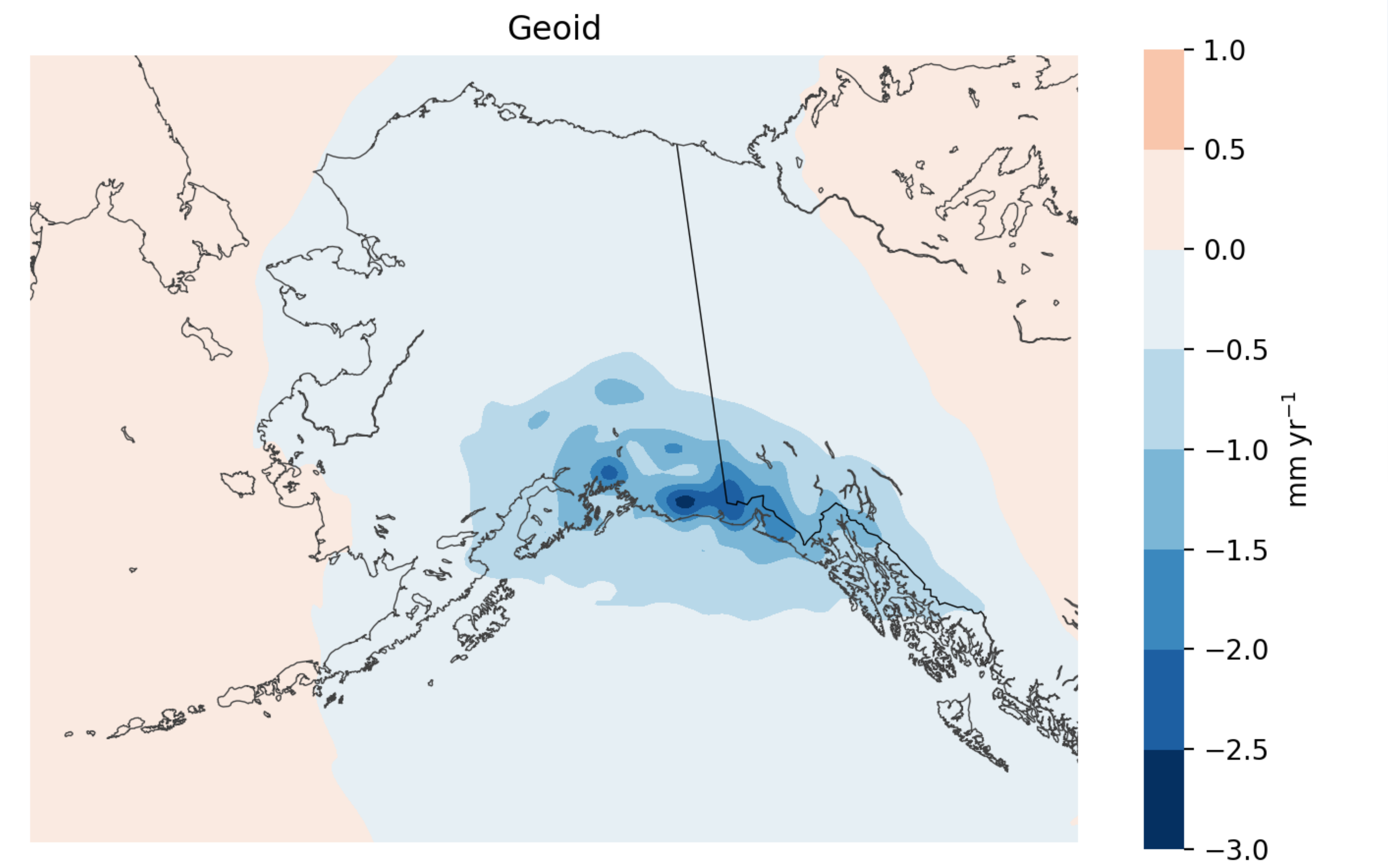
Geoid Change in Alaska

Ryan A. Hardy, PhD
National Academy of Sciences NRC Research Associateship Program
National Geodetic Survey

NGS Webinar Series
November 14th, 2019

Themes

Predicted high-resolution geoid change rates in Alaska



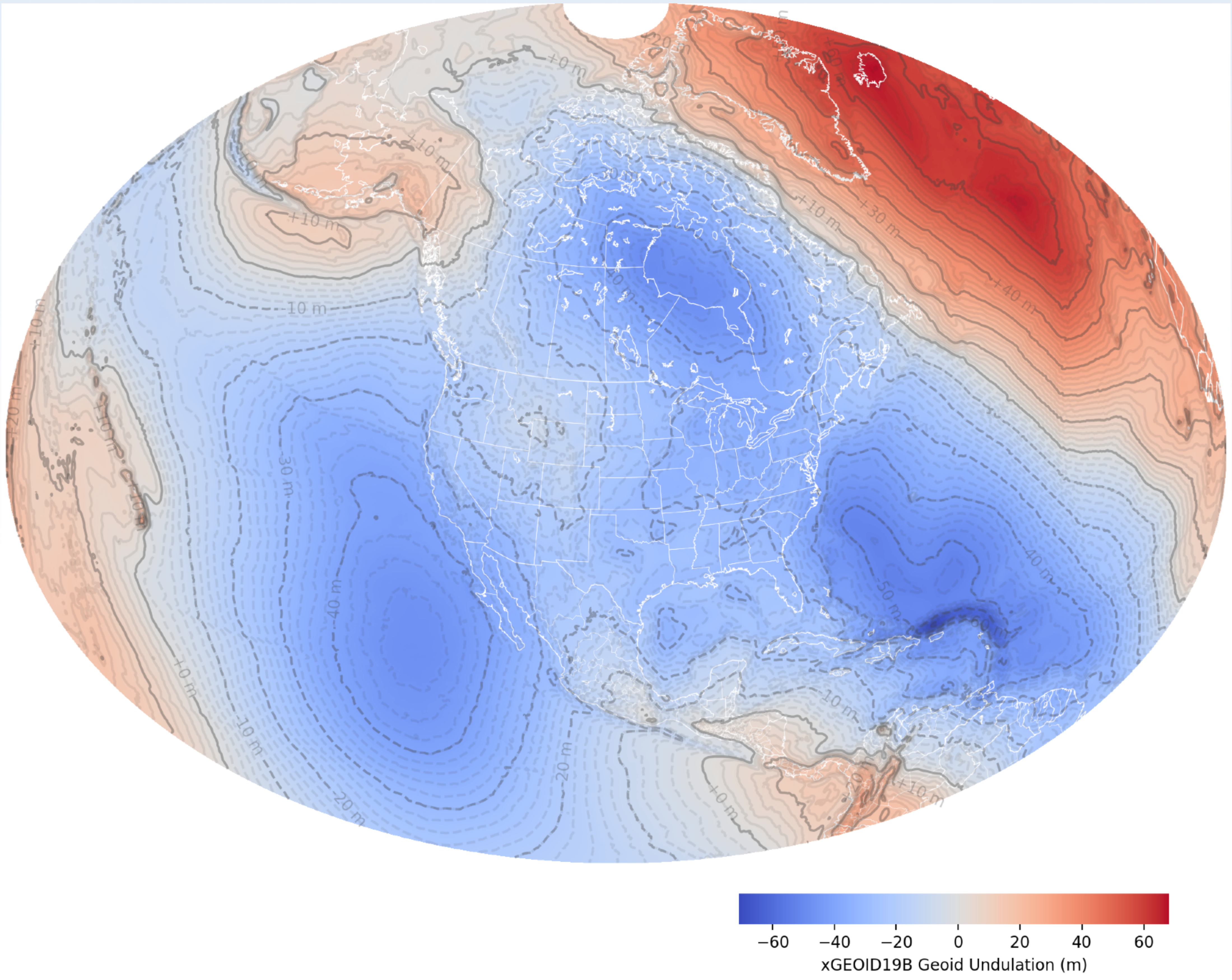
This webinar will overview original research highlighting:

- How the geoid currently changes in time in Alaska
- How the geoid has changed over the 20th century
- How NGS will validate geoid change predictions in Alaska

Background: A New Geopotential Datum

- NGS is committed to replacing NAVD88 with a geoid-based geopotential datum by 2022

- In order to maintain accuracy requirements (1 cm) over the lifetime of the geoid, NGS has specified that the geoid must have time-dependent components



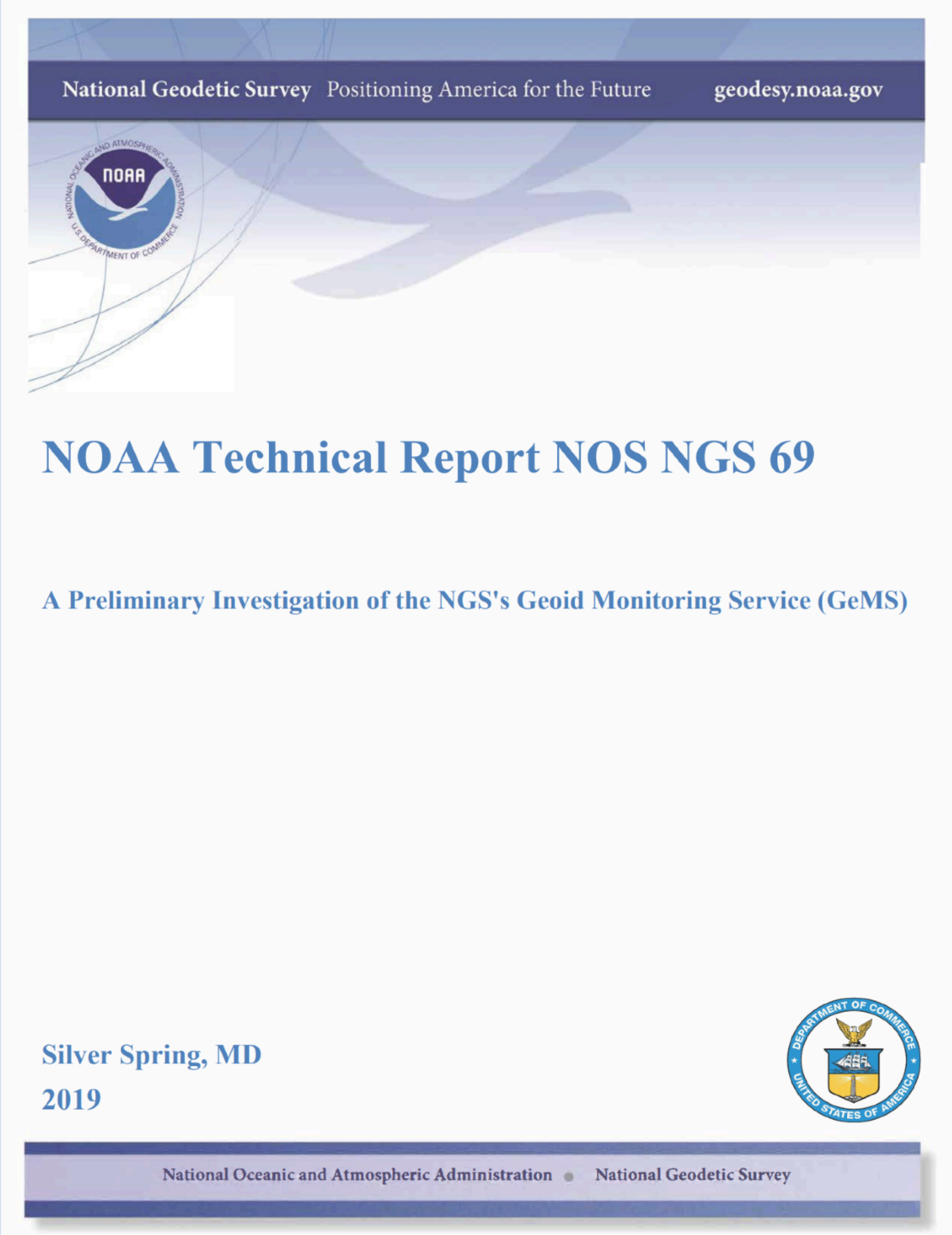
xGEOID19B Beta Geoid Model

The Geoid Monitoring Service (GeMS)

- Maintaining 1 cm geoid accuracy requires tracking where Earth's changing mass distribution (water, ice, solid Earth) changes the geoid

- NGS has committed itself to tracking geoid change over time through a combination of:
  - Satellite gravity measurements
  - Terrestrial gravity and GNSS campaigns
  - Geophysical models

For an exhaustive overview of NGS's geoid monitoring strategy, read:


National Geodetic Survey Positioning America for the Future geodesy.noaa.gov

NOAA Technical Report NOS NGS 69

A Preliminary Investigation of the NGS's Geoid Monitoring Service (GeMS)

Silver Spring, MD
2019

National Oceanic and Atmospheric Administration • National Geodetic Survey

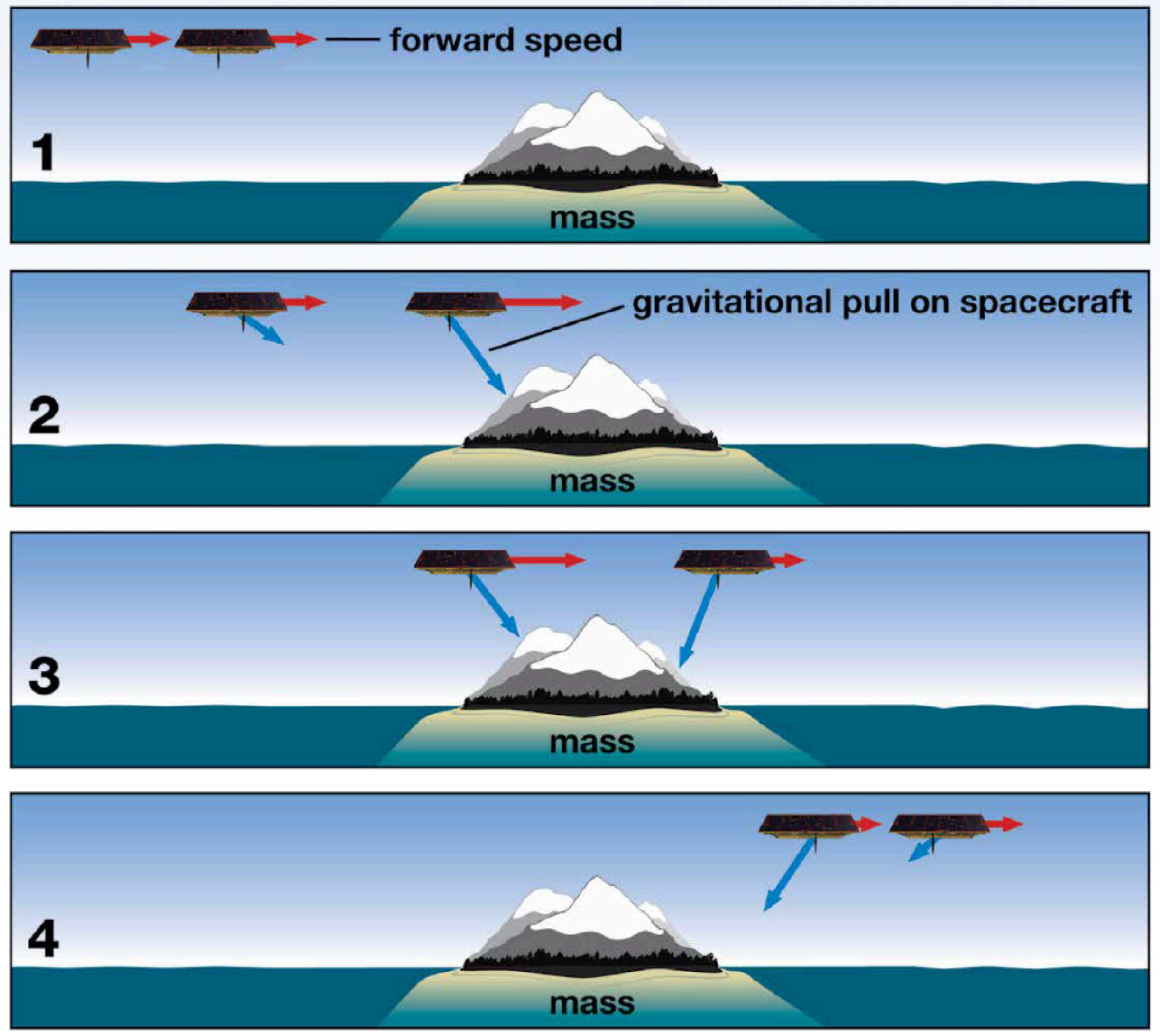
The GRACE and GRACE Follow-On Missions

- **Gravity Recovery and Climate Experiment**: Twin satellites that map changes in Earth's gravity on a monthly basis by precisely tracking the distance between the satellites

