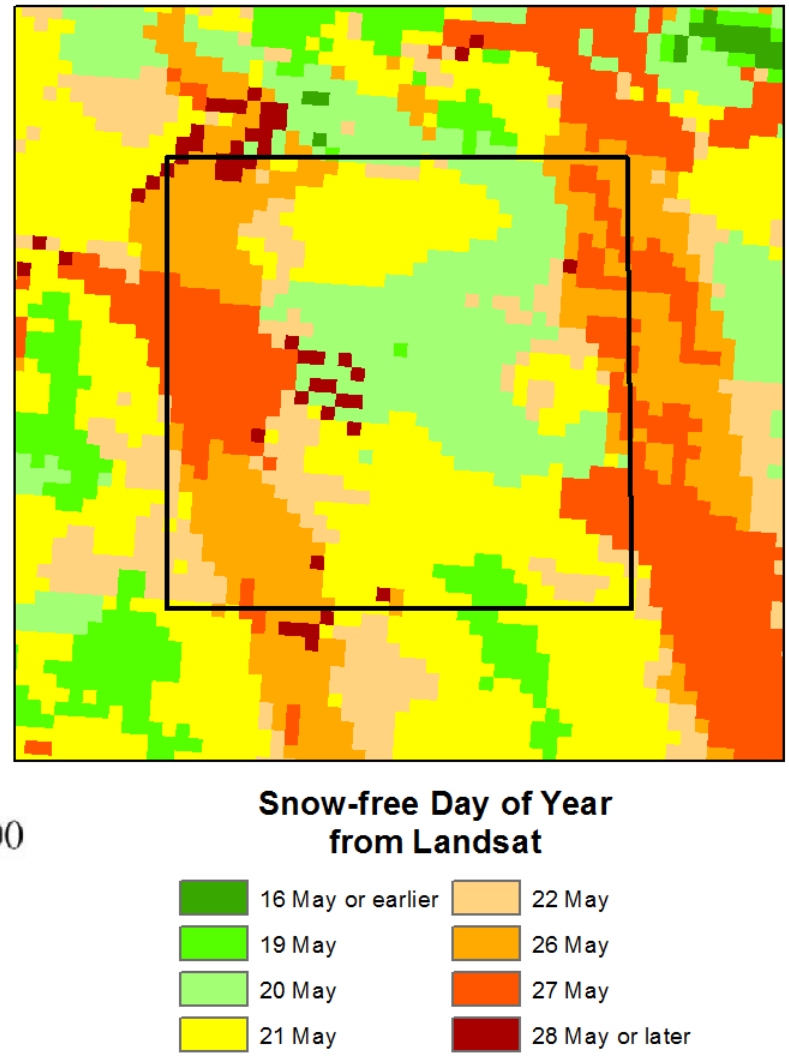
Some Applications of Snow Persistence Maps

3. Locating snowbeds, ice patches, and insect relief habitat
4. Strong predictor in caribou resource selection function models (Ambler Road, Wilson et al. 2014)
5. Snow persistence as a proxy or predictor for snow depth and/or snow water equivalent

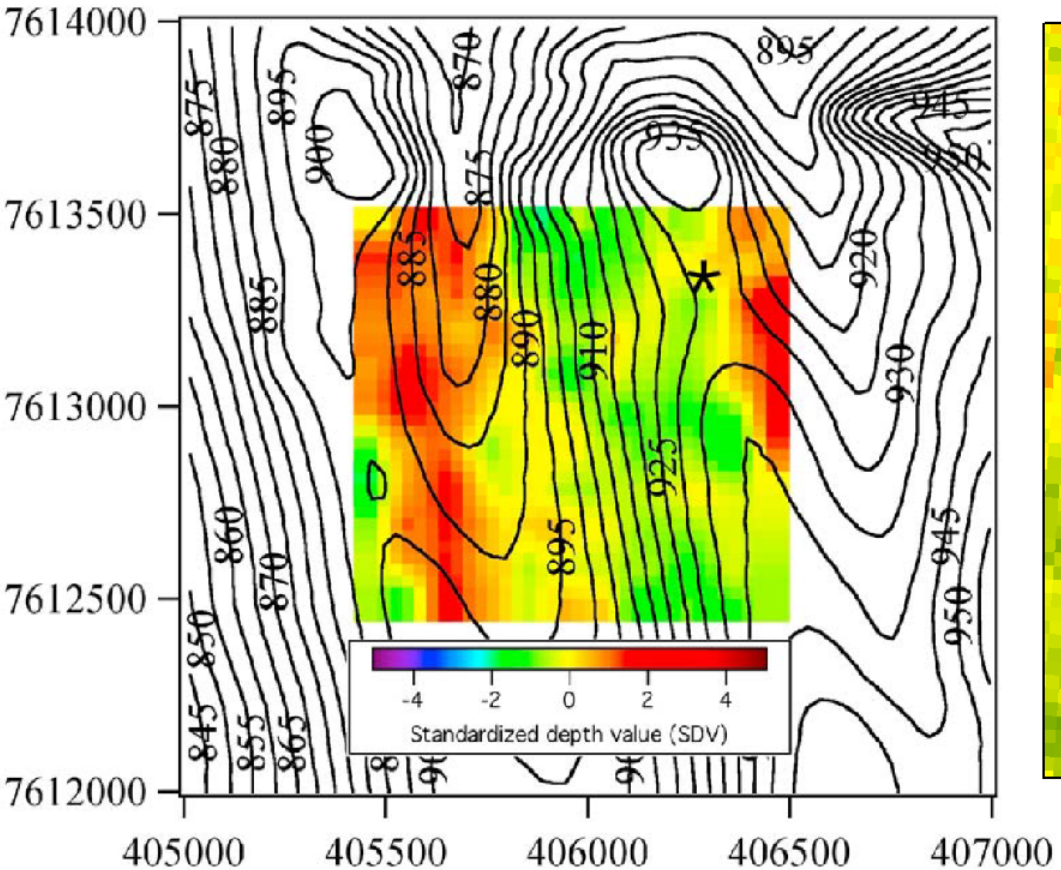
Imnavait Grid Snow Distribution Patterns: Ground and Landsat



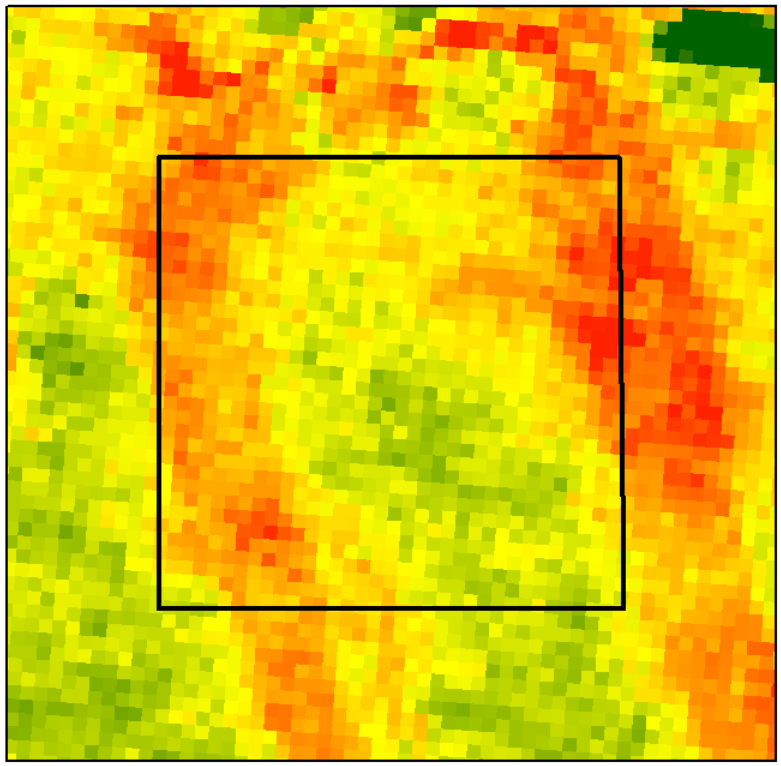
Climatalogical Snow Distribution Pattern (CSDP) based on 9 years of field measurements from Sturm and Wagner (2010).



