Cryosphere Breakout
NASA STV
Incubator Study

Starting at:
8:30 am PT
11:30 am ET

Alex Gardner, JPL

Hosts

Alex Gardner, JPL
STV Cryosphere Lead

Batuhan Osmanoglu, NASA Goddard
STV Information Systems Lead

STV Cryosphere Breakout Agenda (July 21, 2020)

Topic	Presenter	PT	ET
Intro from HQ	Thorsten Markus	8:30 - 8:40	11:30 - 11:40
Intro to DS and STV	Andrea Donnellan	8:40 - 8:50	11:40 - 11:50
Overview of SATM	David Harding	8:50 - 9:00	11:50 - 12:00
Land Ice Needs and Targeted Observables	Alex Gardner	9:00 - 9:30	12:00 - 12:30
Sea Ice Needs and Targeted Observables	Ron Kwok	9:30 - 9:50	12:30 - 12:50
BREAK		9:50 - 10:00	12:50 - 1:00
How to think about what we need	Alex Gardner	10:00 - 10:10	1:00 - 1:10
Review of Key DS White Papers	Alex Gardner	10:10 - 10:20	1:10 - 1:20
Summary of needs and community input	Alex Gardner	10:20 - 12:00	1:20 - 3:00
land ice			
fast moving outlet glaciers		10:20 - 10:50	1:20 - 1:50
slow moving interior ice		10:50 - 11:00	1:50 - 2:00
floating ice shelves		11:00 - 11:10	2:00 - 2:10
large mountain glaciers	rough times	11:10 - 11:20	2:10 - 2:20
static topography		11:20 - 11:30	2:20 - 2:30
sea ice			
smooth ice		11:30 - 11:45	2:30 - 2:45
rough ice		11:45 - 11:55	2:45 - 2:55
wrap up		11:55 - 12:00	2:55 - 3:00

Intro from HQ

What STV Cryo is tasked with doing

***Step 1*: Identify ice sheet, ice shelf, glacier and sea ice topography measurements that are needed to answer key science questions posed by the Decadal Survey**

Step 2: Review current technologies and assess readiness to address identified needs

Step 3: Make recommendations to NASA HQ, via white paper, outlining measurement needs and technology gaps.

Alex Gardner, JPL

Guided by two overarching Decadal Survey questions:

1. How will sea level change, globally and regionally, over the next decade and beyond? [S-3, C-1] [Most Important]
2. What will be the consequences of amplified climate change in the Arctic and Antarctic? [C-8] [Very Important]