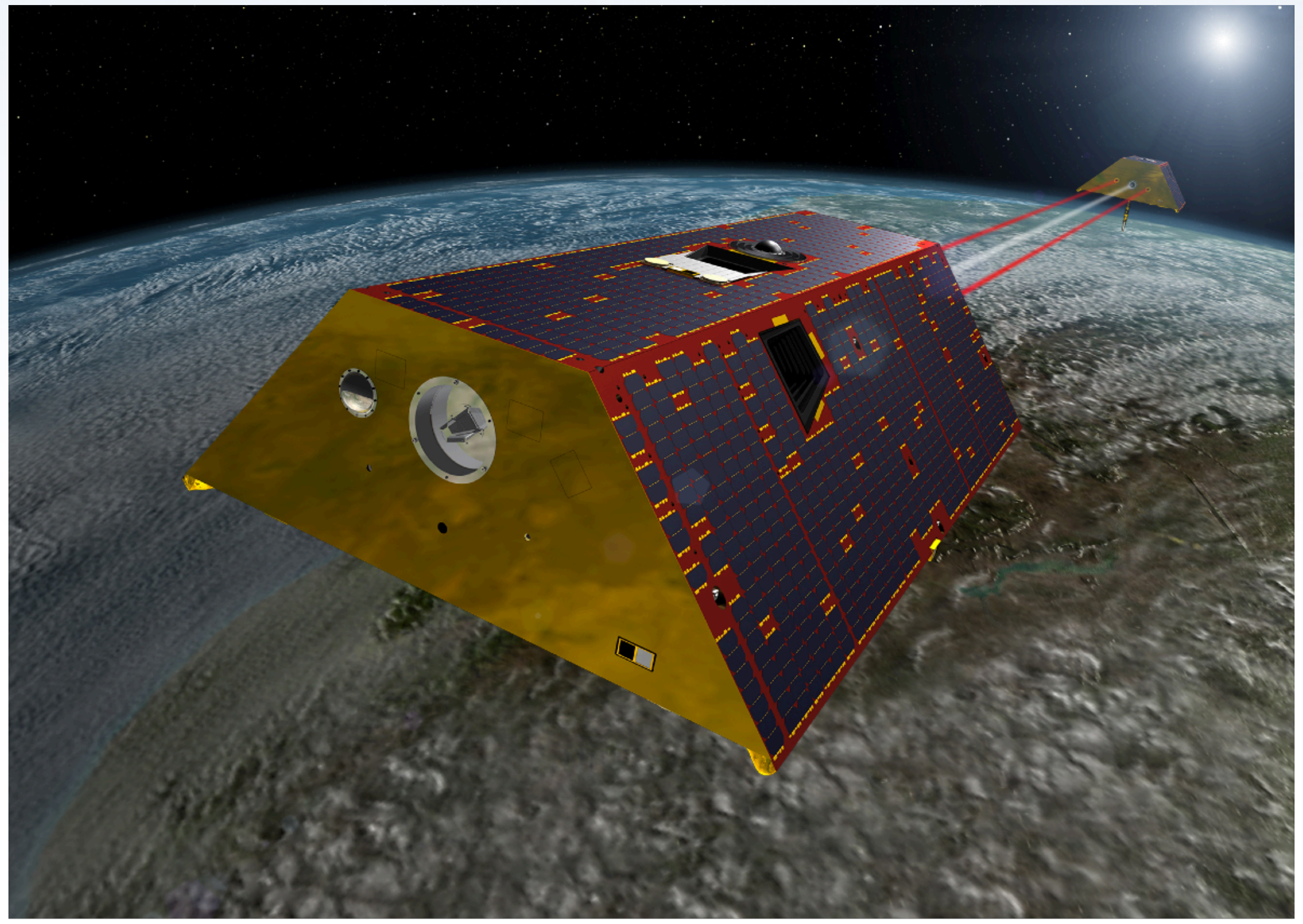
- GRACE: 2002—2017

- GRACE-FO: 2018—present

GRACE Measurement Principle



GRACE Follow-On



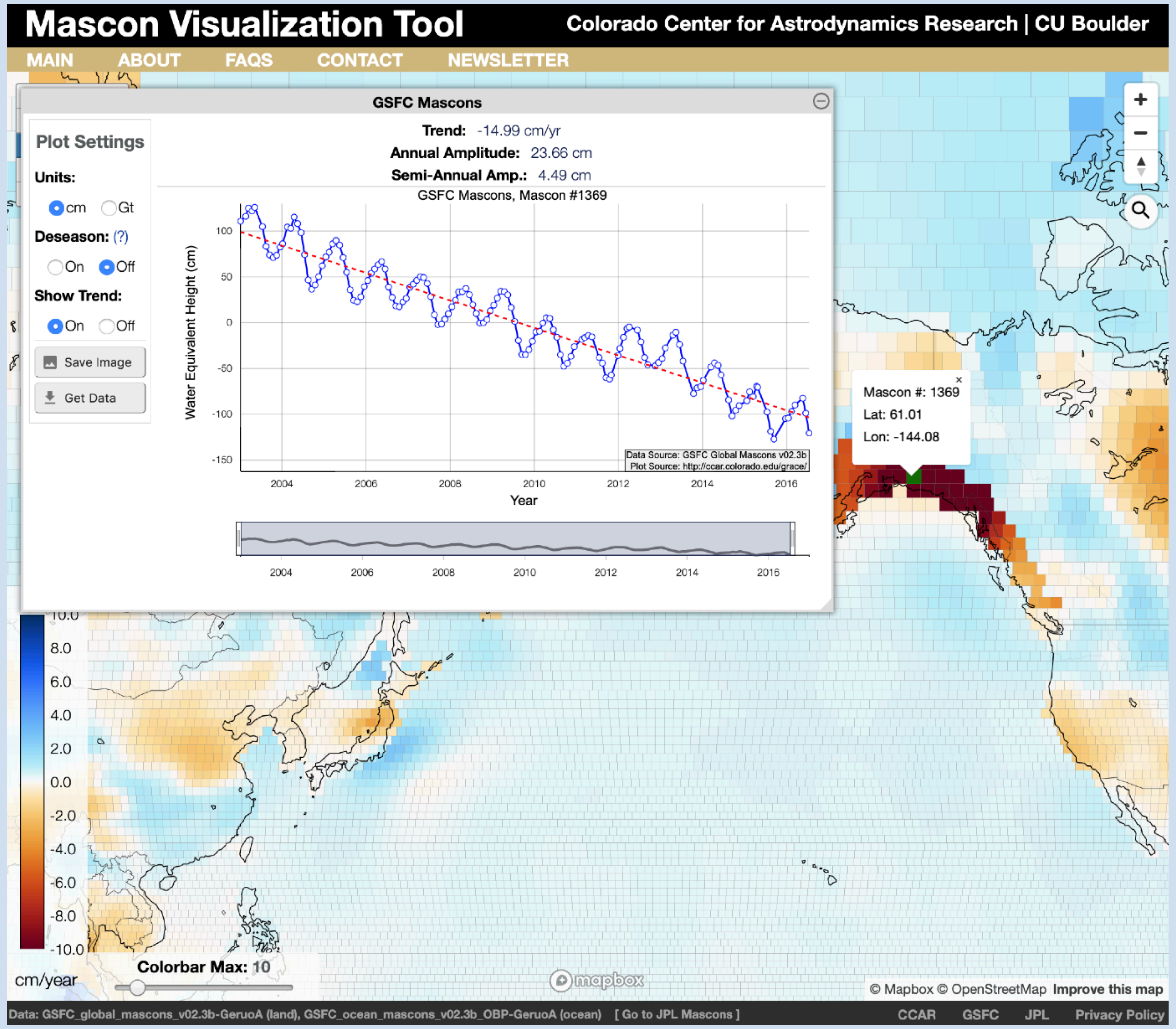
Images: NASA

GRACE and GRACE Follow-On

- GRACE solutions may be used to map mass change on Earth's surface (expressed in equivalent water height)
- GRACE solutions for Earth's gravity can also be expressed in terms of discrete mass concentrations, or "mascons"
- These solutions are a starting point for NGS's dynamic geoid change models

Explore GRACE data:

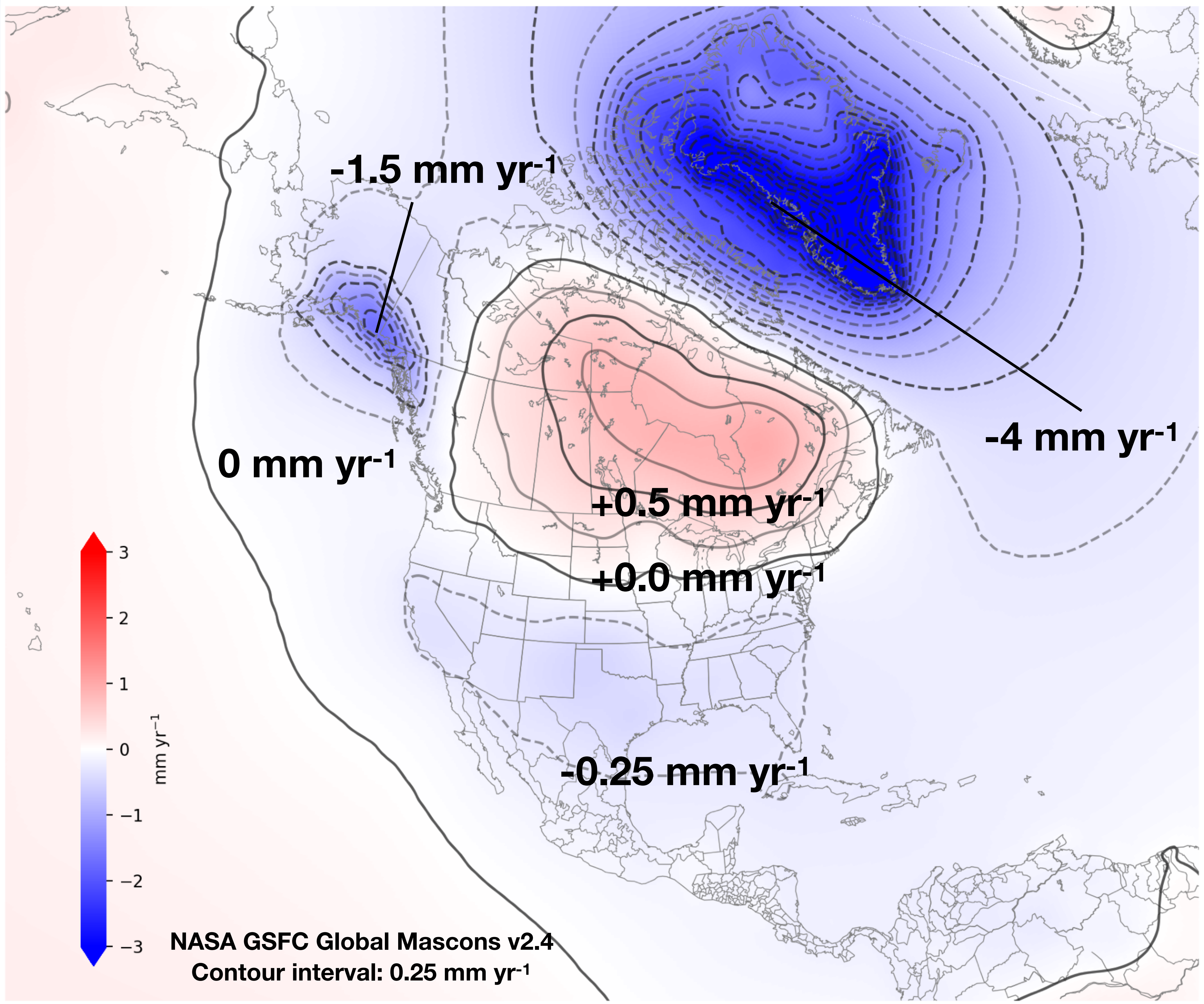
ccar.colorado.edu/grace



Geoid Change According to GRACE

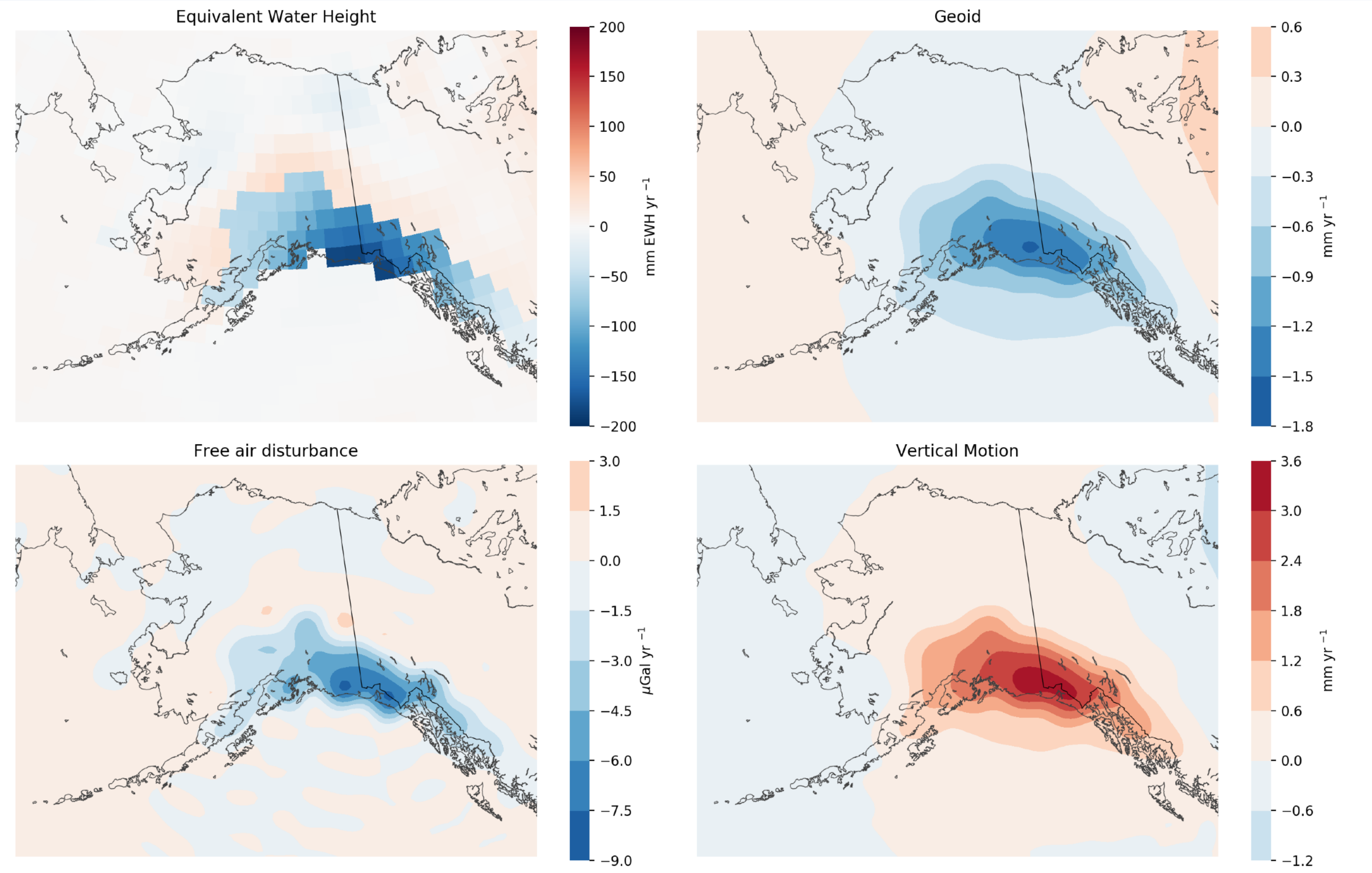
- 2002—2016 GRACE geoid rates are currently the basis of NGS's alpha dynamic geoid model, xDGEOID19
- Geoid change in North America is dominated by glacial isostatic adjustment
- Ice mass loss creates more pronounced gravity change in Alaska and Greenland