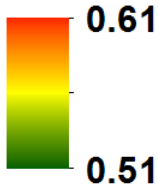
Imnavait Grid Snow Distribution Patterns: Ground and Landsat



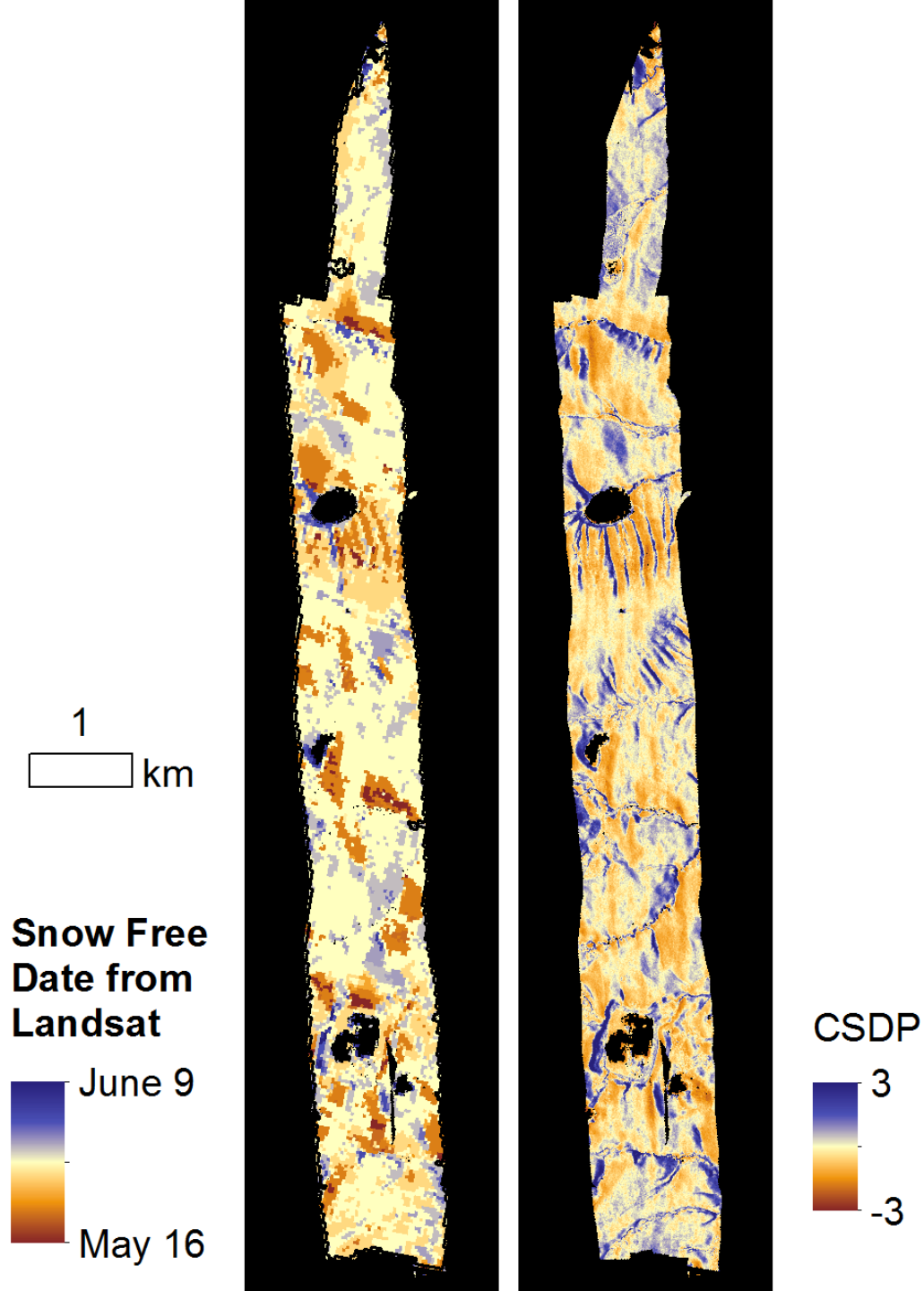
Climatalogical Snow Distribution Pattern (CSDP) based on 9 years of field measurements from Sturm and Wagner (2010).

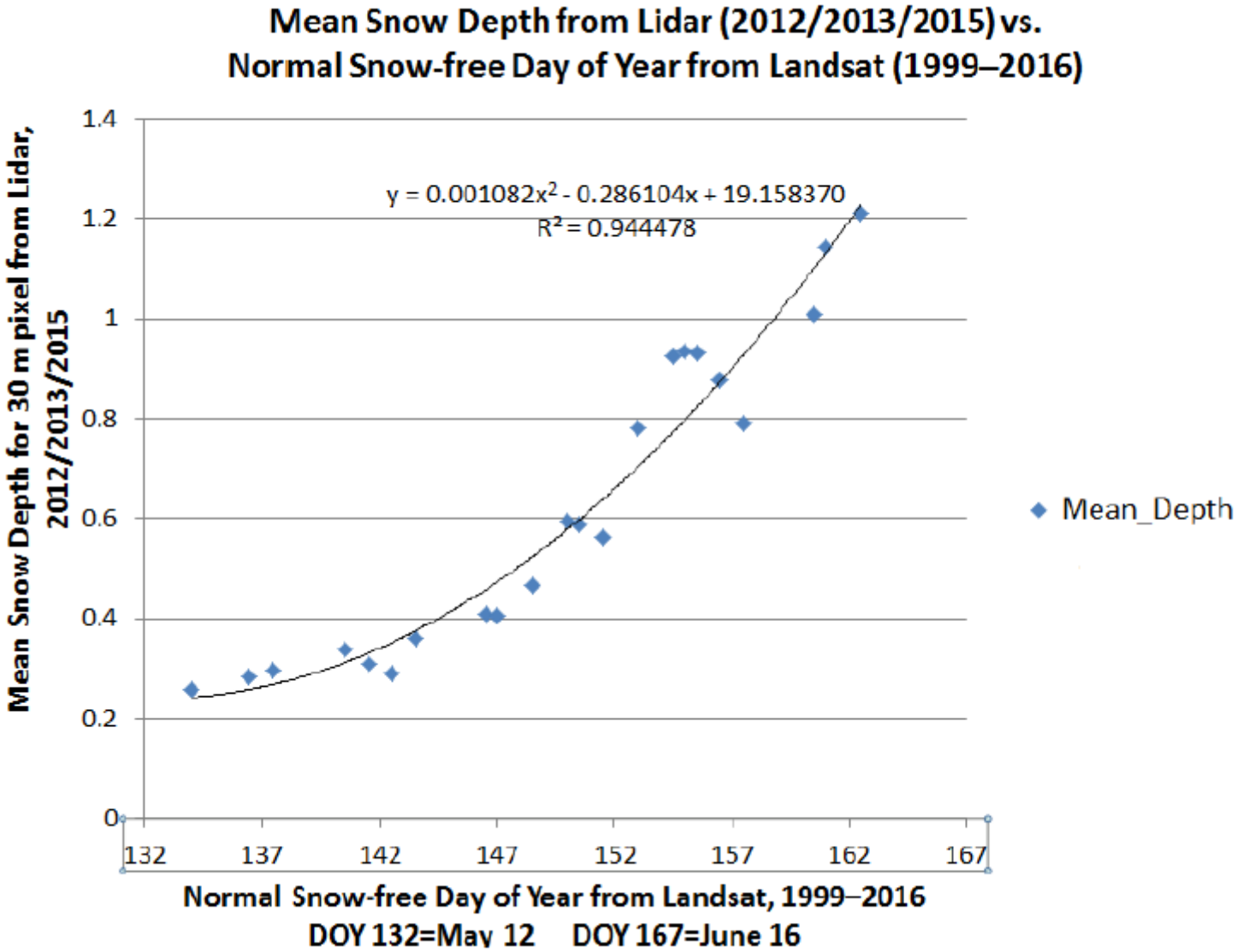


Proportion of Snow Observations to Total Cloud-free Land Observations (March 1–August 31, 1999–2015)