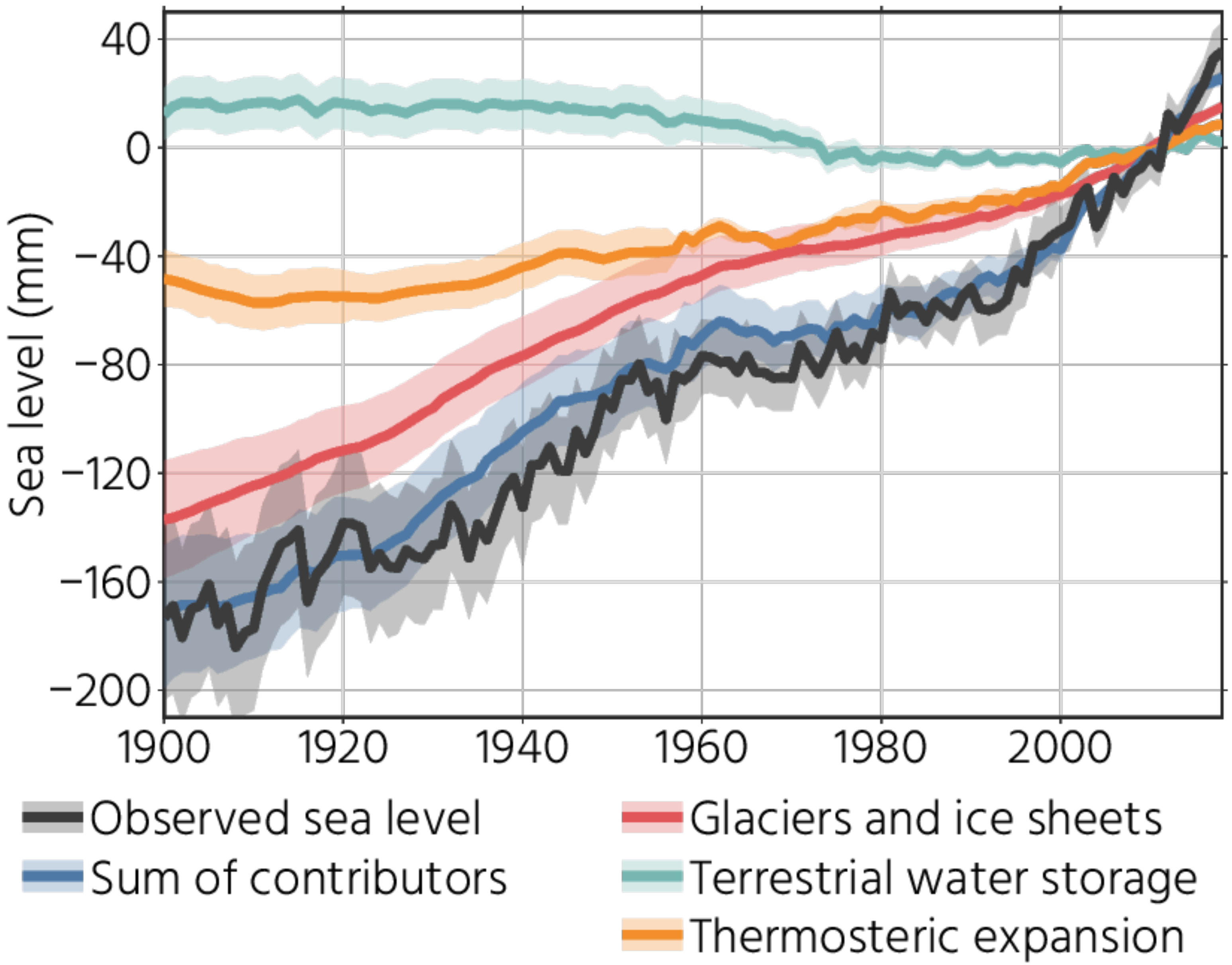
Alex Gardner, JPL

Guided by two overreaching Decadal Survey questions:

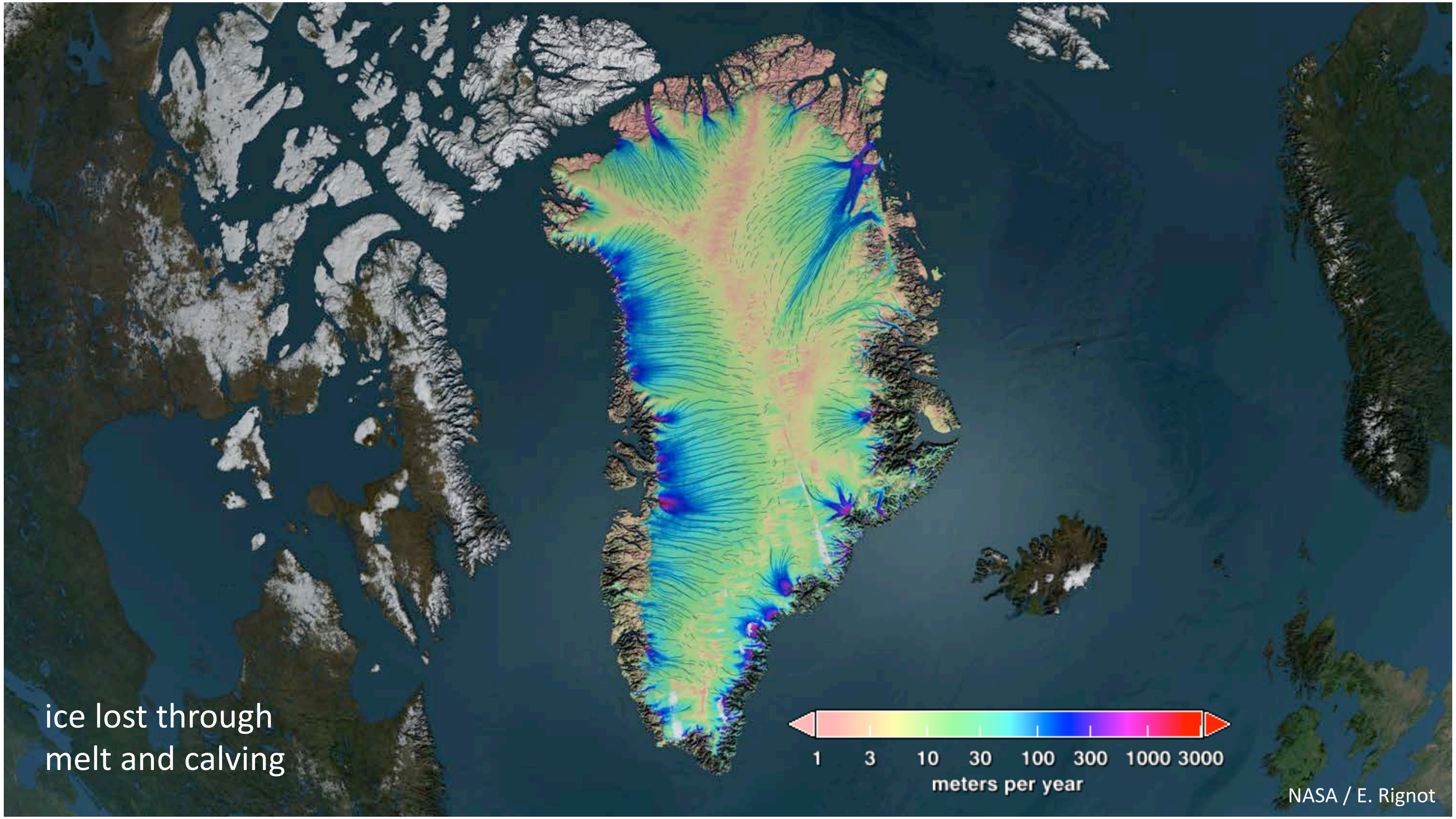
1. **How will sea level change, globally and regionally, over the next decade and beyond? [S-3, C-1] [Most Important]**
2. What will be the consequences of amplified climate change in the Arctic and Antarctic? [C-8] [Very Important]