2002-2016 Geoid Change Rate



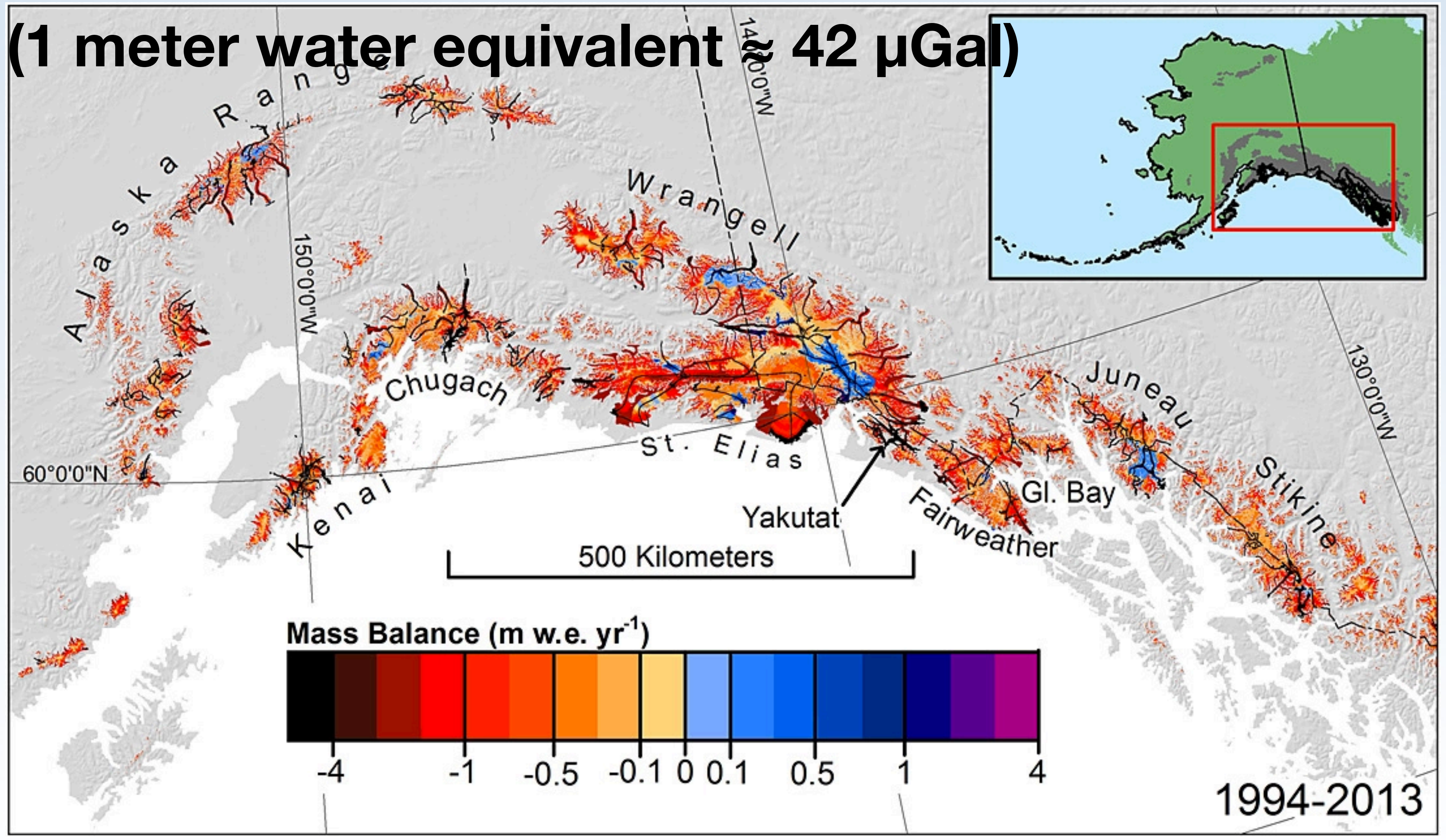
A Closer Look at Alaska

- Geopotential models from GRACE enable us to predict
  - Mass change (in equivalent water height)
  - Geoid change
  - Gravity change
  - Vertical crustal motion (depending on model assumptions)

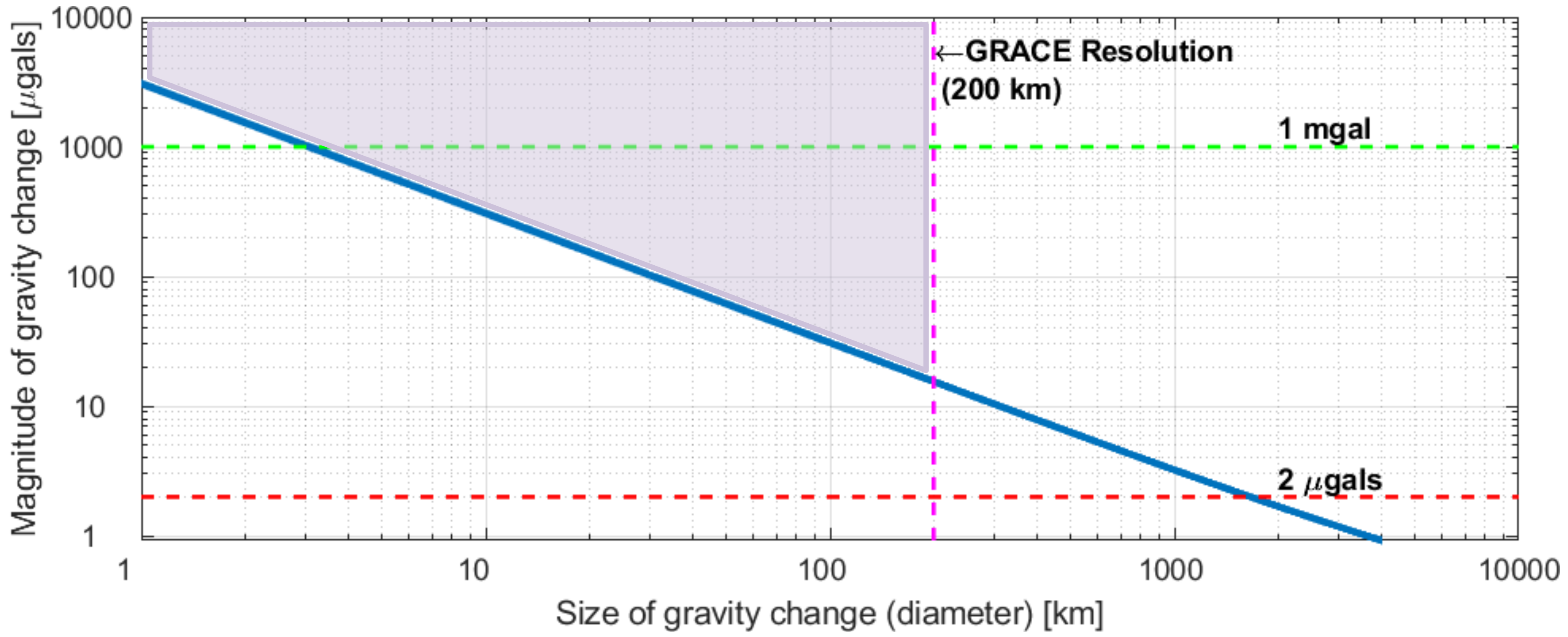


Resolution Limits

- Geoid change depends on both the scale and extent of gravity change or mass change
- Geoid change in Alaska is primarily attributable to ice mass loss on scales below GRACE's resolution limits
- Therefore, **GRACE geoid change models may underestimate the amplitudes of geoid change in Alaska**



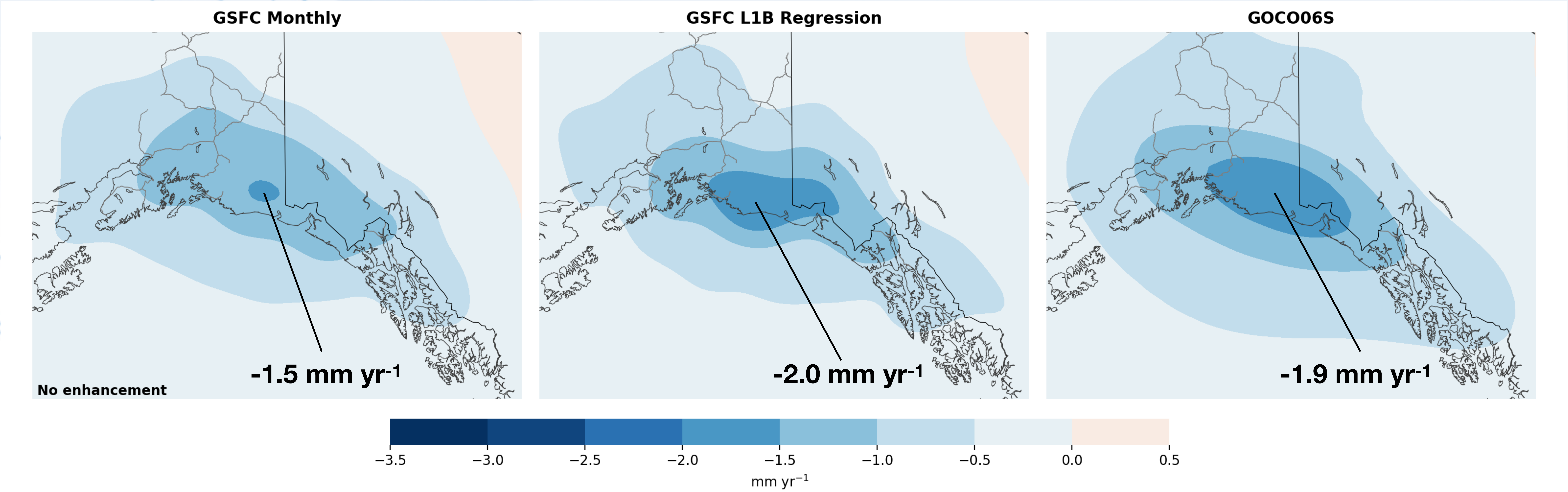
Rates of ice mass change in Alaska measured at short scales by airborne lidar, (Larsen et al. 2015)



Relationship between extent and magnitude of gravity change required for 1 cm geoid change and (NOS NGS TR69)

Enhanced GRACE Solutions

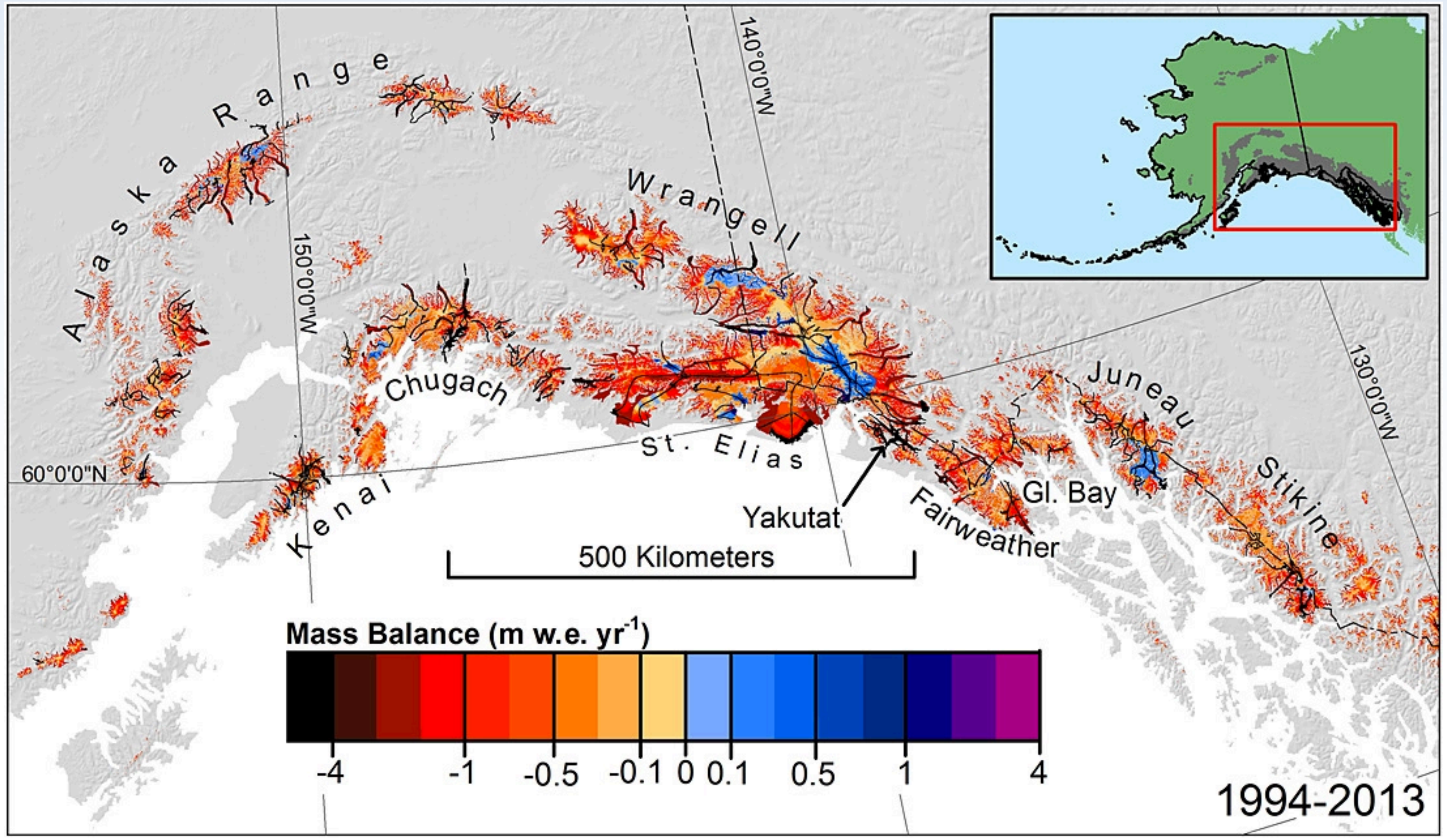
GRACE solutions can trade temporal resolution for improved spatial resolution (~100 km) by solving for geoid trends instead of monthly solutions



These solutions confirm truncation errors hide at least 0.5 mm yr^{-1} of geoid change

Going Deeper: Hybrid Geoid Change Models

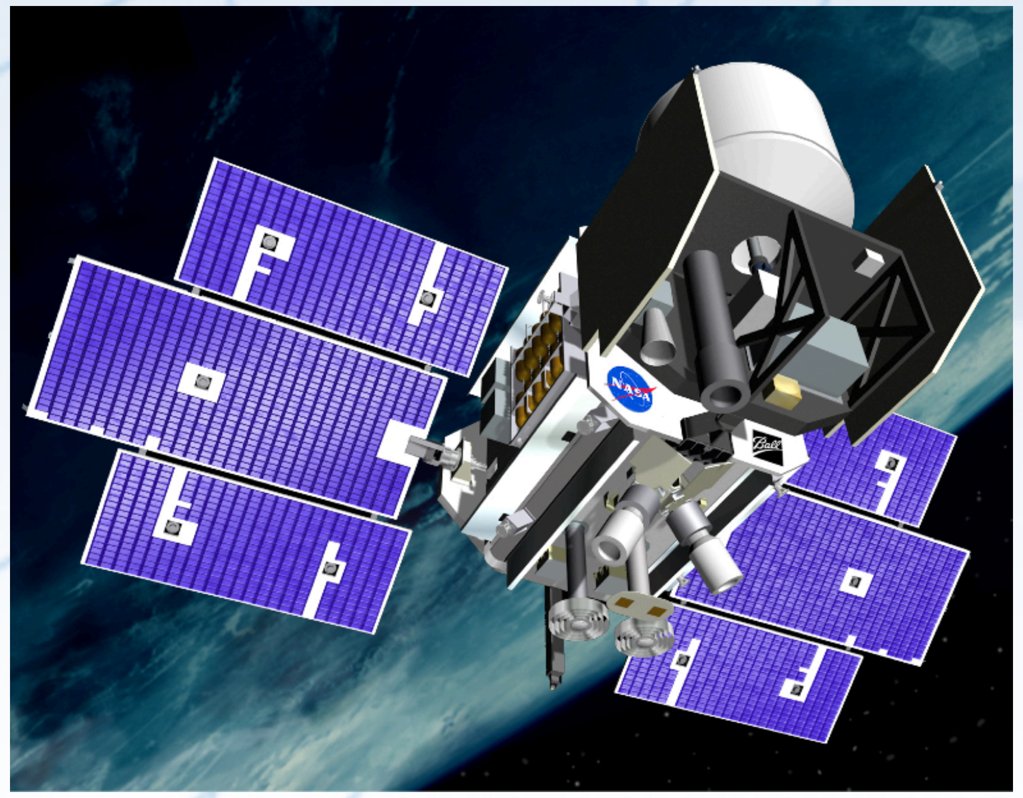
- While little, if any data for high-resolution gravity change in Alaska exists, we can predict concentrated mass change due to ice melt in Alaska
- If we know the distribution of mass change on Earth's surface, we can predict the instantaneous effect on
  - Geoid change
  - Gravity change
  - Elastic crustal deformation (uplift)