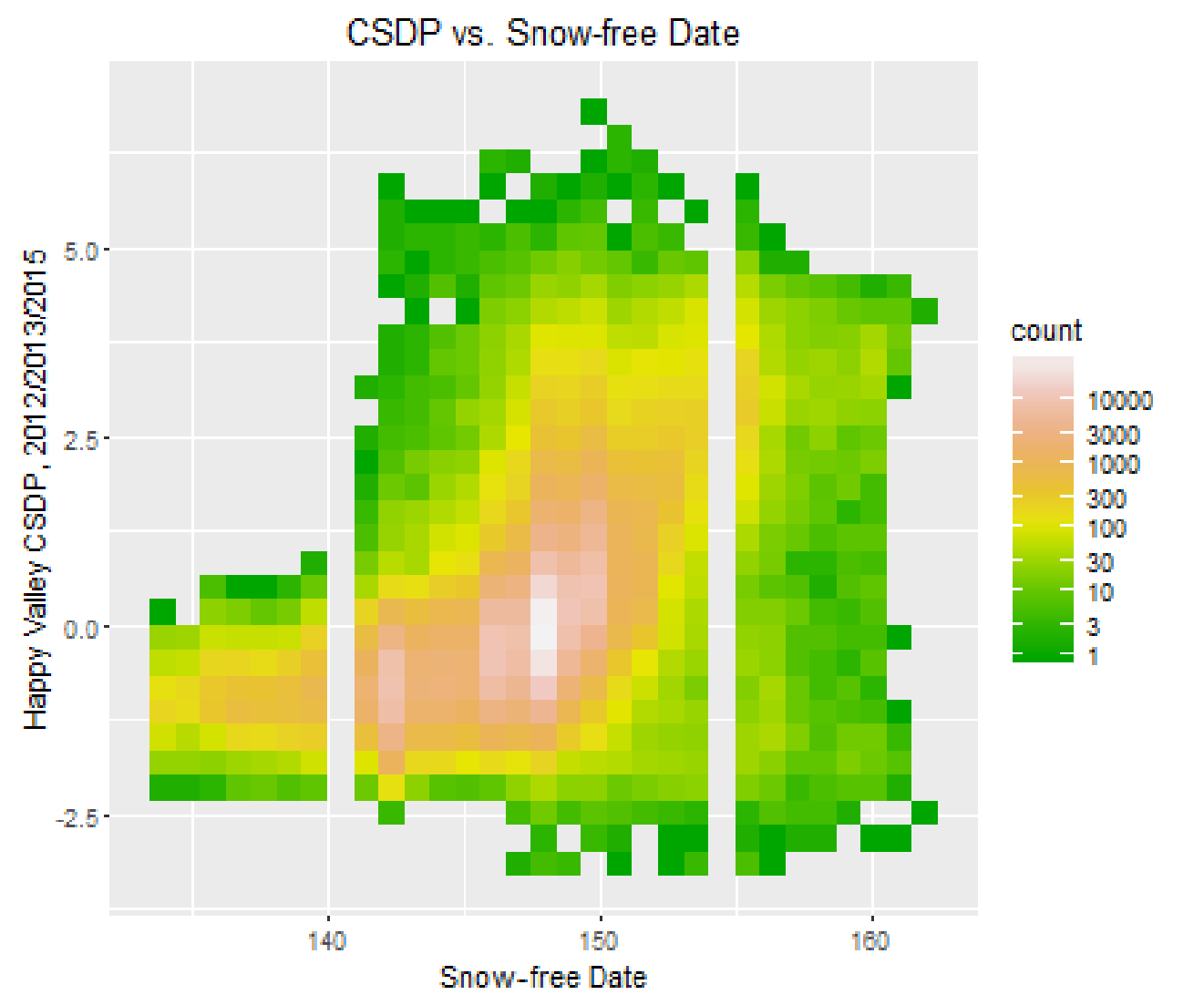


Happy Valley Snow Patterns: Lidar and Landsat

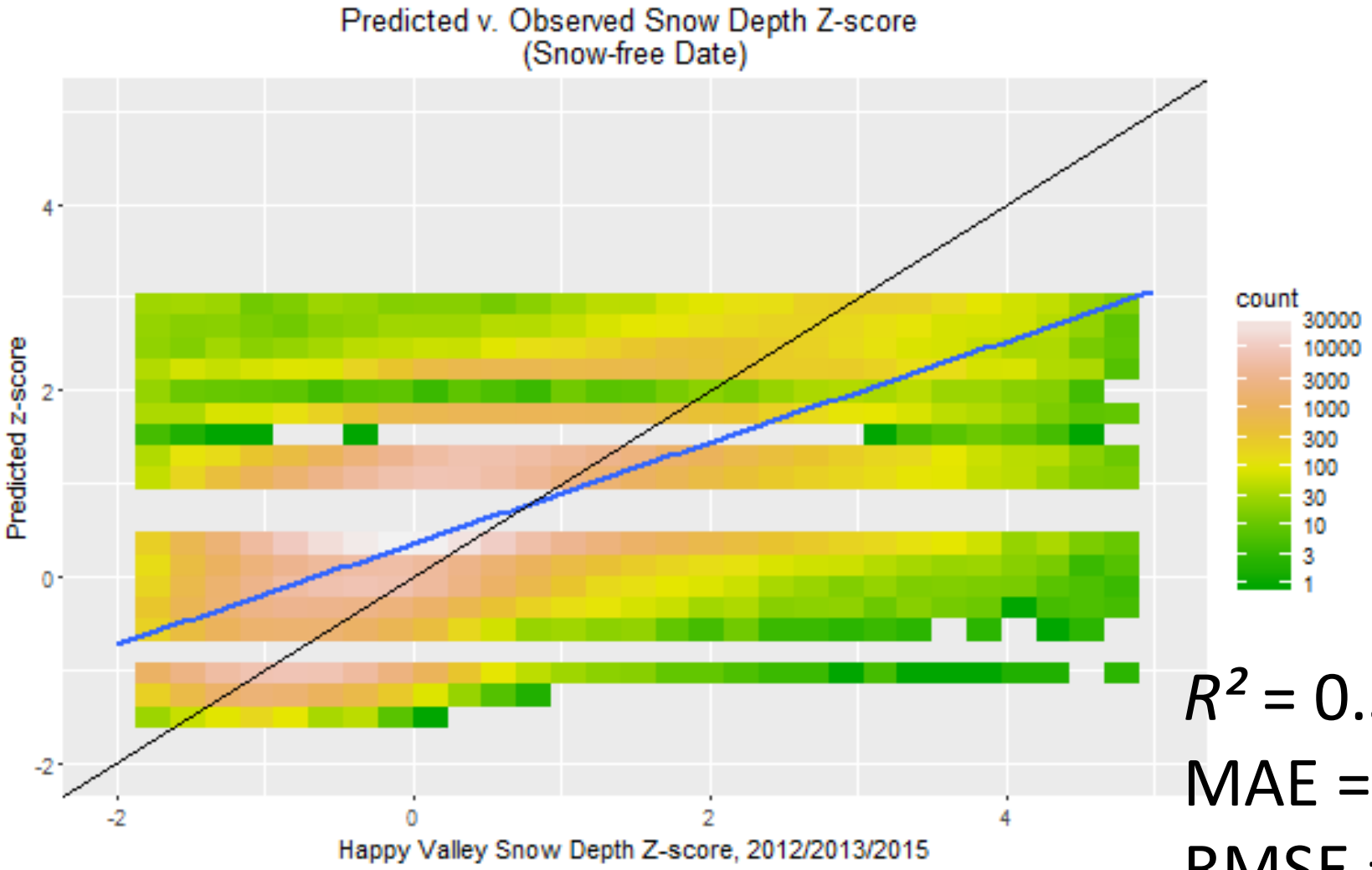



Mean Snow Depth from Lidar (2012/2013/2015) vs.
Normal Snow-free Day of Year from Landsat (1999–2016)
y = 0.001082x² - 0.286104x + 19.158370
R² = 0.944478
Mean Snow Depth for 30 m pixel from Lidar, 2012/2013/2015
1.4
1.2
1
0.8
0.6
0.4
0.2
0
132
137
142
147
152
157
162
167
Mean_Depth
Normal Snow-free Day of Year from Landsat, 1999–2016
DOY 132=May 12 DOY 167=June 16