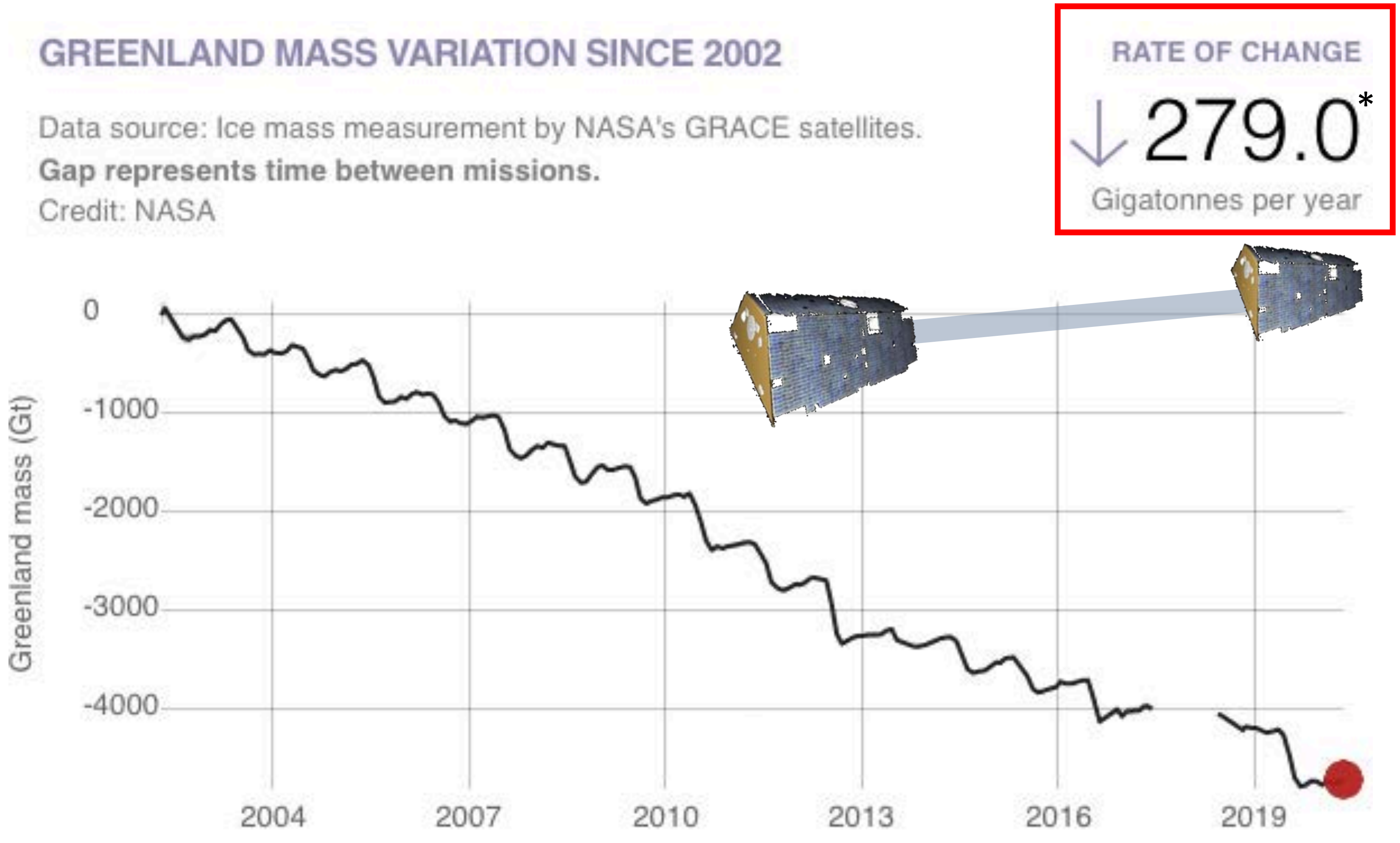
Alex Gardner, JPL

Historic sea level change

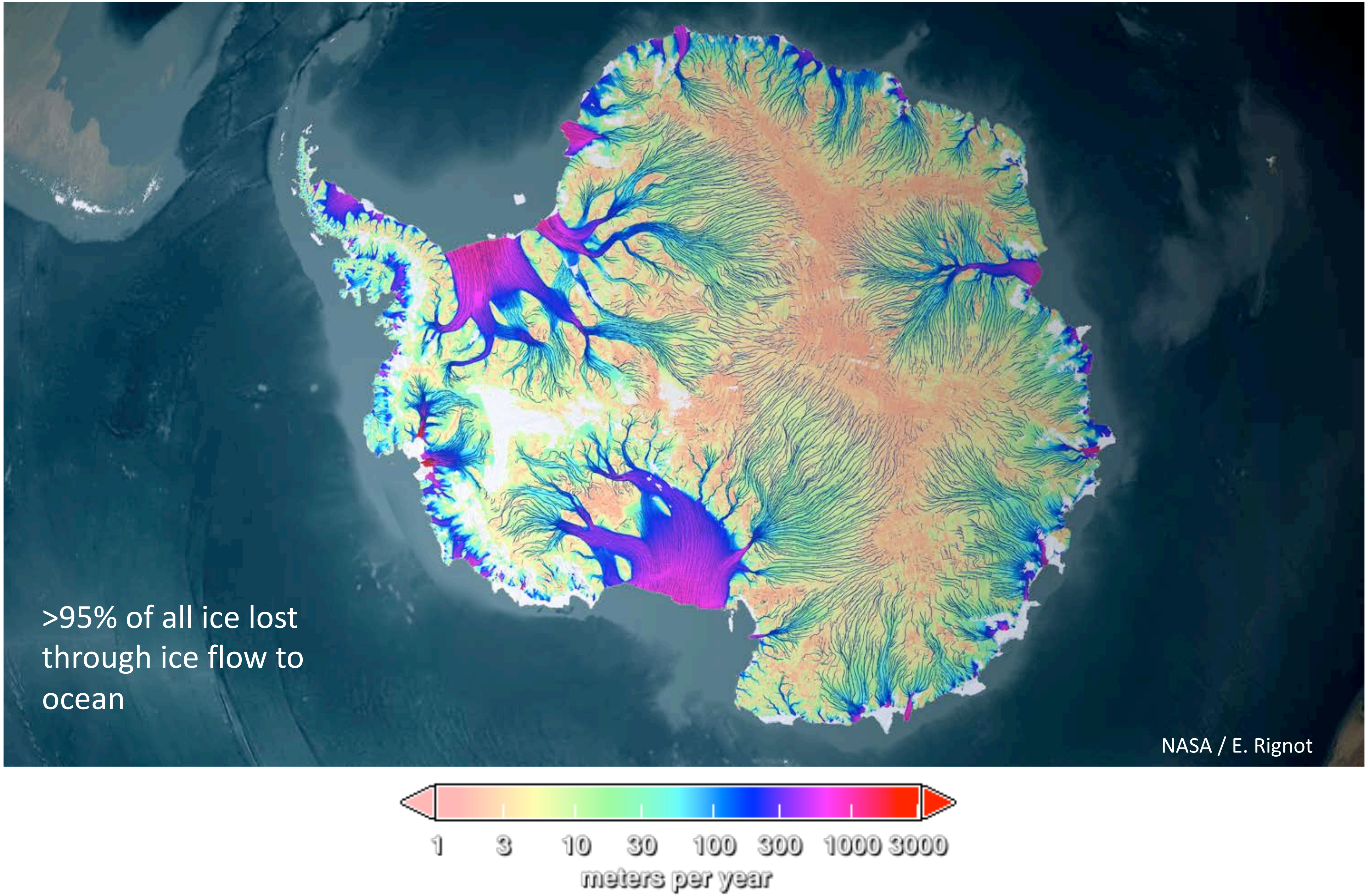


Frederikse, in press