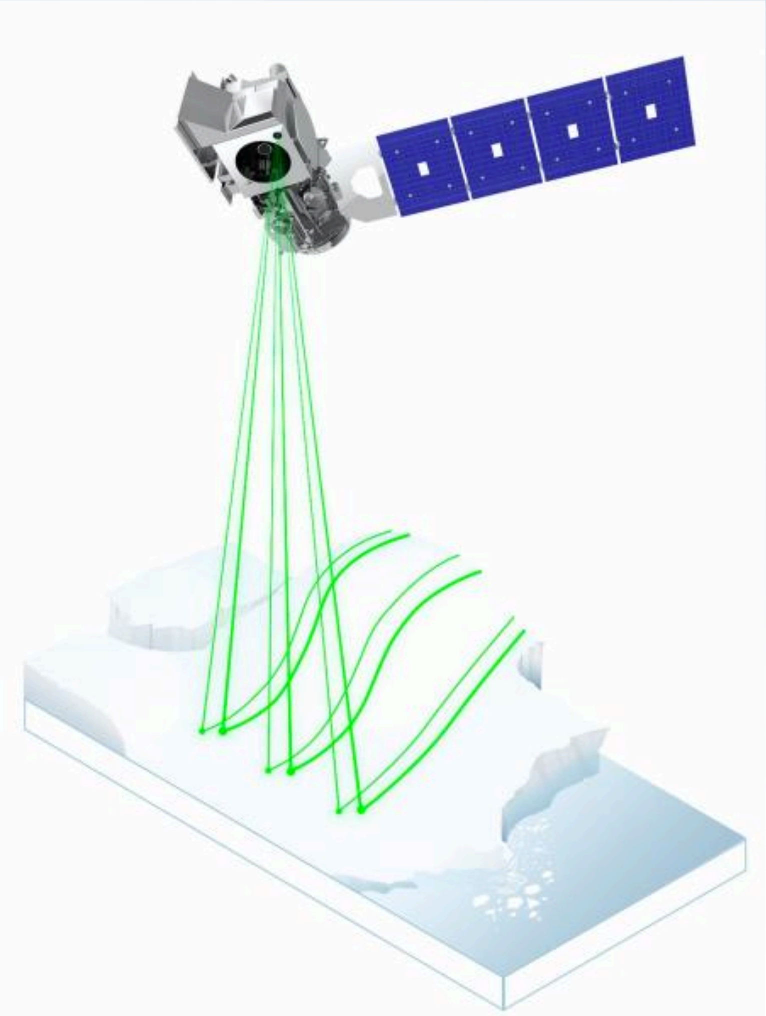
Rates of ice mass change in Alaska measured at short scales by airborne lidar (Larsen et al. 2015)

Additional Height Change Data: ICESat/ICESat-2

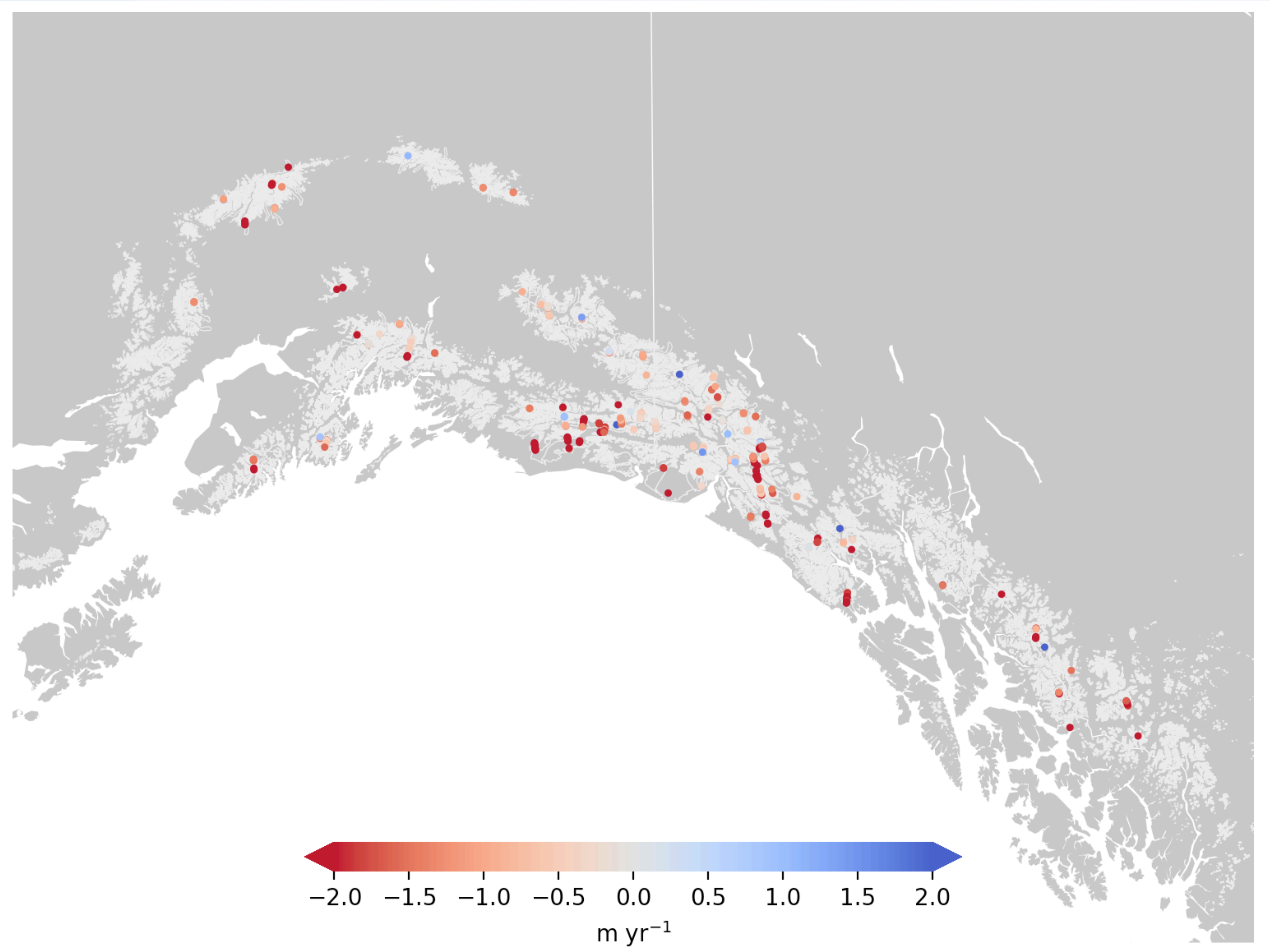
ICESat



ICESat-2



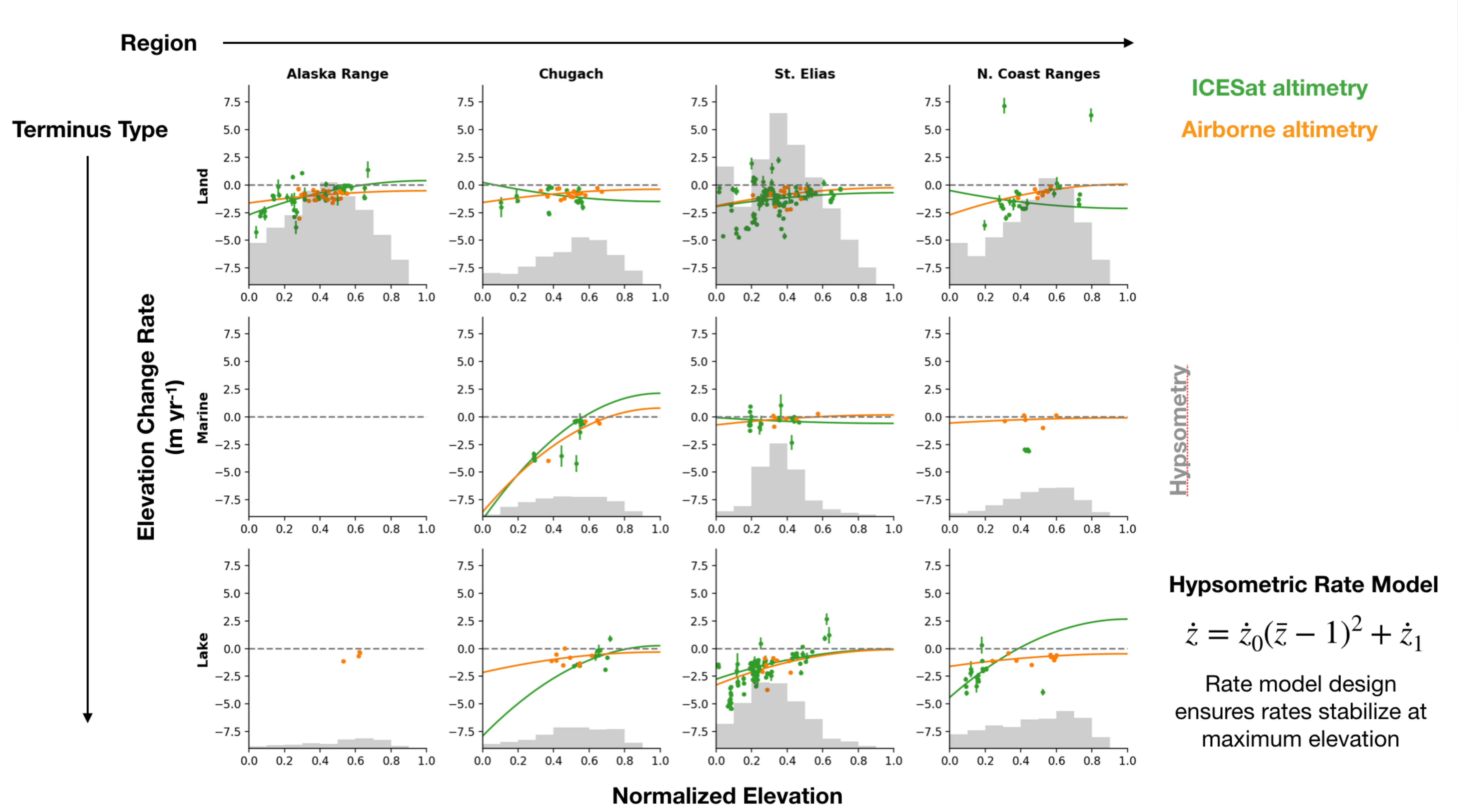
2003—2019 ICESat/ICESat-2 Elevation Rates



- Space-based laser altimetry provides spot measurements of elevation change across a long timespan
- These measurements confirm high rates of ice mass loss

Extrapolating Ice Elevation Change

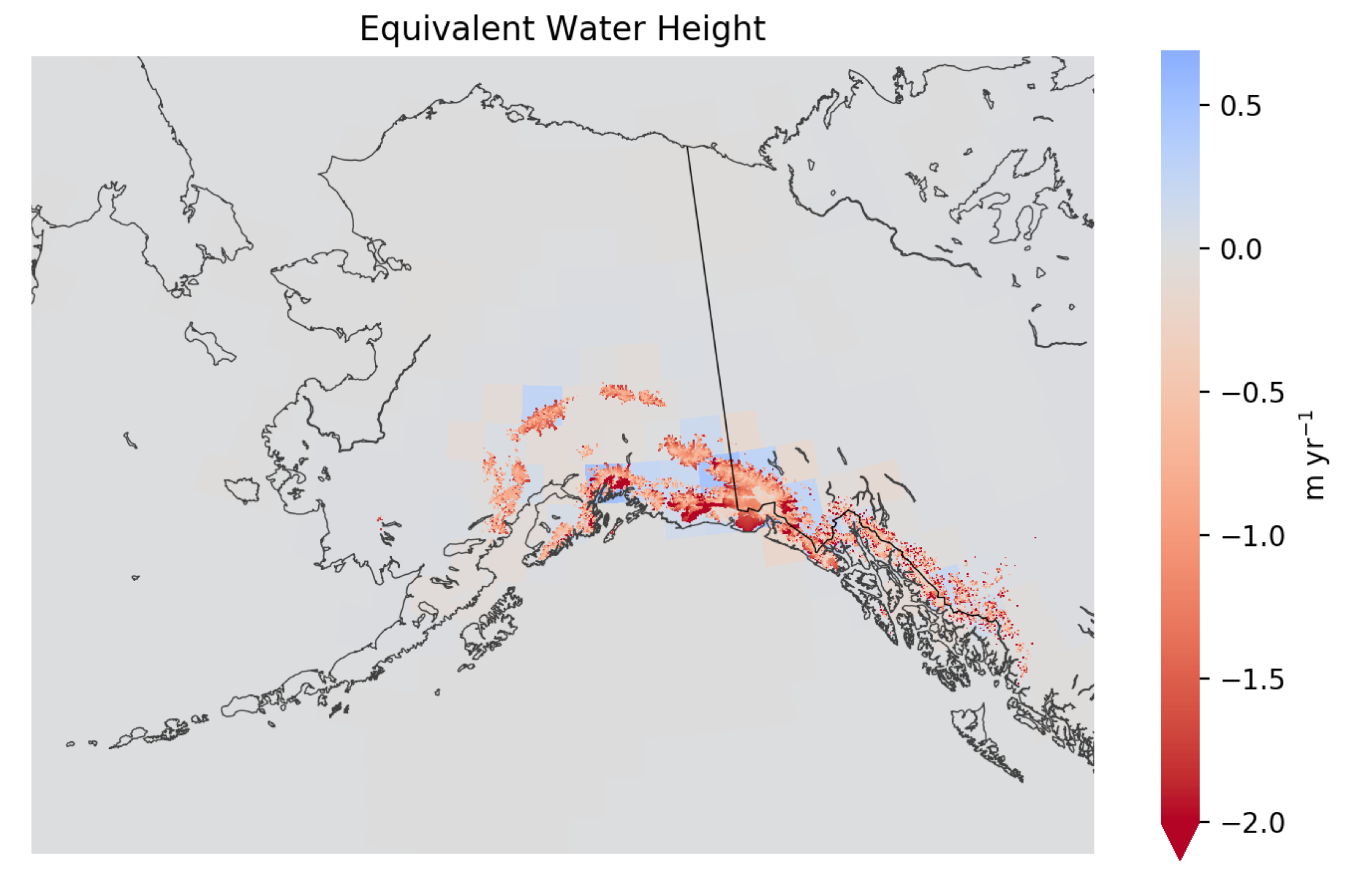
- Glacier elevation rates may be predicted by elevation, glacier type, and catalog regions
- Fitting simple elevation—height relationships to the elevation rates enables extrapolation of measured height rates using a digital elevation model