Happy Valley Snow Patterns:
Landsat Snow-free data vs. Lidar CSDP



Modeling CSDP from Landsat Snow-free date
Random Forest Model (trained with 2% of pixels)



$R^2 = 0.35$

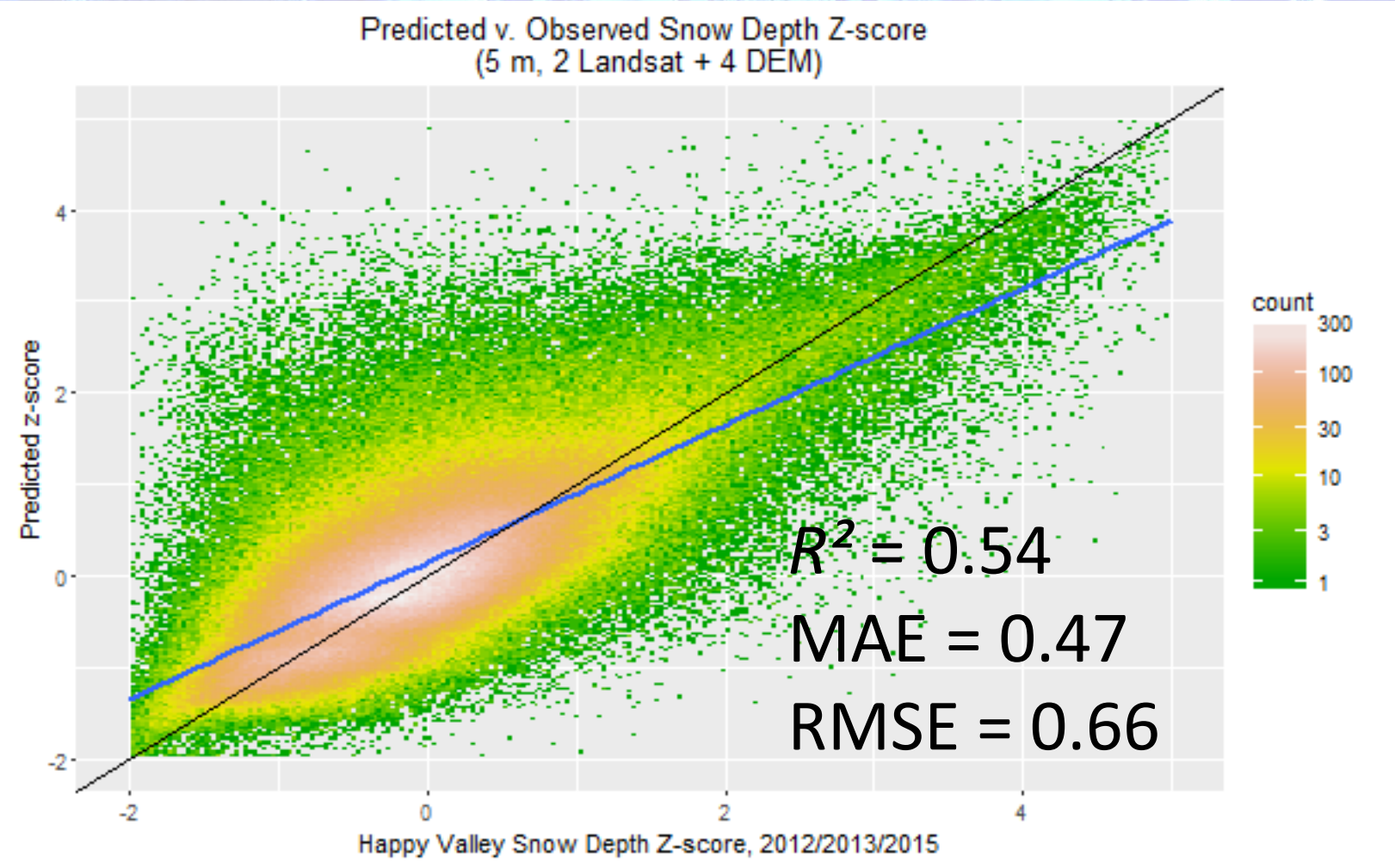
MAE = 0.64

RMSE = 0.84

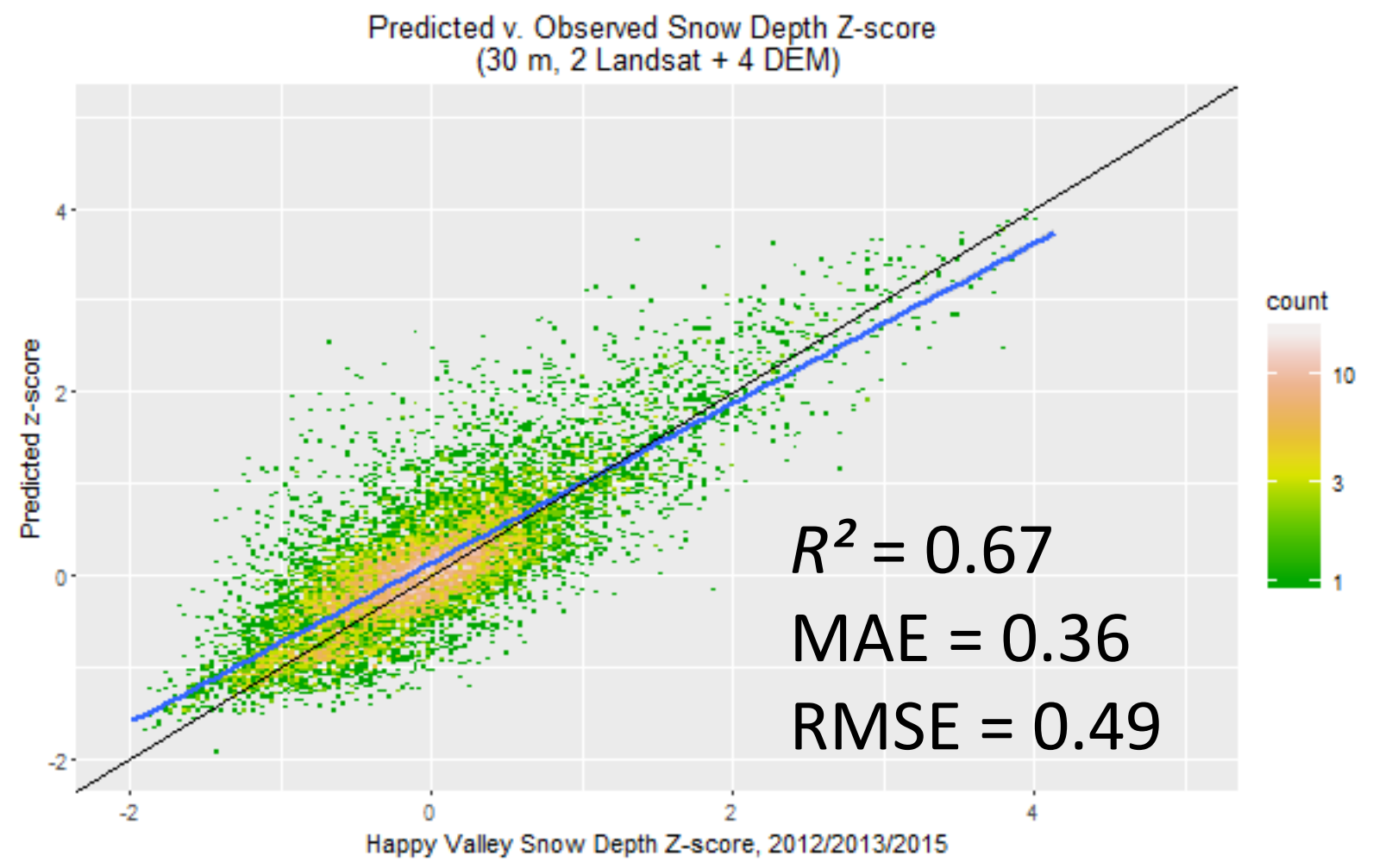
Modeling CSDP: Additional Predictors

- Landsat Snow Proportion
- Topographic Metrics (5m IFSAR DEM)
  - Elevation
  - Slope
  - Vector Ruggedness Measure (35 m)
  - Vector Ruggedness Measure(55 m)

Modeling CSDP from Landsat Snow-free date, Landsat Snow Proportion, + 4 DEM Metrics (5m IFSAR)



Modeling CSDP from Landsat Snow-free date, Landsat Snow Proportion, + 4 DEM Metrics (5m IFSAR) Aggregate from 5 m to 30 m outputs



Modeling Snow Depth from Modeled CSDP

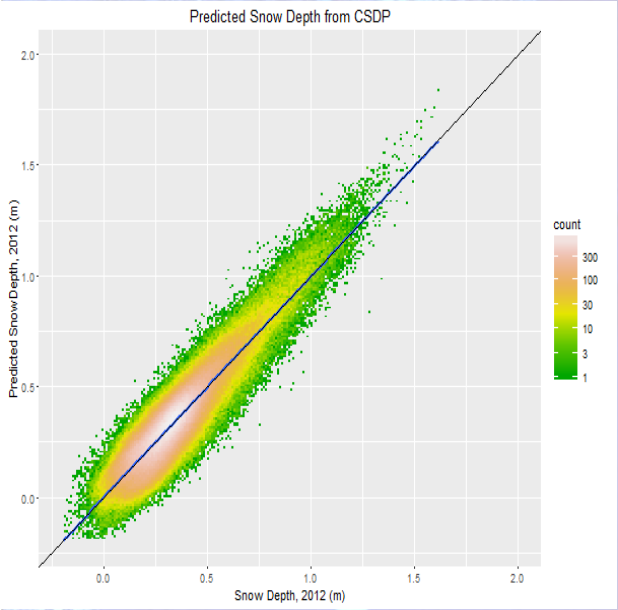
- Modeled Climatological Snow Distribution Pattern can be extrapolated over larger area using Landsat and DEM metrics
- Requires mean and standard deviation values for end-of-winter snowpack based on representative field samples or other measurements
  - Standard deviation relatively constant

Happy Valley Snow Depths Summary

Year	Mean Snow Depth (m)	SD Snow Depth (m)
2012	0.3397	0.1916
2013	0.3990	0.2079
2015	0.6365	0.1881