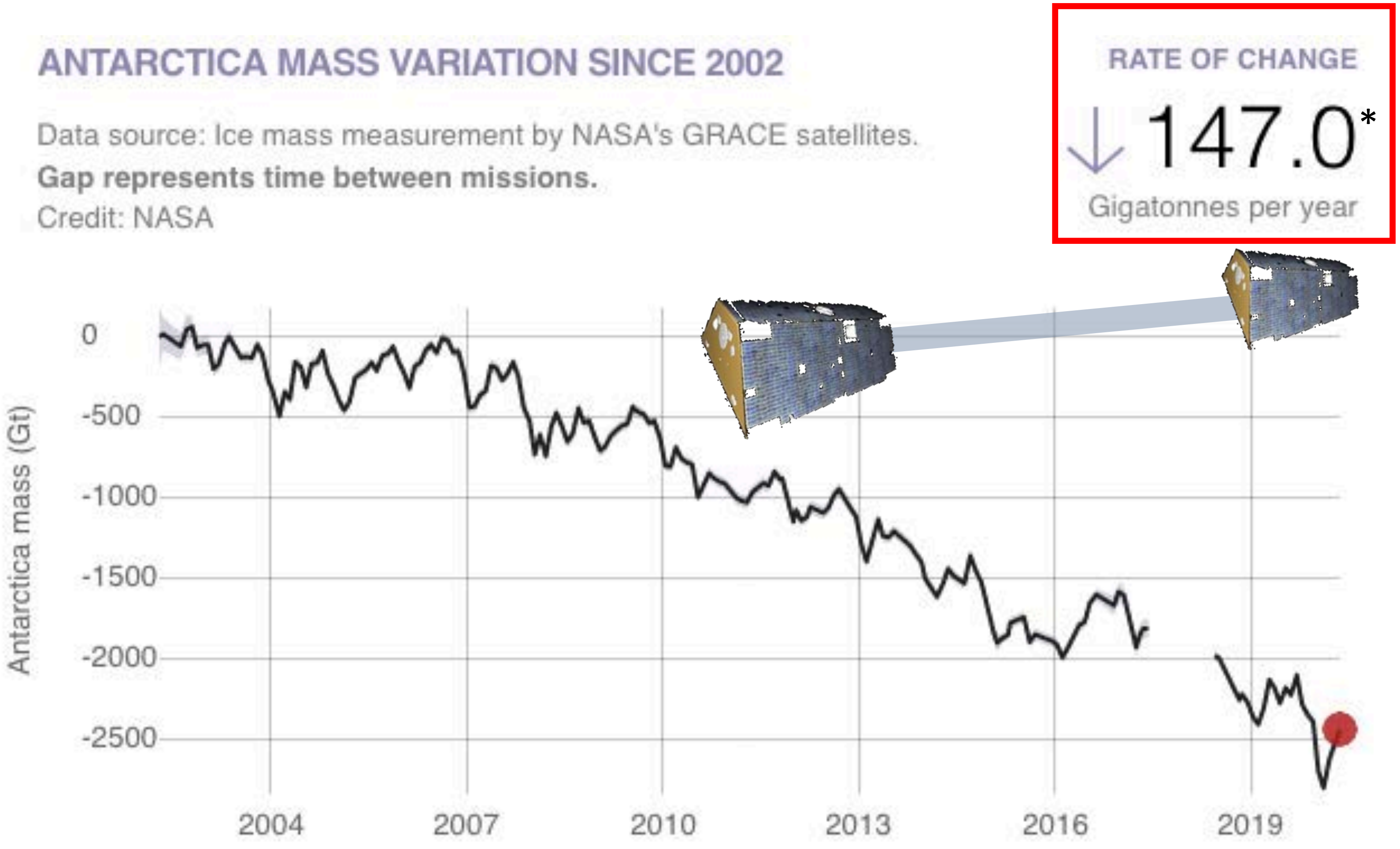

ice lost through
melt and calving
1 3 10 30 100 300 1000 3000
meters per year
NASA / E. Rignot