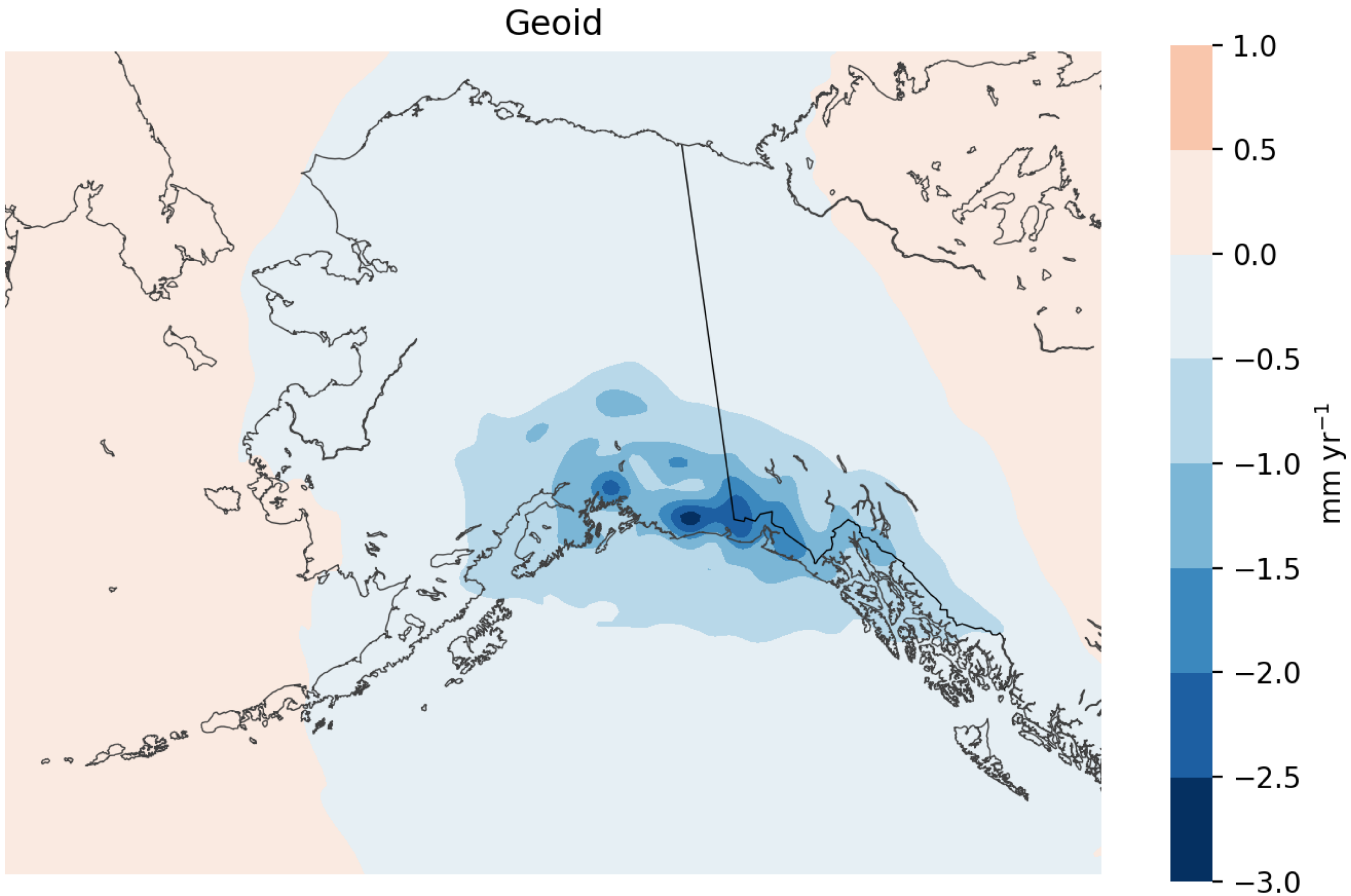
Altimetry-based Mass Loss Rates

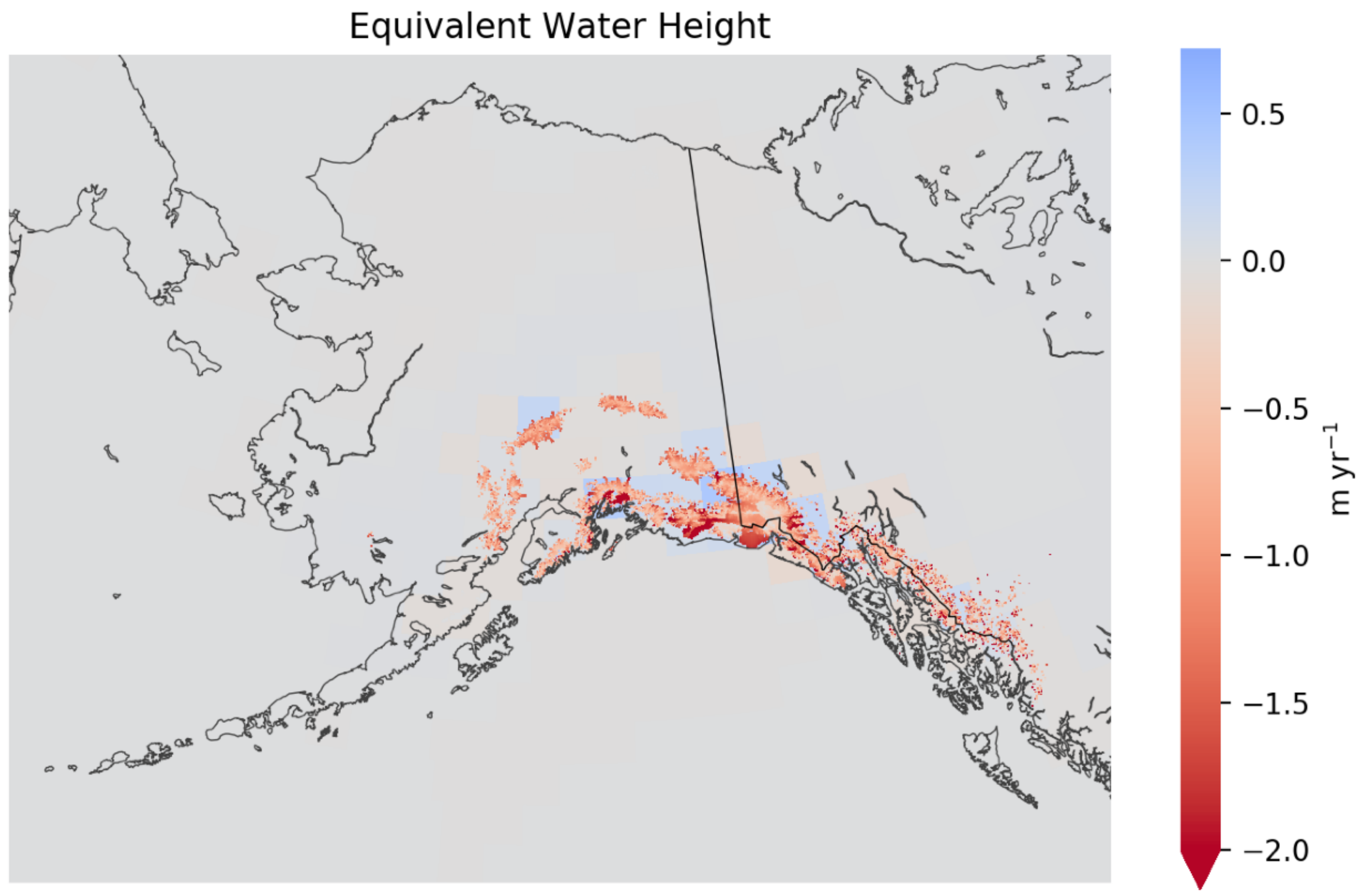
- Observed elevation rates may be extrapolated over the glaciated area of Alaska using a DEM

- The high-resolution components of these models may be combined with low-resolution GRACE rates to predict mass change rates at full resolution from ice mass loss and unmodeled processes



High-Resolution Geoid Change Predictions





GRACE provides large scale information while altimetry provides short-scale information

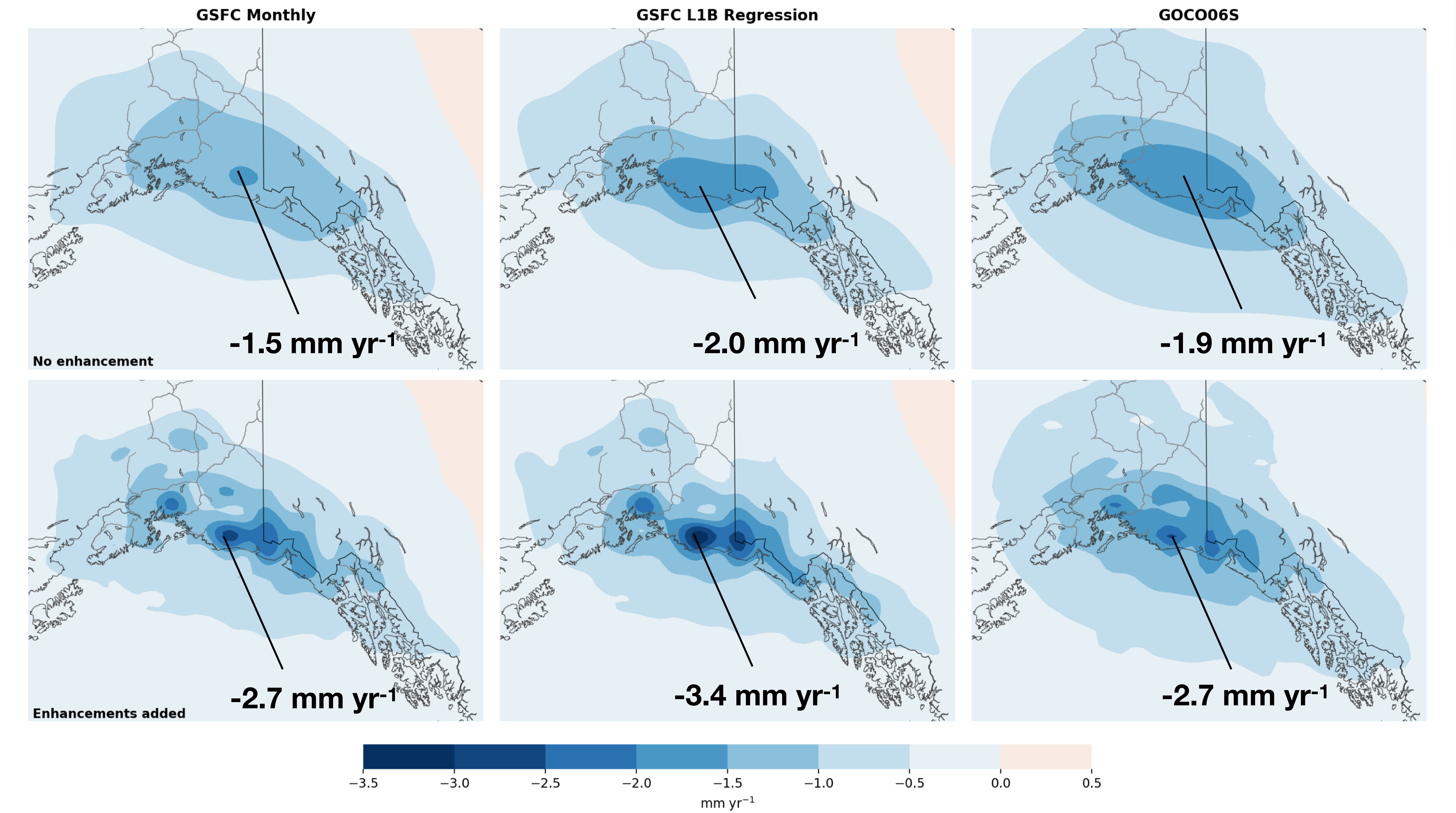
Altimetry: Added Value

GRACE Solutions

Resolution: ~100-200 km

GRACE Solutions + Airborne Altimetry

Resolution: ~50 km



Validation

- Our models show that GRACE monthly solutions underestimate more than 1 mm yr^{-1} of geoid change, which demonstrates that enhancements are needed to maintain an accurate geopotential datum

- However, these models have no external feedback and only *predict* geoid change signals

- We need high-resolution data from Alaska to verify these high-resolution predictions

Validation Questions

- Can we observe present-day geoid change in the field with terrestrial gravity measurements?
- Can we observe predicted geoid change signals by revisiting historical observation sites?
- Does geoid change introduce error to our static gravity field models?

Historical Gravity Measurements in Alaska

- Gravity measurements in Alaska were first aggregated by Thiel et al. (1958). Many of these measurements were performed mostly along roads and included NGS-cataloged benchmarks.

- The USGS and partners performed tens of thousands of subsequent measurements enabled by helicopters and riverboats in the 1960s and 1970s

- Additional surveys since contribute to more than 90,000 present-day terrestrial gravity holdings

Thiel et al. (1958)

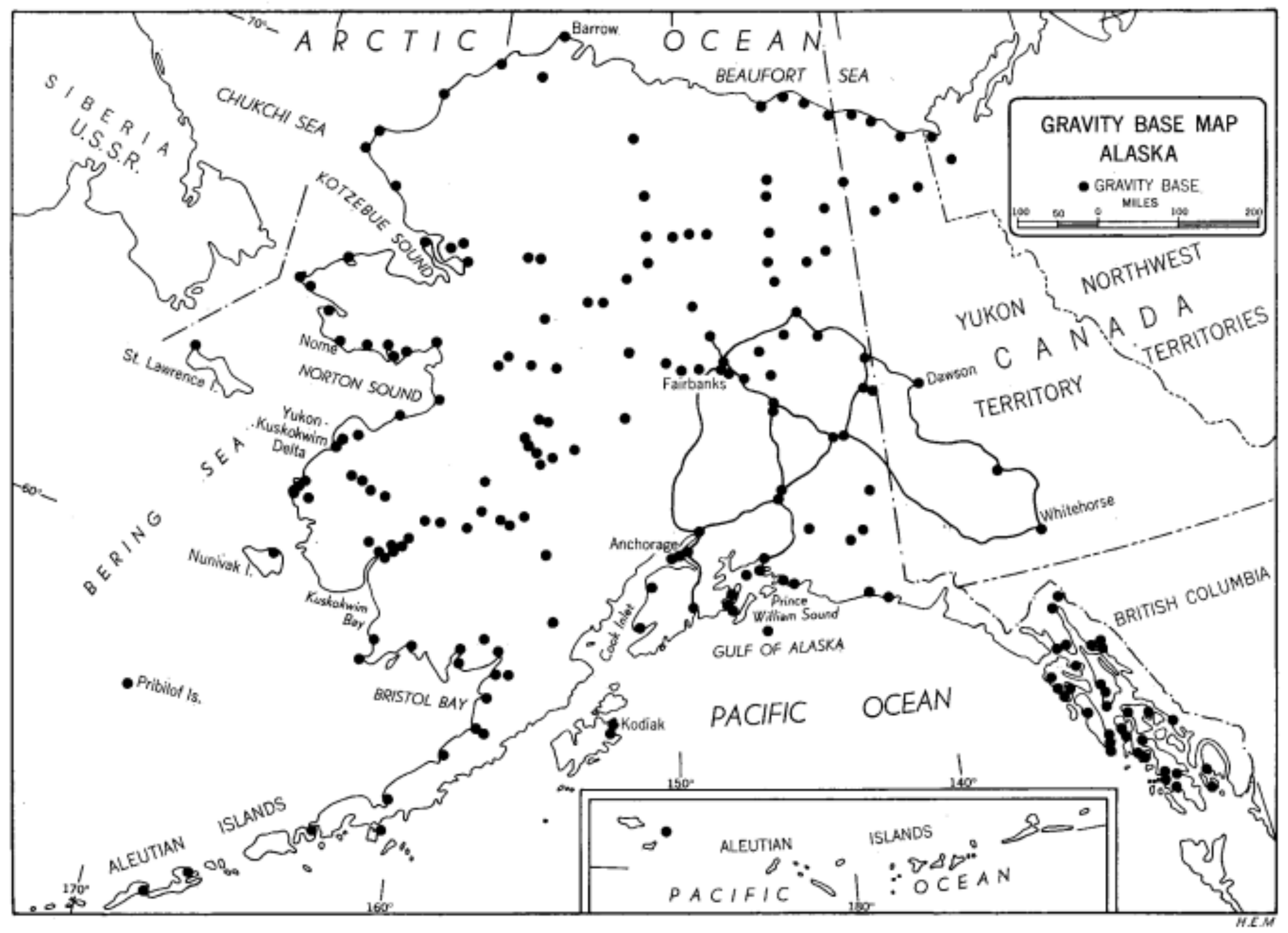


Fig. 1. Gravity stations and traverses.