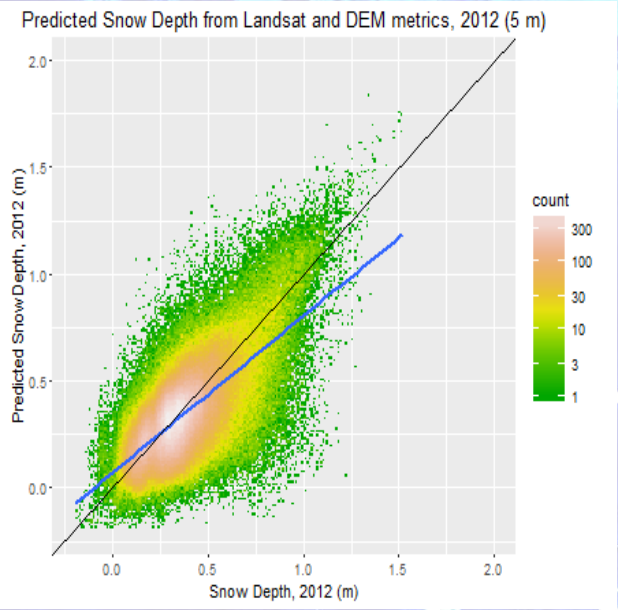
Modeled Snow Depth, 2012

Lidar CSDP



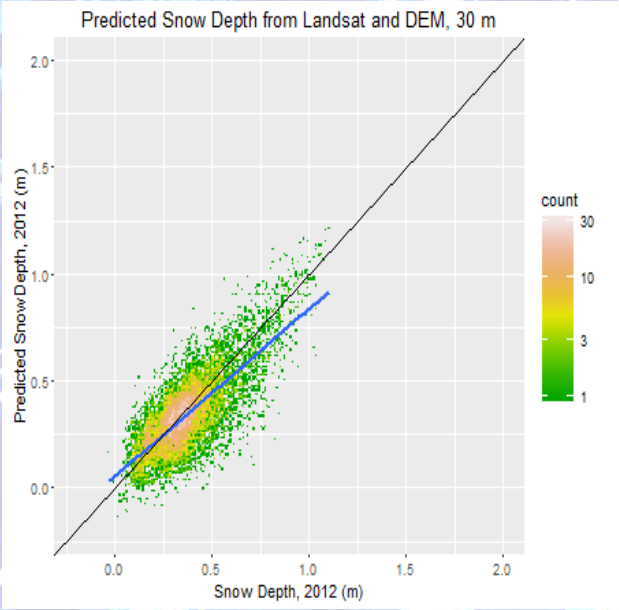
R^2 = 0.84
MAE = 5.9 cm
RMSE = 7.5 cm

2 Landsat
+ 4 DEM (5 m)

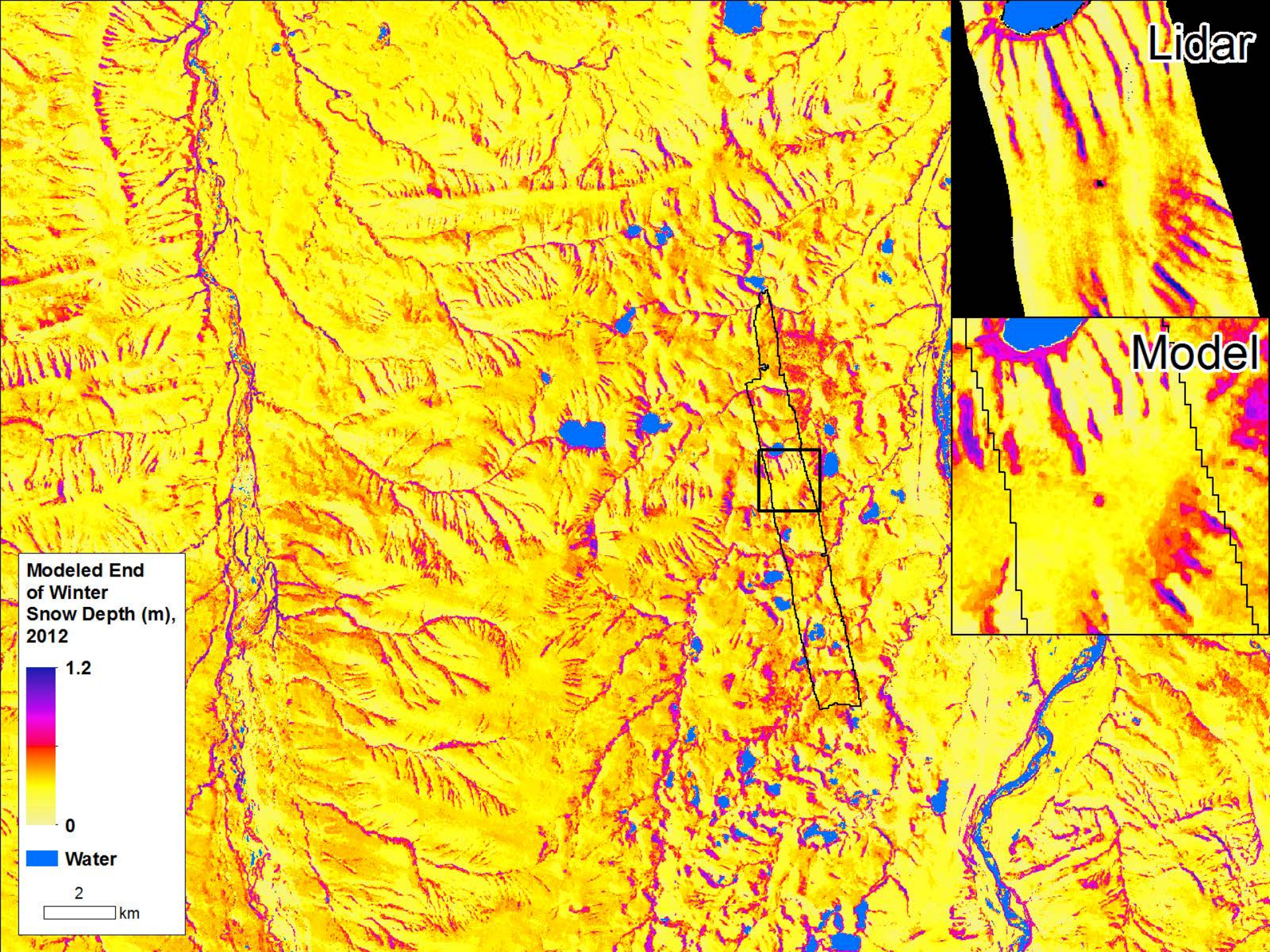


R^2 = 0.47
MAE = 10.7 cm
RMSE = 14.4 cm

2 Landsat
+ 4 DEM (30 m)

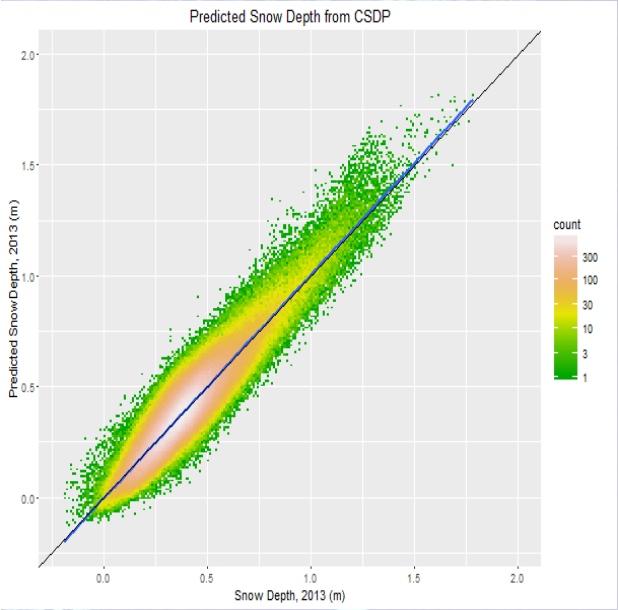


R^2 = 0.57
MAE = 8.7 cm
RMSE = 11.3 cm


Lidar
Model
Modeled End of Winter Snow Depth (m), 2012
1.2
0
Water
2
km

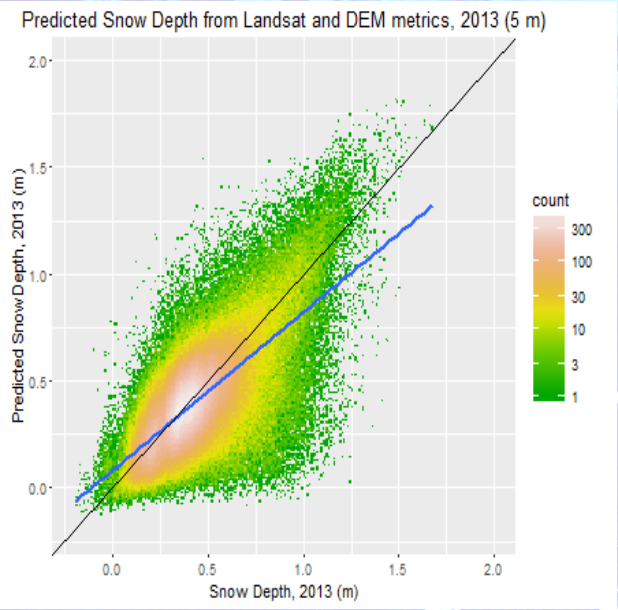