* Approximately 35 Gt/yr from peripheral glaciers


>95% of all ice lost through ice flow to ocean
NASA / E. Rignot
1 3 10 30 100 300 1000 3000
meters per year

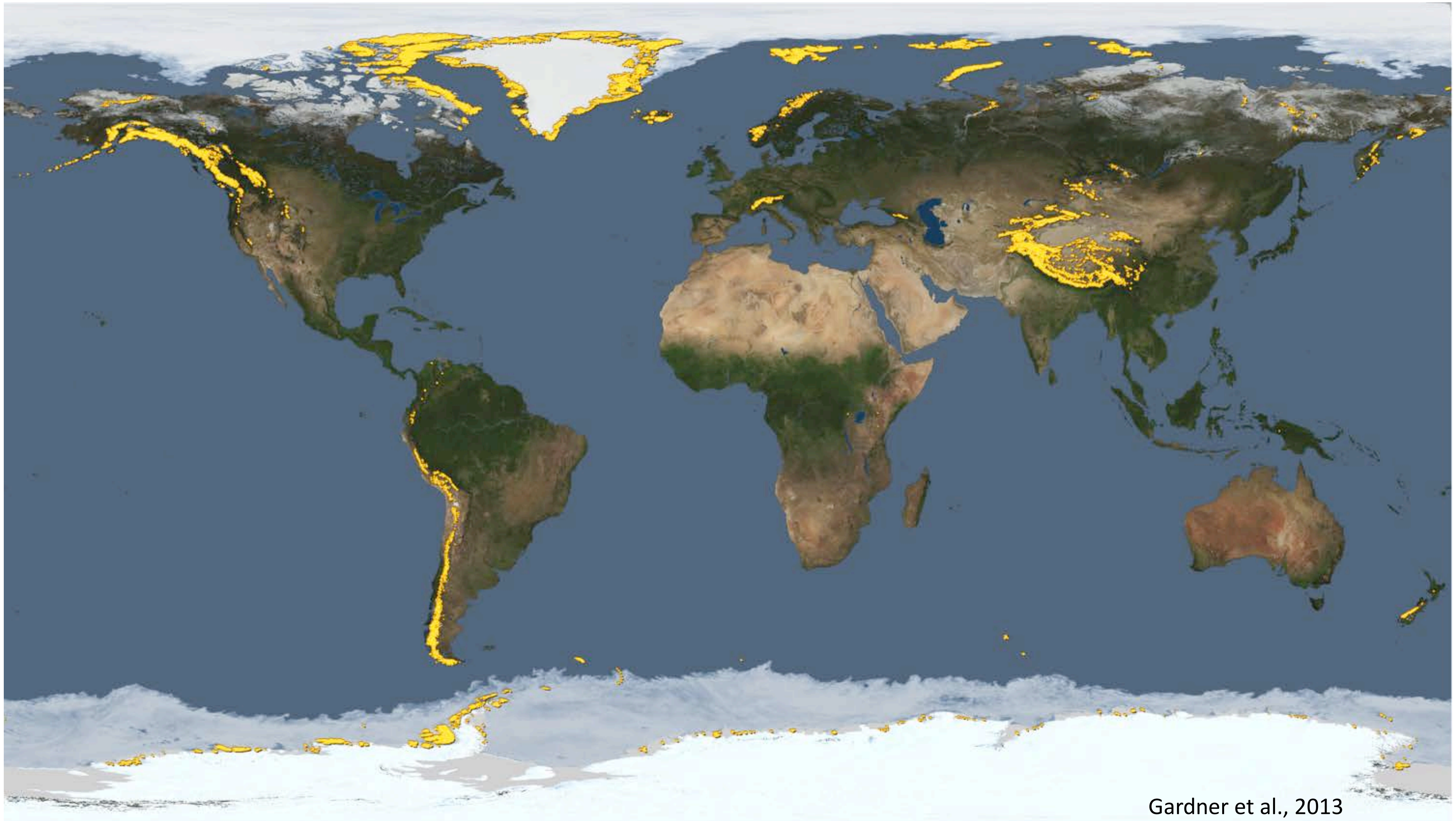