Barnes et al. (1976)

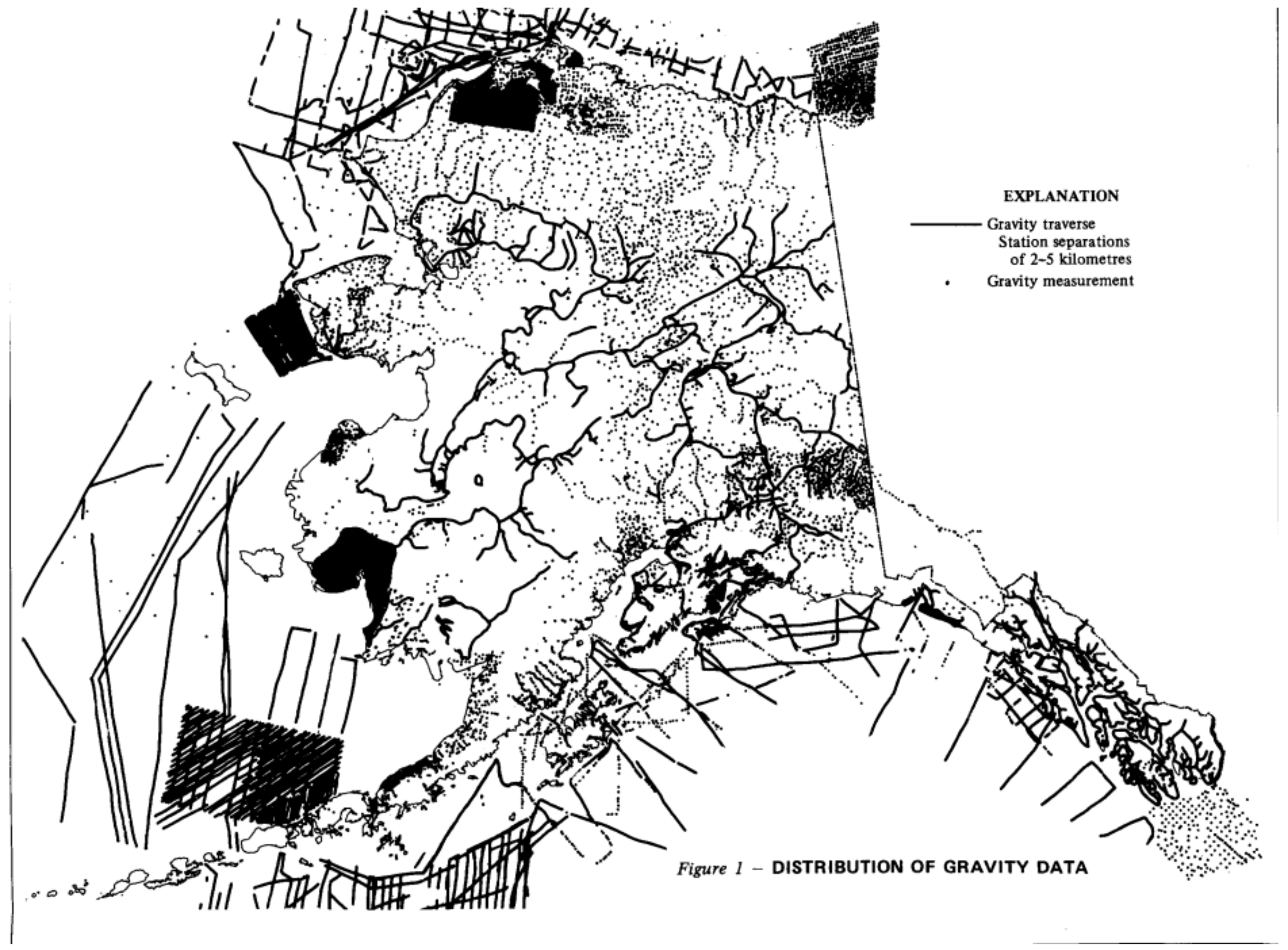
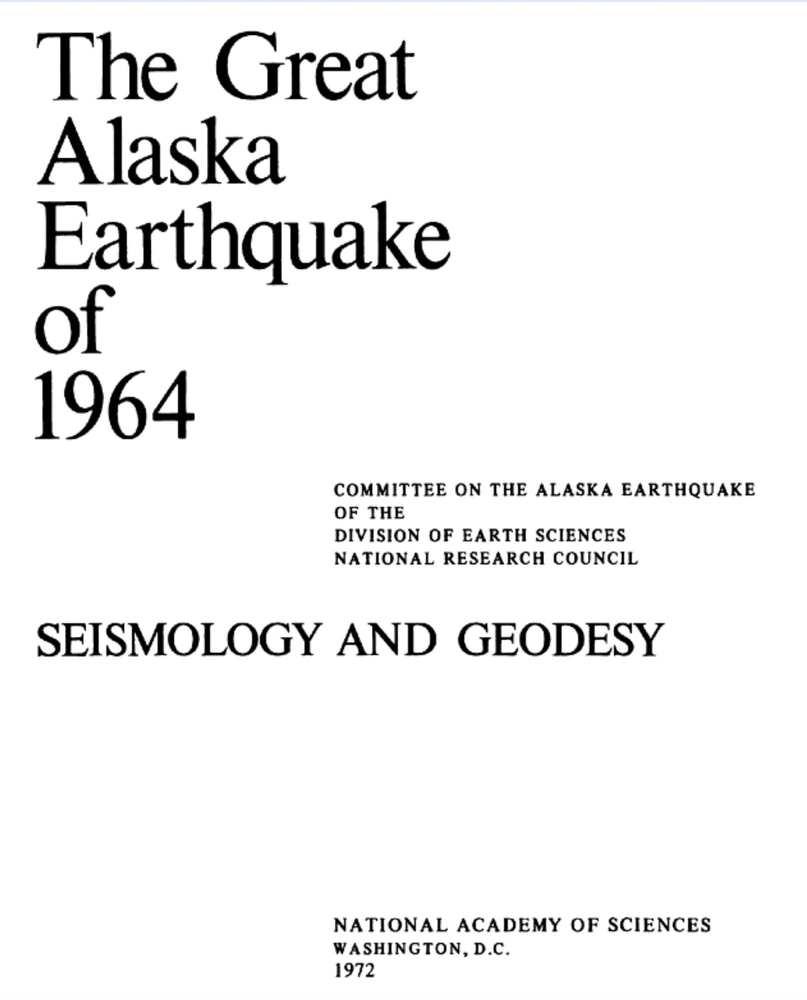


Figure 1 – DISTRIBUTION OF GRAVITY DATA

Post-1964 Earthquake Gravity and Leveling

- The 1964 Alaska Earthquake caused elevations in Alaska to change by up to two meters and may have resulted in 1 cm geoid change (Jacob et al., 2012)
- The USGS and US Coast & Geodetic Survey releveled Alaska and observed precise relative gravity profiles
- These elevation and gravity profiles preserve the state of the geoid at a 1964—1965 epoch



The Great Alaska Earthquake of 1964

COMMITTEE ON THE ALASKA EARTHQUAKE OF THE DIVISION OF EARTH SCIENCES NATIONAL RESEARCH COUNCIL

SEISMOLOGY AND GEODESY

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C.
1972

Right: Status of leveling in Alaska ca. 1965

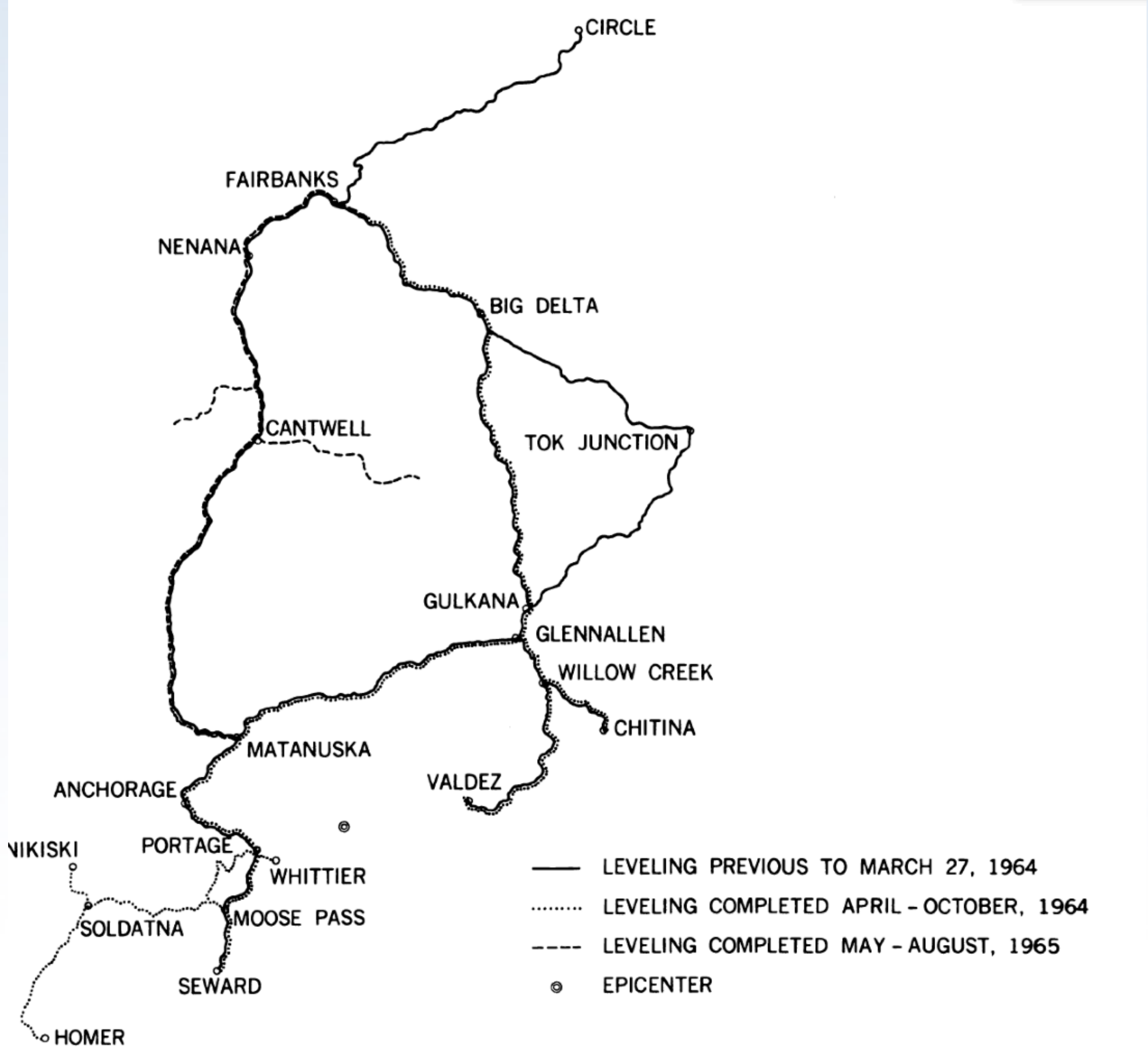


FIGURE 6.—Level net of Alaska and releveling of 1964–1965.

Right: Post-earthquake relative gravity profiles

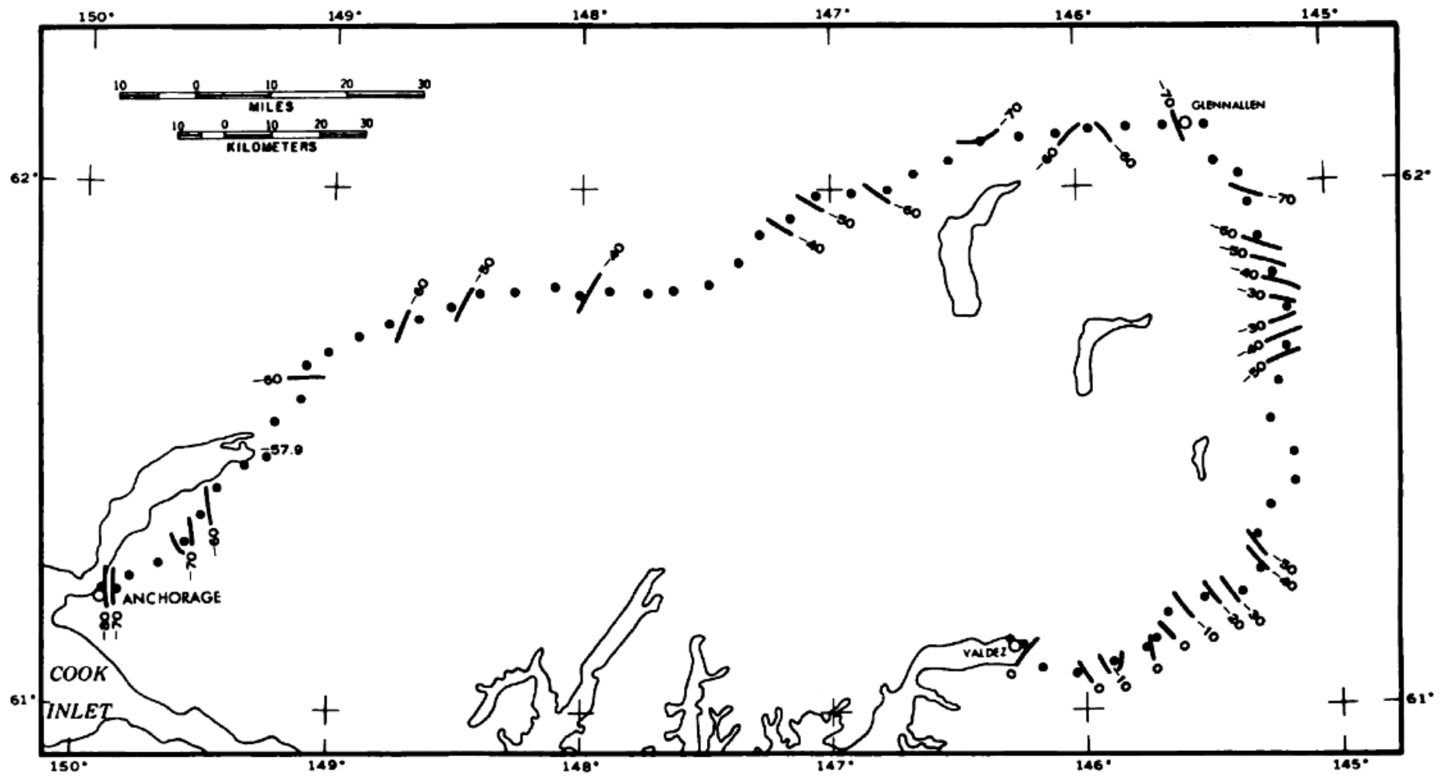
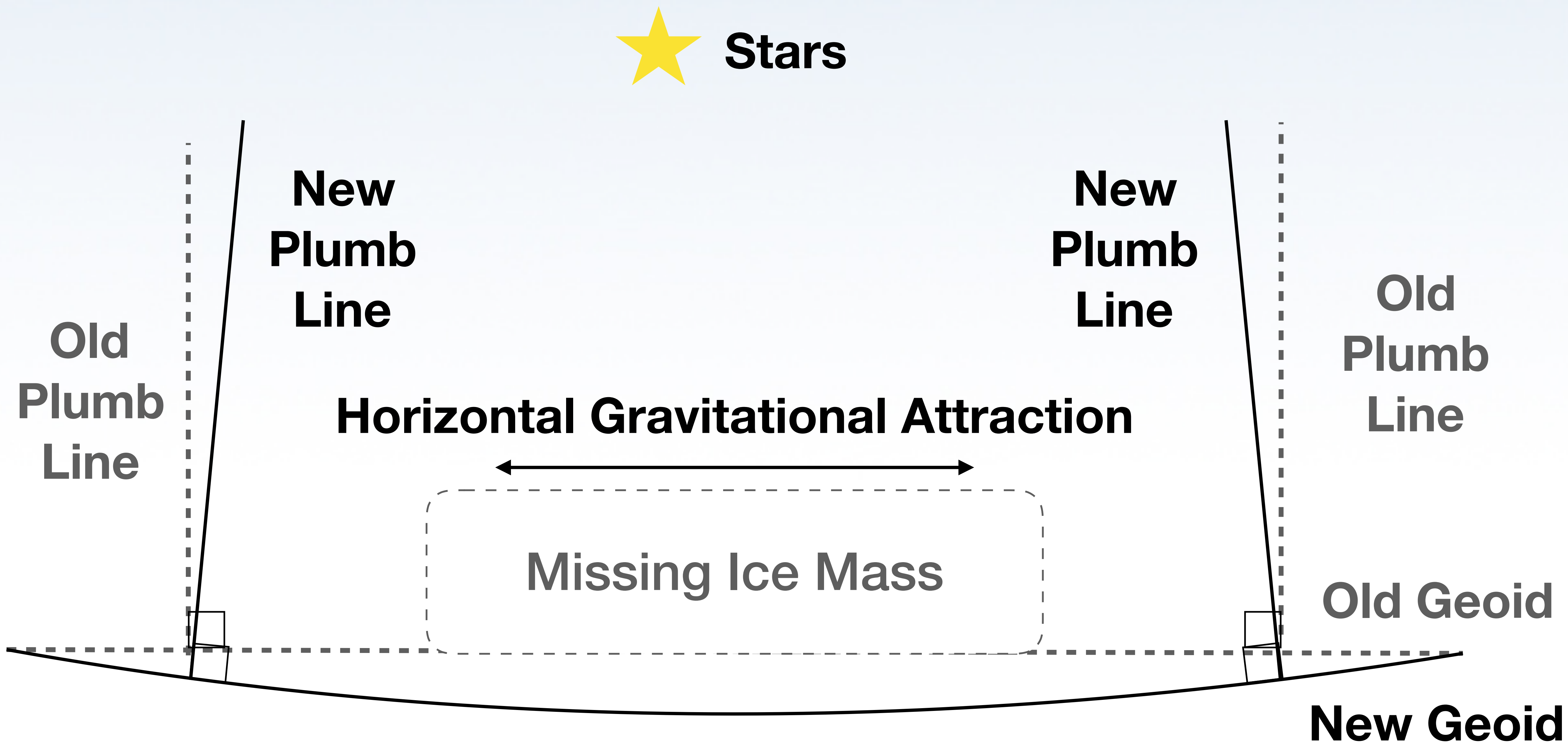


FIGURE 3 Bouguer anomalies on gravity traverse, Anchorage to Valdez via Palmer and Glennallen, 1965.