Modeled Snow Depth, 2013

Lidar CSDP



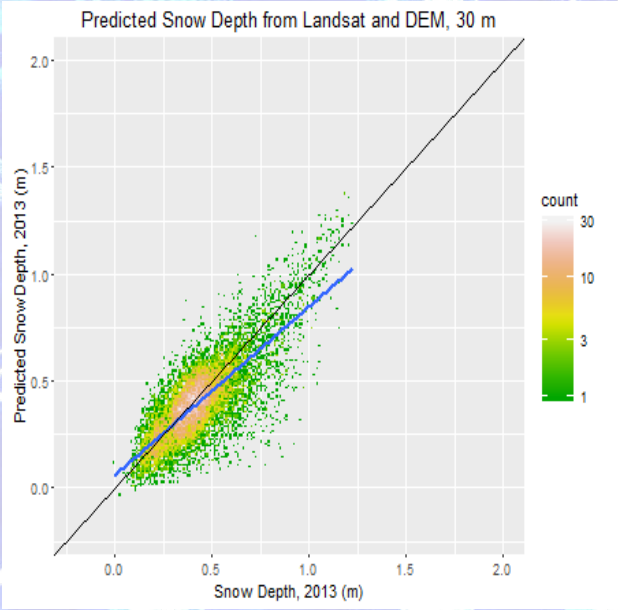
R^2 = 0.87
MAE = 5.7 cm
RMSE = 7.3 cm

2 Landsat
+ 4 DEM (5 m)

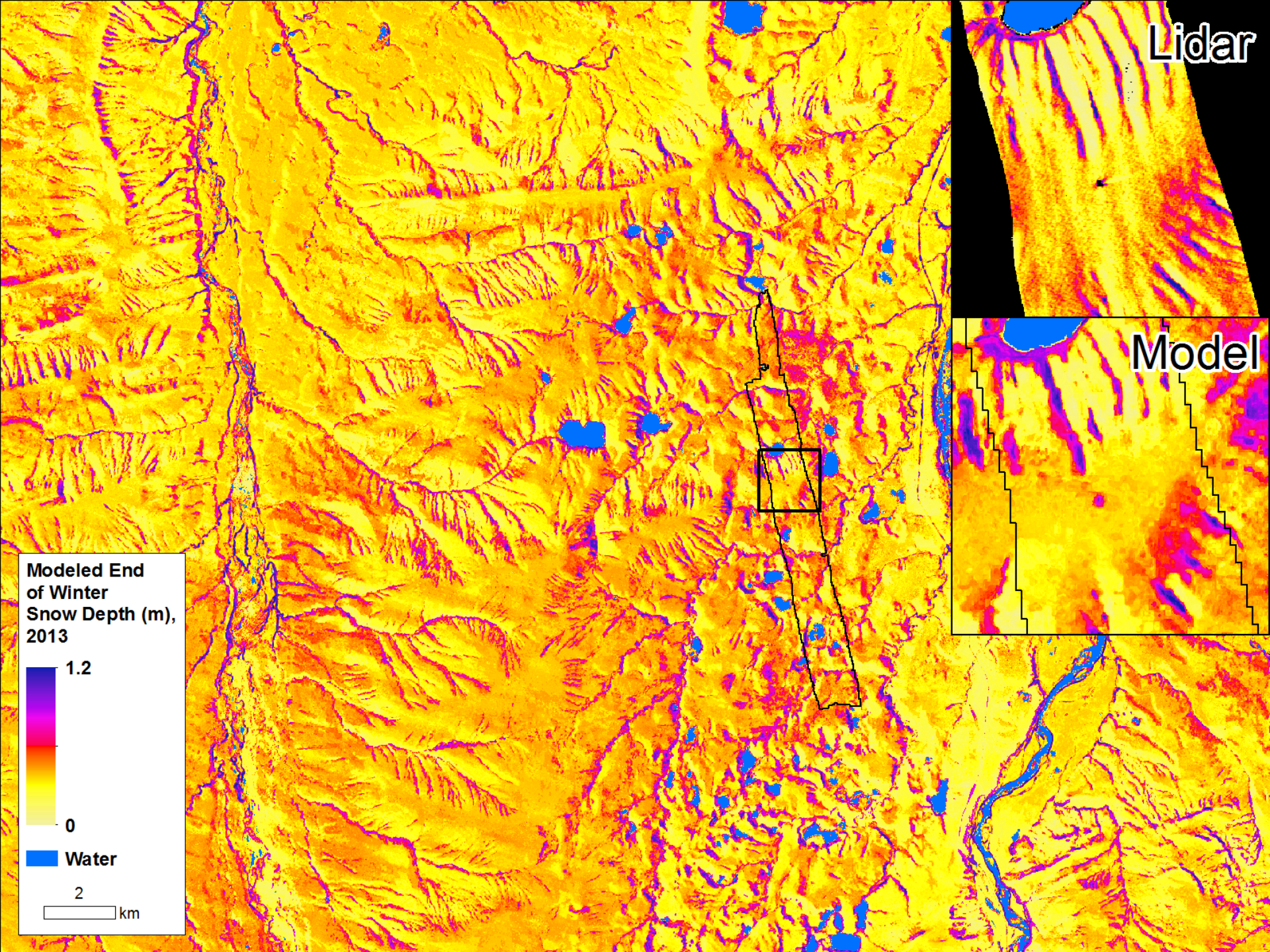


R^2 = 0.48
MAE = 11.2 cm
RMSE = 15.4 cm

2 Landsat
+ 4 DEM (30 m)

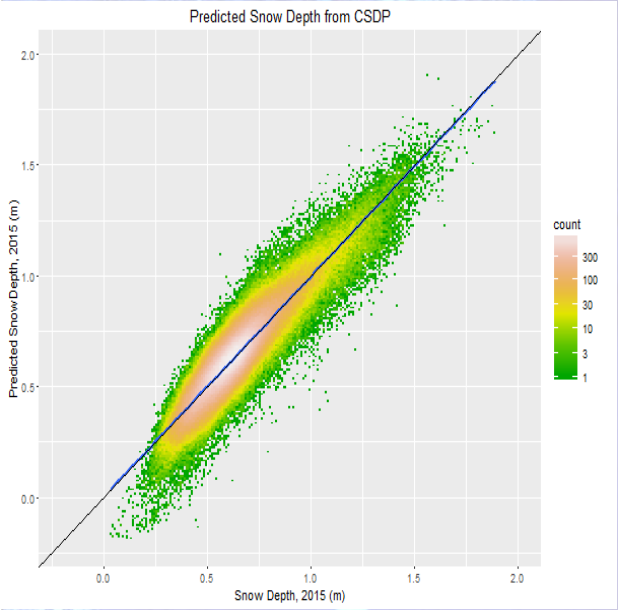


R^2 = 0.61
MAE = 8.5 cm
RMSE = 11.5 cm


Lidar
Model
Modeled End of Winter Snow Depth (m), 2013
1.2
0
Water
2
km

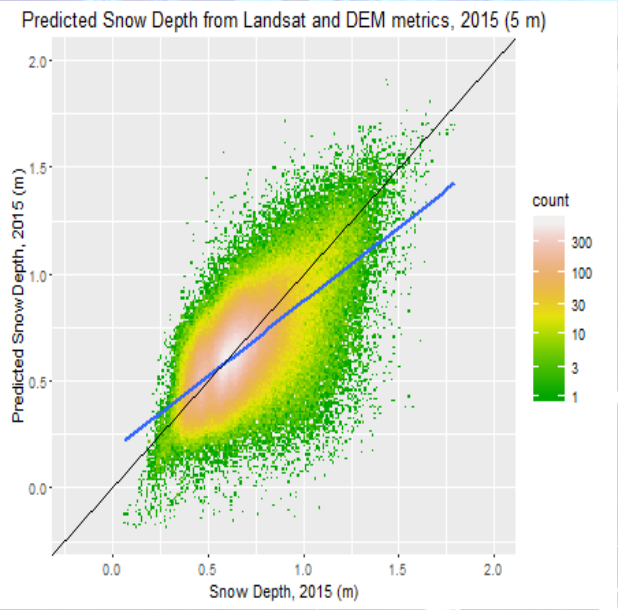
Modeled Snow Depth, 2015

Lidar CSDP