Deflections of the Vertical

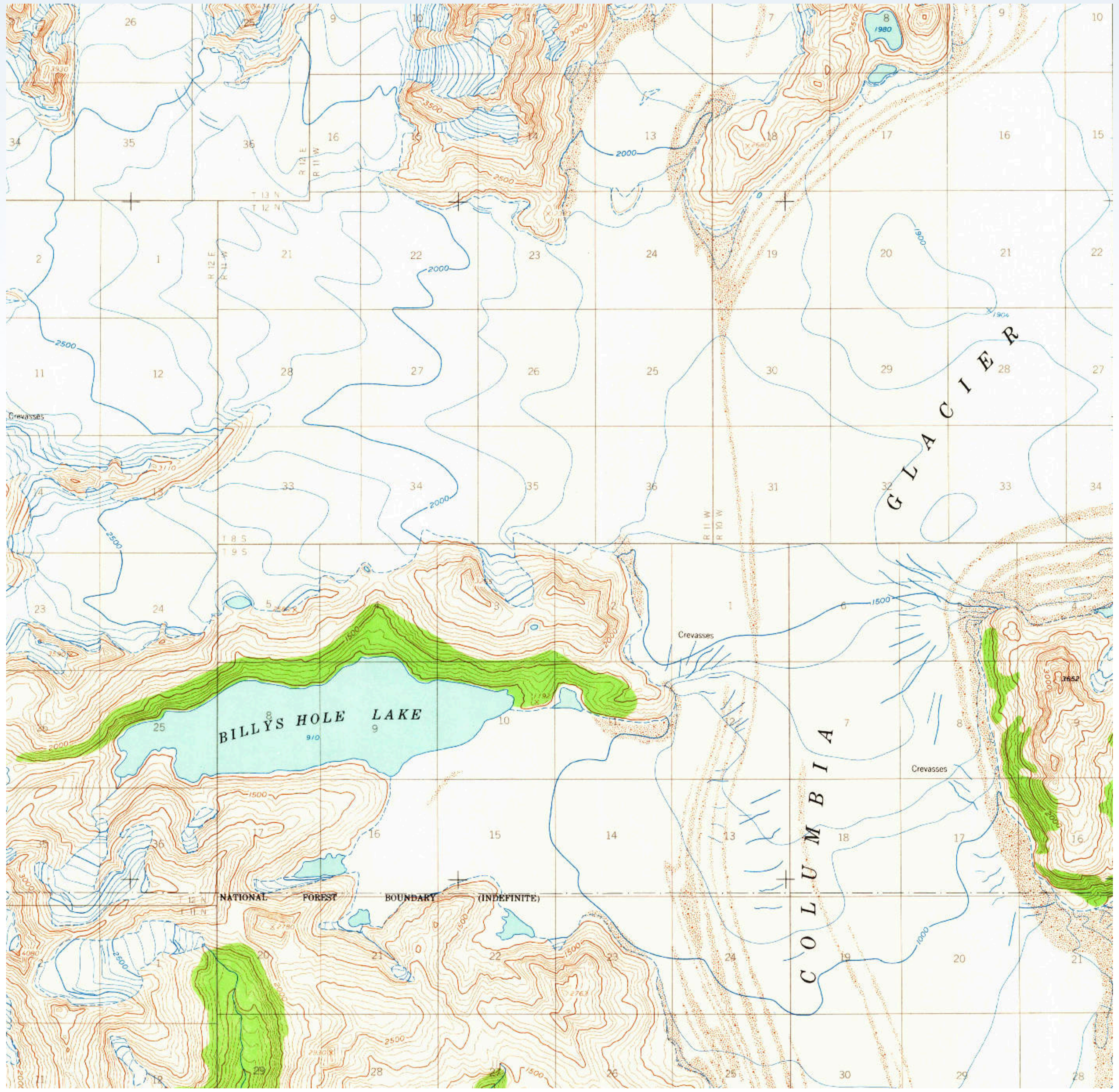
- Deflections of the vertical (DOV) describe the slope of the geoid, or the amount by which geodetic latitude and longitude differs from latitude and longitude as measured astronomically
- The Coast & Geodetic Survey observed deflections of the vertical at nearly 100 sites in Alaska to augment horizontal control between 1890 and 1960, often within ±0.2" (1 mm/km)
- Some of these DOV sites were situated near glaciers and may reveal several tenths of an arcsecond of geoid change



Predicting Past Geoid Change

- Aerial stereo photos provides a key source of evidence of glacial elevation change over the past 70 years
- Echelmeyer et al. (2002) compared airborne lidar data captured in the 1990s with aerial photogrammetry contours captured starting in 1950
- Measured elevation changes can reach hundreds of meters

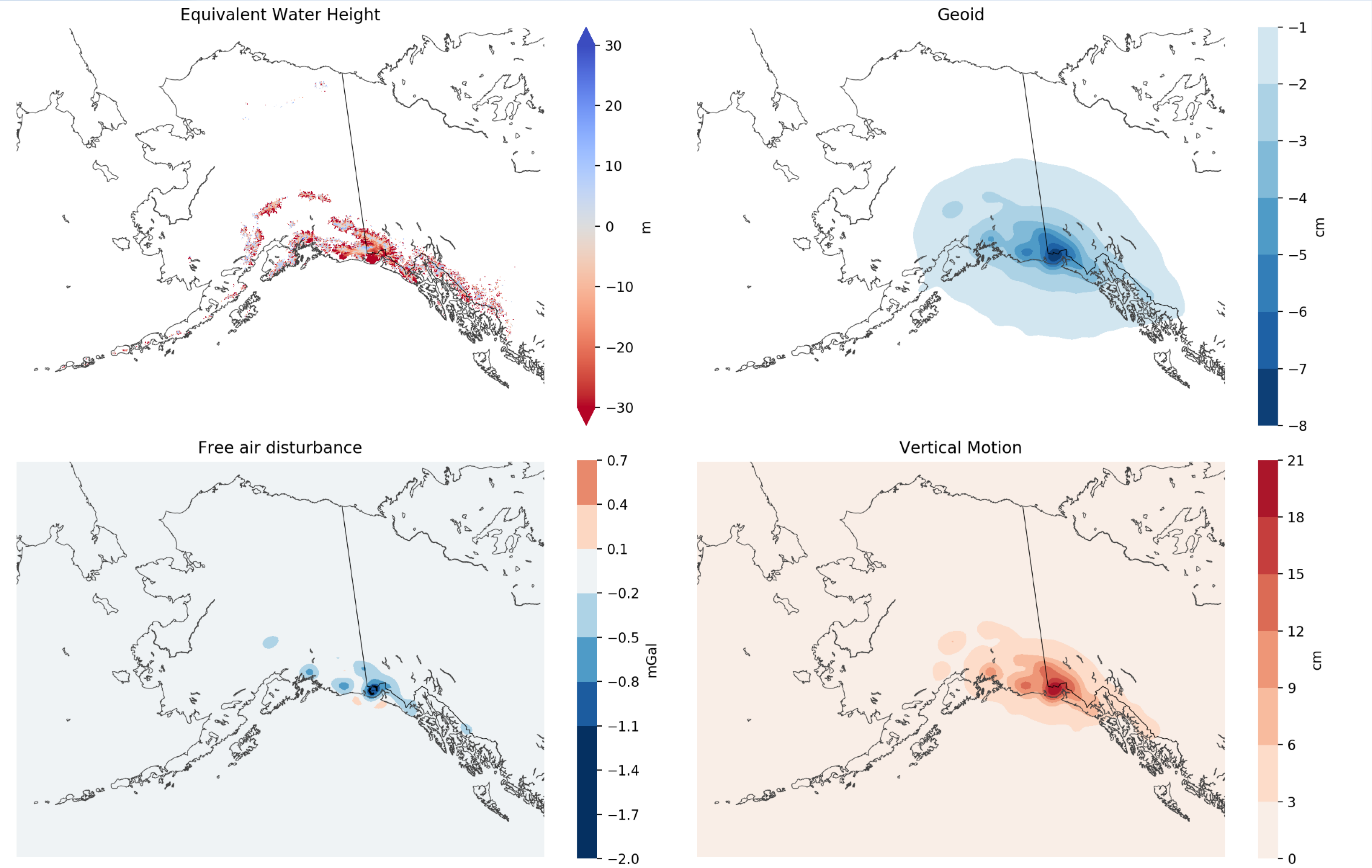
Detail of USGS Columbia Glacier Topographic Map (1963)



Predicting Past Geoid Change

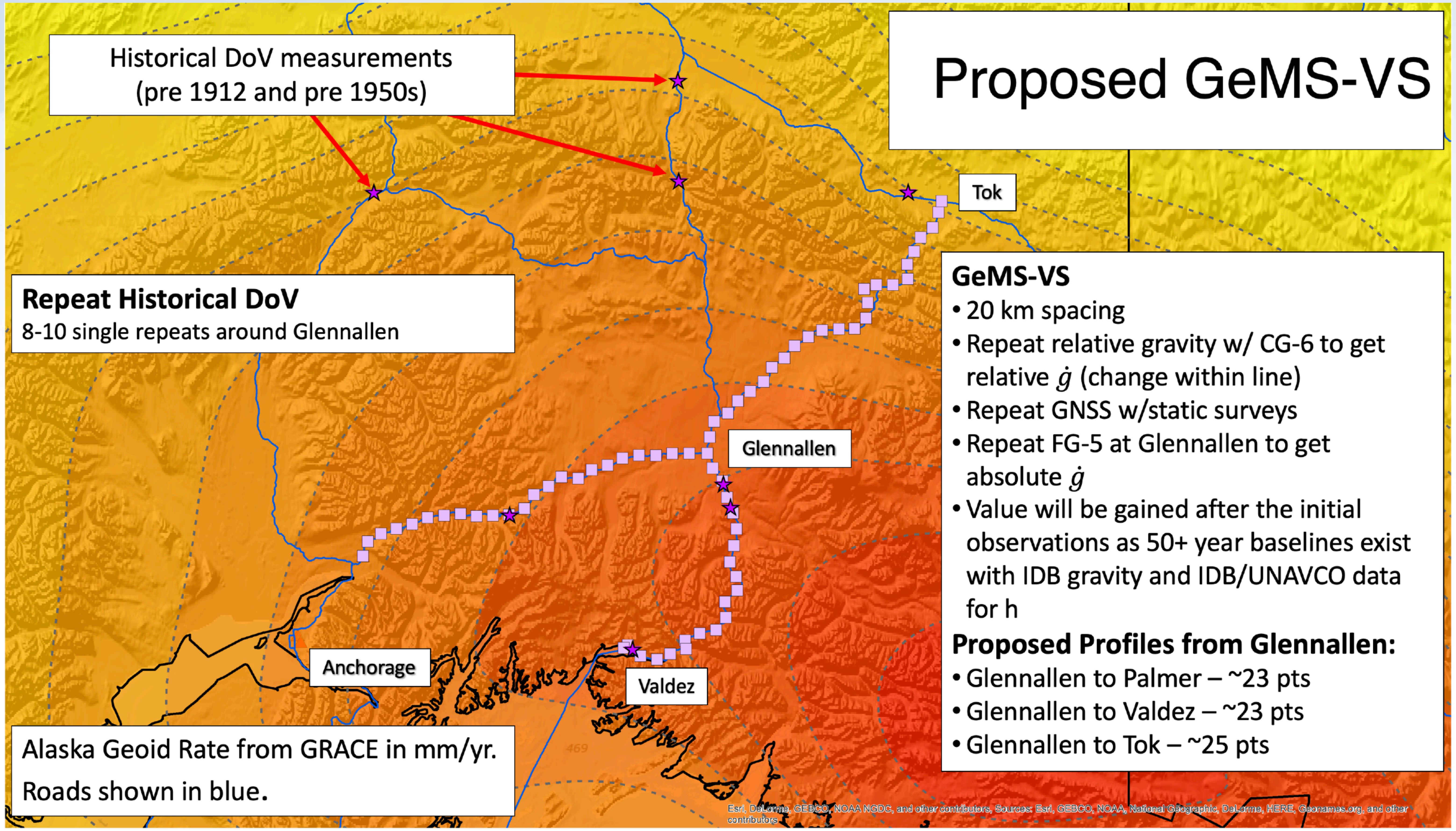
- The Echelmeyer results may be handled in the same manner as present day velocities to obtain 1954—1996 geoid change

- These results suggest geoid change of up to 8 cm across this interval



GeMS-VS High-Resolution Surveys

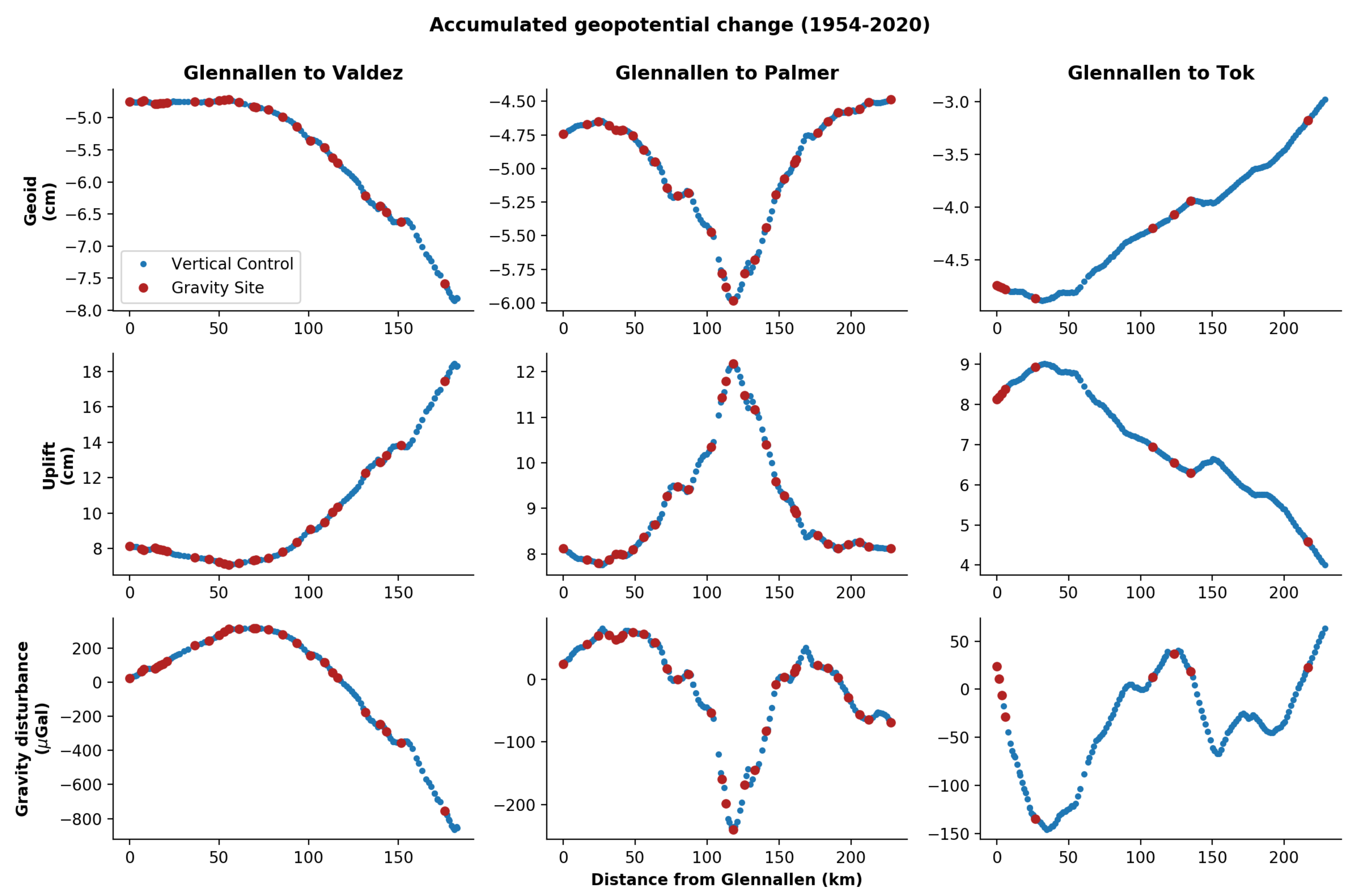
- This "GeMS Validation Survey" preliminary survey design collects dense (~20 km) profiles of gravity and GNSS elevations
- Observations at historical sites will constrain past geoid change
- Survey profiles will isolate ice melt load centers

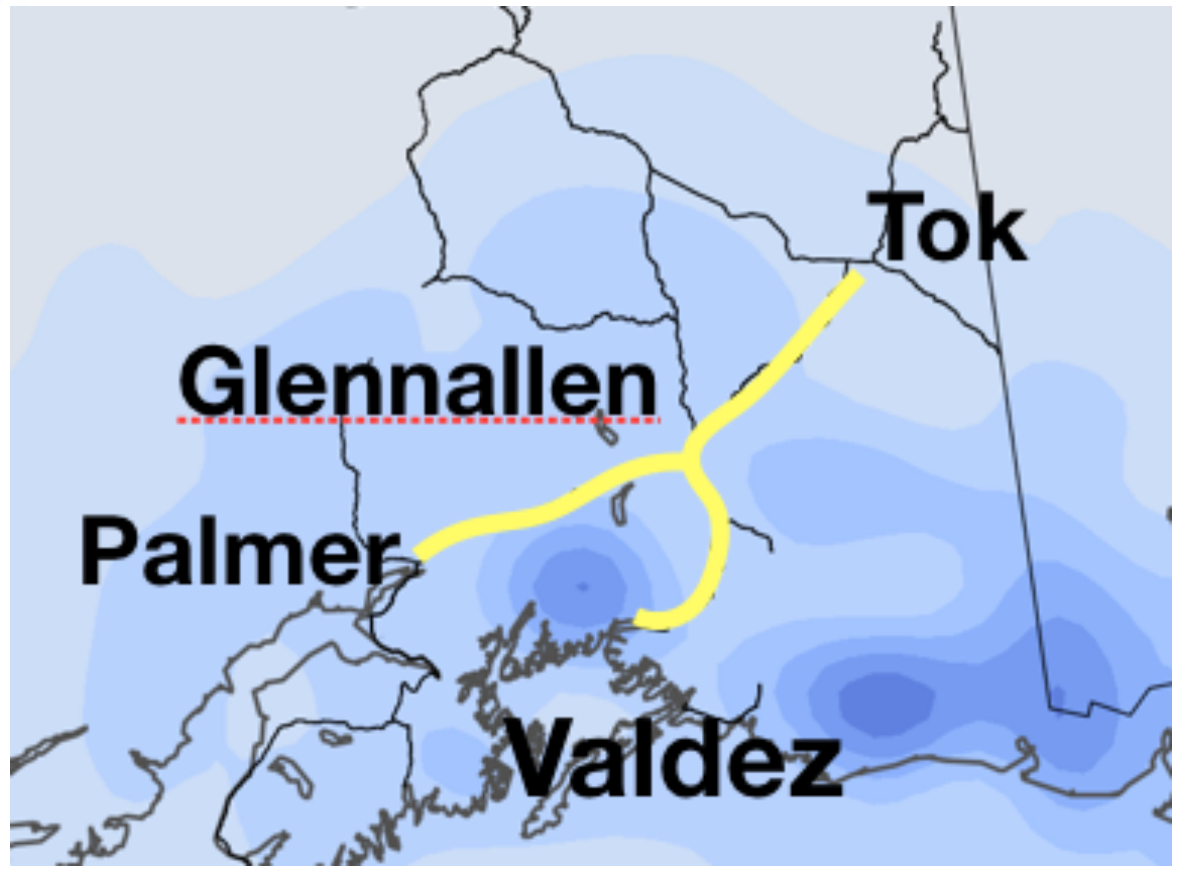


From "NGS's Geoid Monitoring Service (GeMS)" September 2019 Webinar

Measuring Past Geoid Change

- Combining both approaches enables predictions of geodetic change across 1954—2020 baseline
- Observed gravity and precise elevations may be compared with historical (ca. 1940—1970) measurements

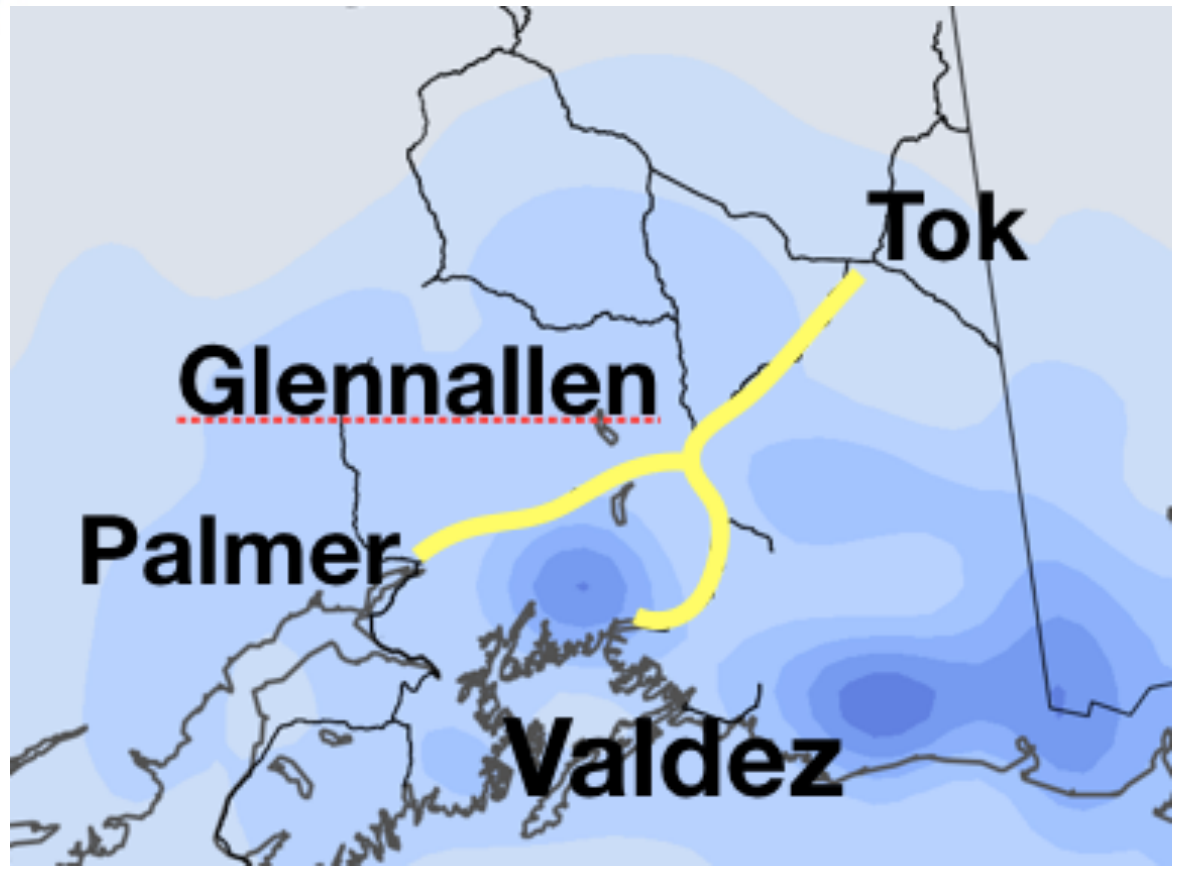


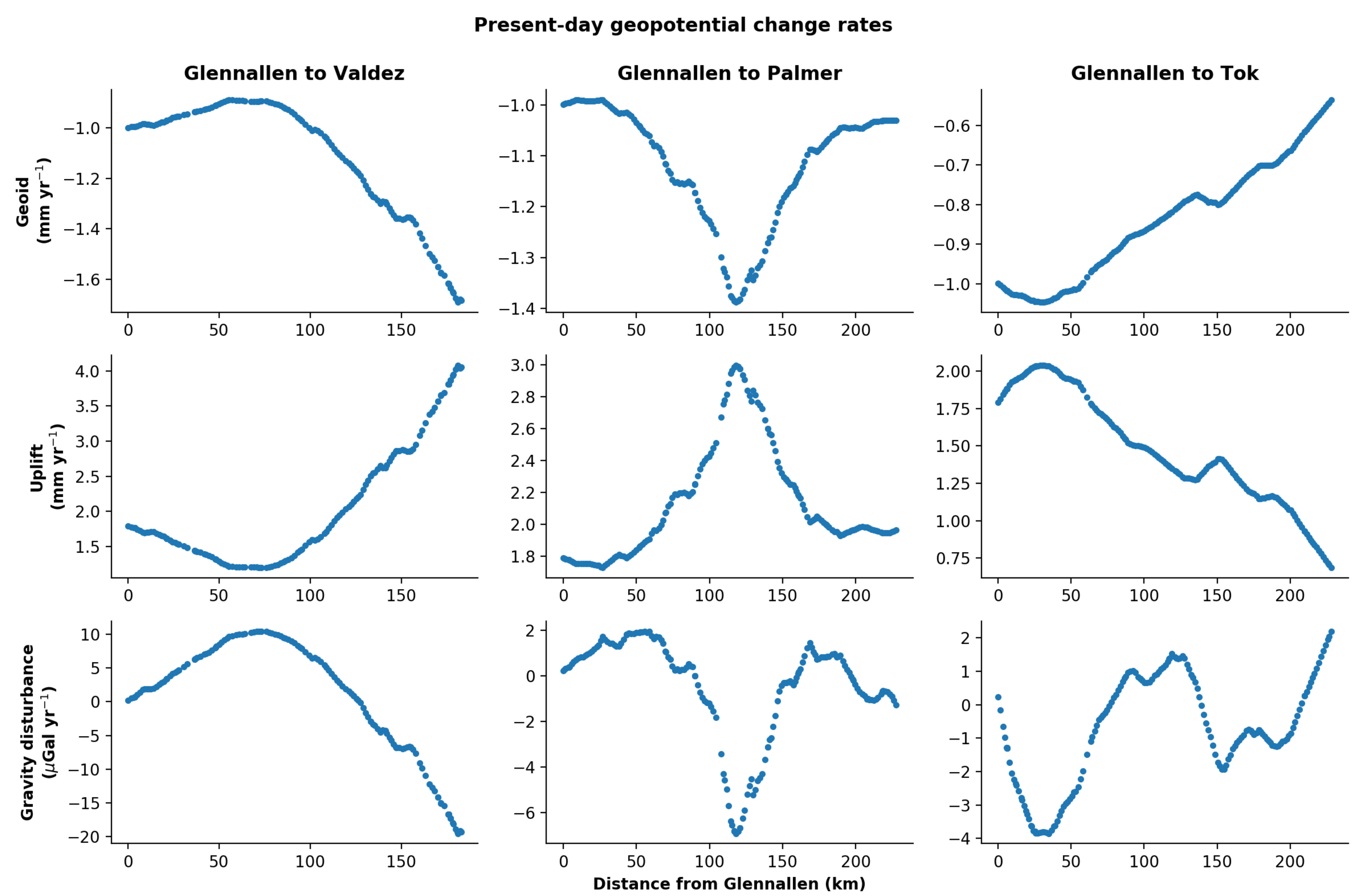


Measuring Current Geoid Change

- Annual-to-biennial revisits of this profiles will enable validation of present-day rates of geopotential change

- Geoid change will be reflected in differential gravity and elevation change rates

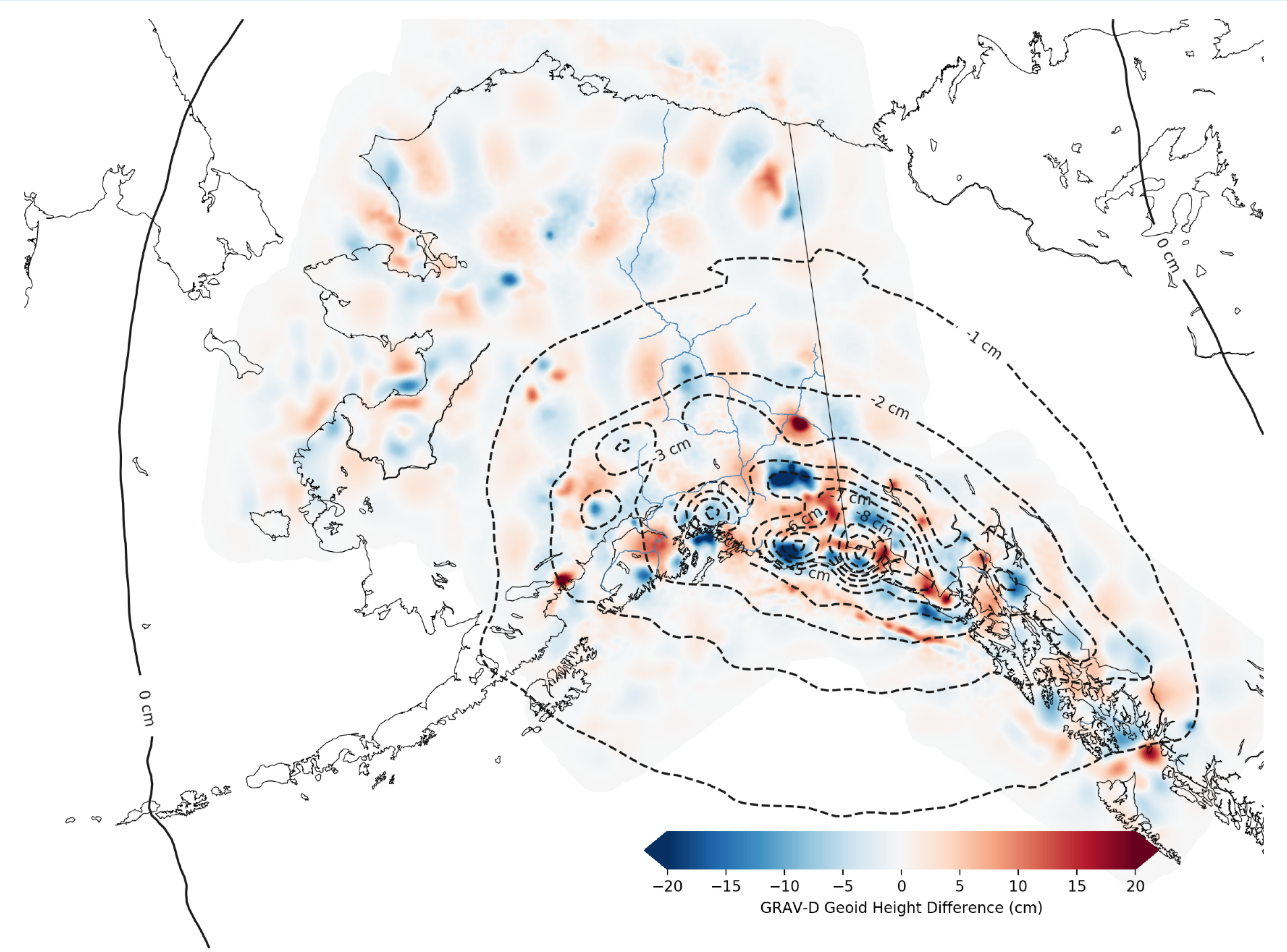




Temporal Gravity Signals in the Static Geoid?

- NGS geoid models are a mix of 20th century terrestrial gravity and modern satellite and airborne models (ca. 2010)
- Most gravity data in Alaska was collected before 1980
- The difference between airborne and terrestrial-only solutions (right) should, in part, reflect geoid change

Colors: Geoid differences after GRAV-D airborne data additions
Contours: Predicted 1954—2010 geoid change



Conclusions

- Ice mass loss in southern Alaska changes the geoid by 1-3 cm per decade
- Satellite gravity solutions can only capture the low-resolution components of geoid change in Alaska and can miss more than 1 cm per decade of geoid change
- The geoid has likely changed by more than 10 centimeters since the 1950s
- On-the-ground profile measurements of gravity, elevation, and deflections of the vertical will capture geoid change, both past and present

More Information

- NOAA Technical Report NOS NGS 69: A Preliminary Investigation of the NGS's Geoid Monitoring Service (GeMS)
- September 2019 NGS Webinar "NGS's Geoid Monitoring Service (GeMS)"
- xGEOID19, NGS's beta geoid model with dynamic components https://beta.ngs.noaa.gov/GEOID/xGEOID19/

Questions? Contact Me:
Ryan Hardy, PhD
ryan.hardy@noaa.gov

Selected References

Bolt, Bruce A. "The Great Alaska Earthquake of 1964: Seismology and Geodesy: by the Committee on the Alaska Earthquake of the Division of Earth Sciences, National Research Council, National Academy of Sciences, Washington, DC, 1972, 596+ xvii pp. $25.00." (1973): 740-742.

Echelmeyer, K. A., V. B. Valentine, and S. L. Zirnheld. 2002, updated 2004. Airborne Surface Profiling of Alaskan Glaciers, Version 1. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: https://doi.org/10.7265/N5RF5RZJ

Jacob, Thomas, et al. "Estimating geoid height change in North America: past, present and future." *Journal of Geodesy* 86.5 (2012): 337-358.

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