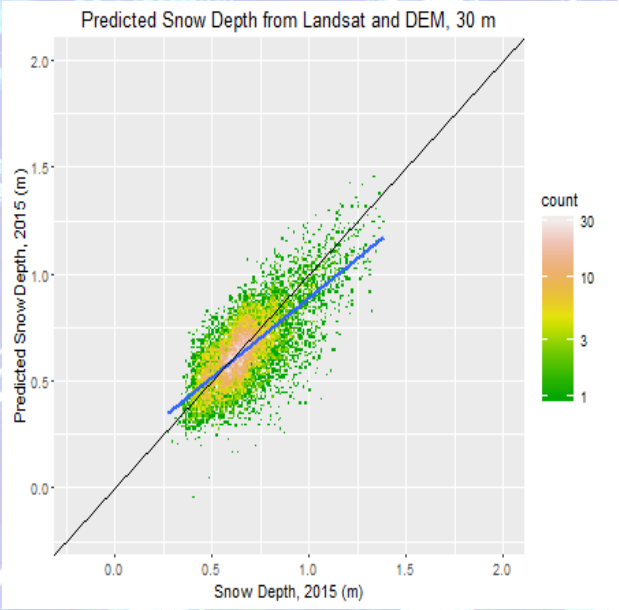
R^2 = 0.84
MAE = 5.6 cm
RMSE = 7.2 cm

2 Landsat
+ 4 DEM (5 m)

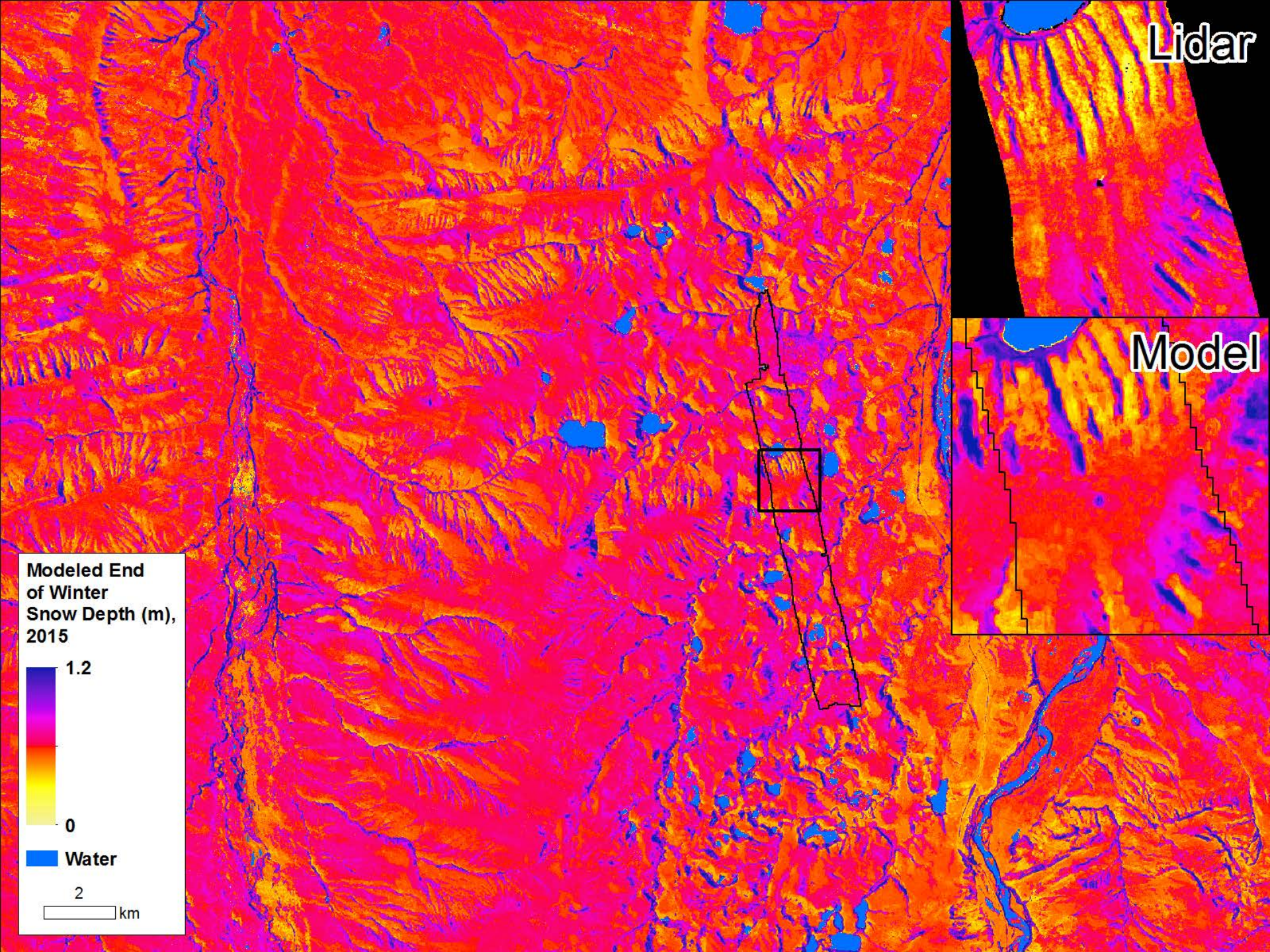


R^2 = 0.43
MAE = 10.8 cm
RMSE = 14.8 cm

2 Landsat
+ 4 DEM (30 m)

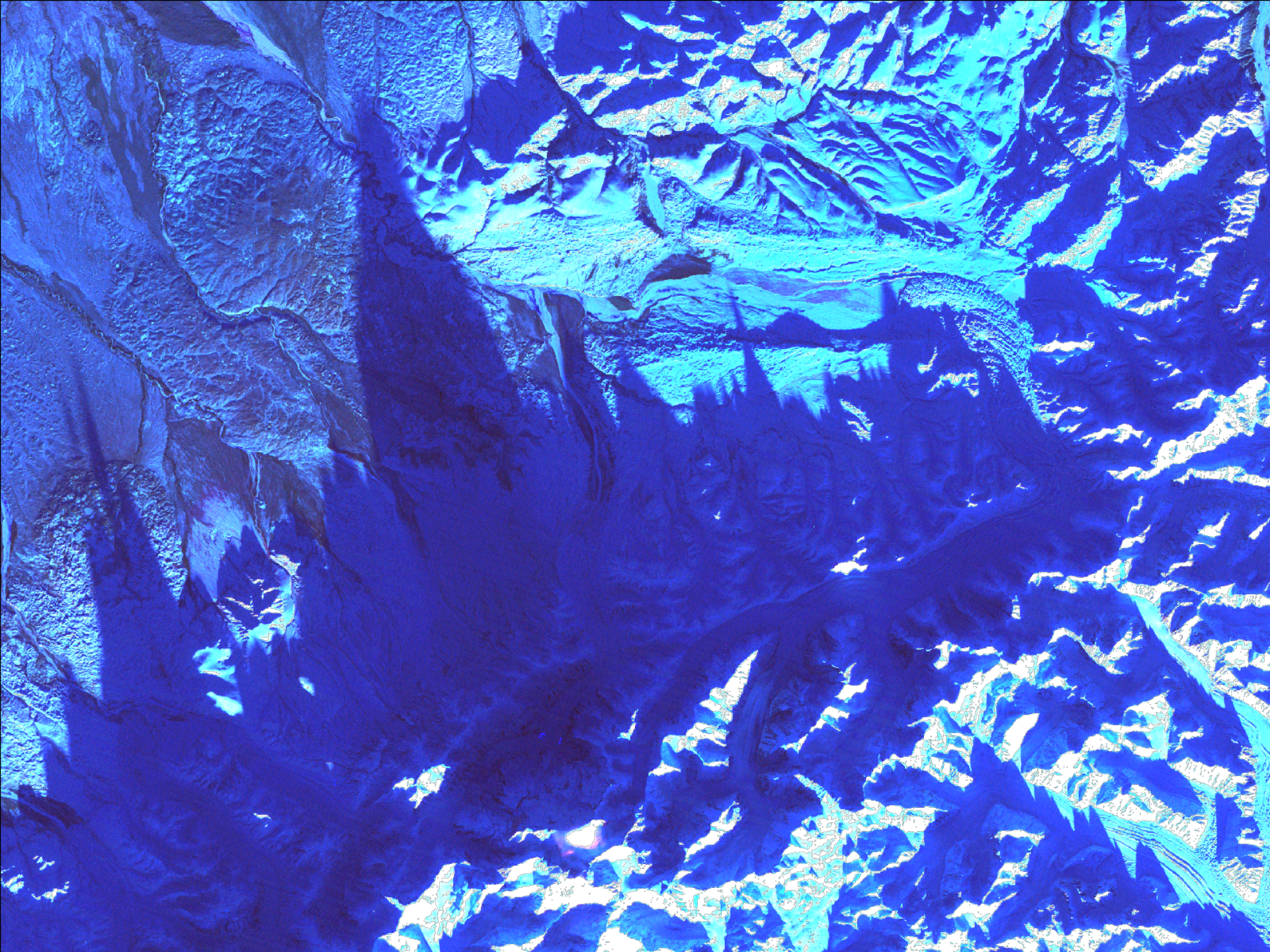


R^2 = 0.53
MAE = 8.7 cm
RMSE = 11.5 cm


Lidar
Model
Modeled End of Winter Snow Depth (m), 2015
1.2
0
Water
2
km

Conclusions

- Snow Persistence mapping from Landsat can capture many fine-scale details at a statewide to circumarctic scale
- Applications include
  - Snow distribution modeling
  - Wildlife habitat availability
  - Hydrology of headwater basins

Conclusions

- Dense Landsat time-series covering snowmelt from 2000 to present
- Landsat resolution (30 m) too coarse to resolve some fine-scale snow patterns
  - Commercial high resolution satellite acquisitions are being tasked and collected at high temporal frequency over selected sites
  - UAV (drone) will provide an inexpensive tool for daily monitoring of snow cover, perhaps snow depth