Antarctic Ice Sheet



SEA LEVEL CHANGE
Observations from Space

* Approximately 8 Gt/yr from peripheral glaciers

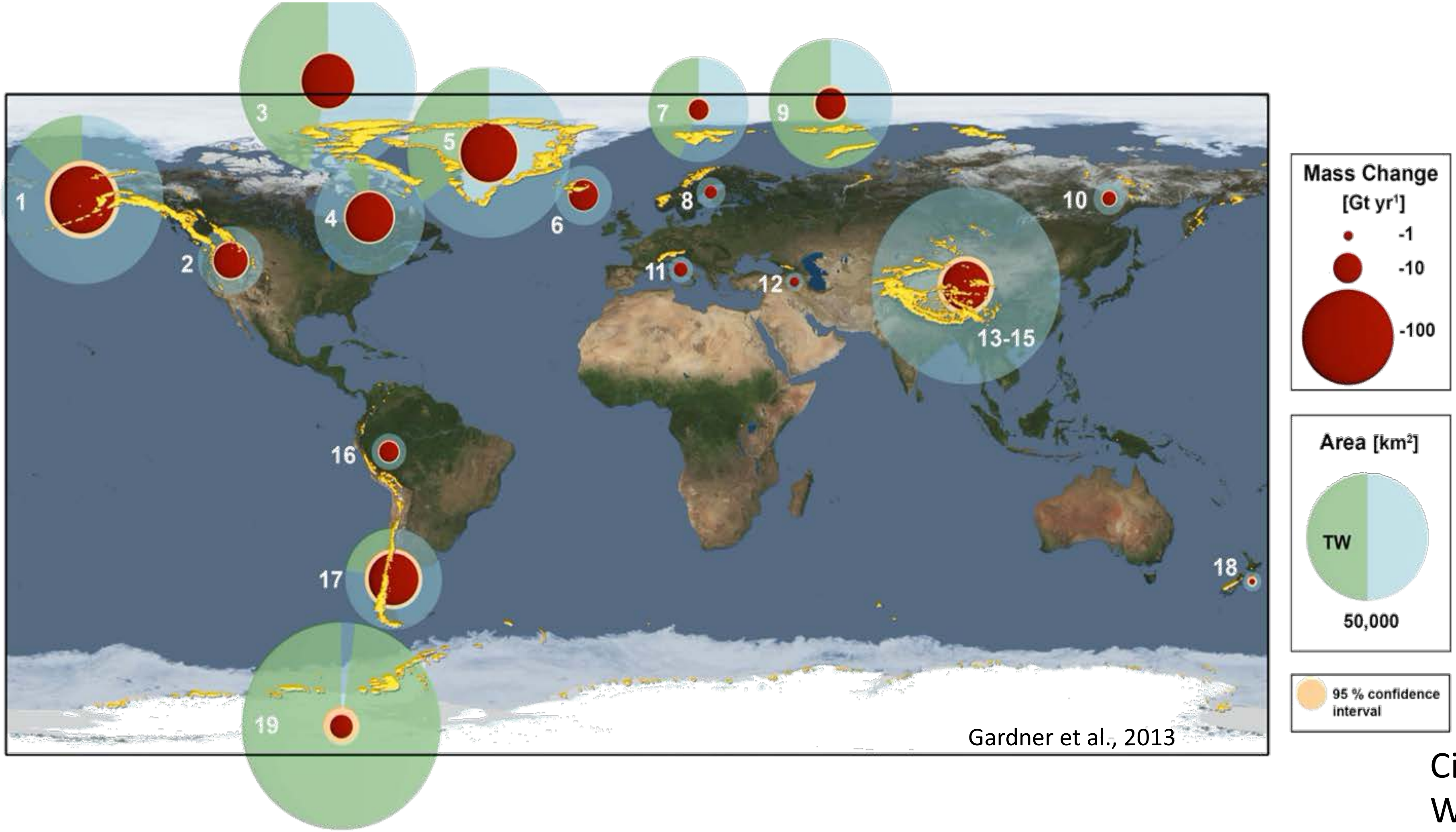
Mountain Glaciers (shown in yellow)



Gardner et al., 2013

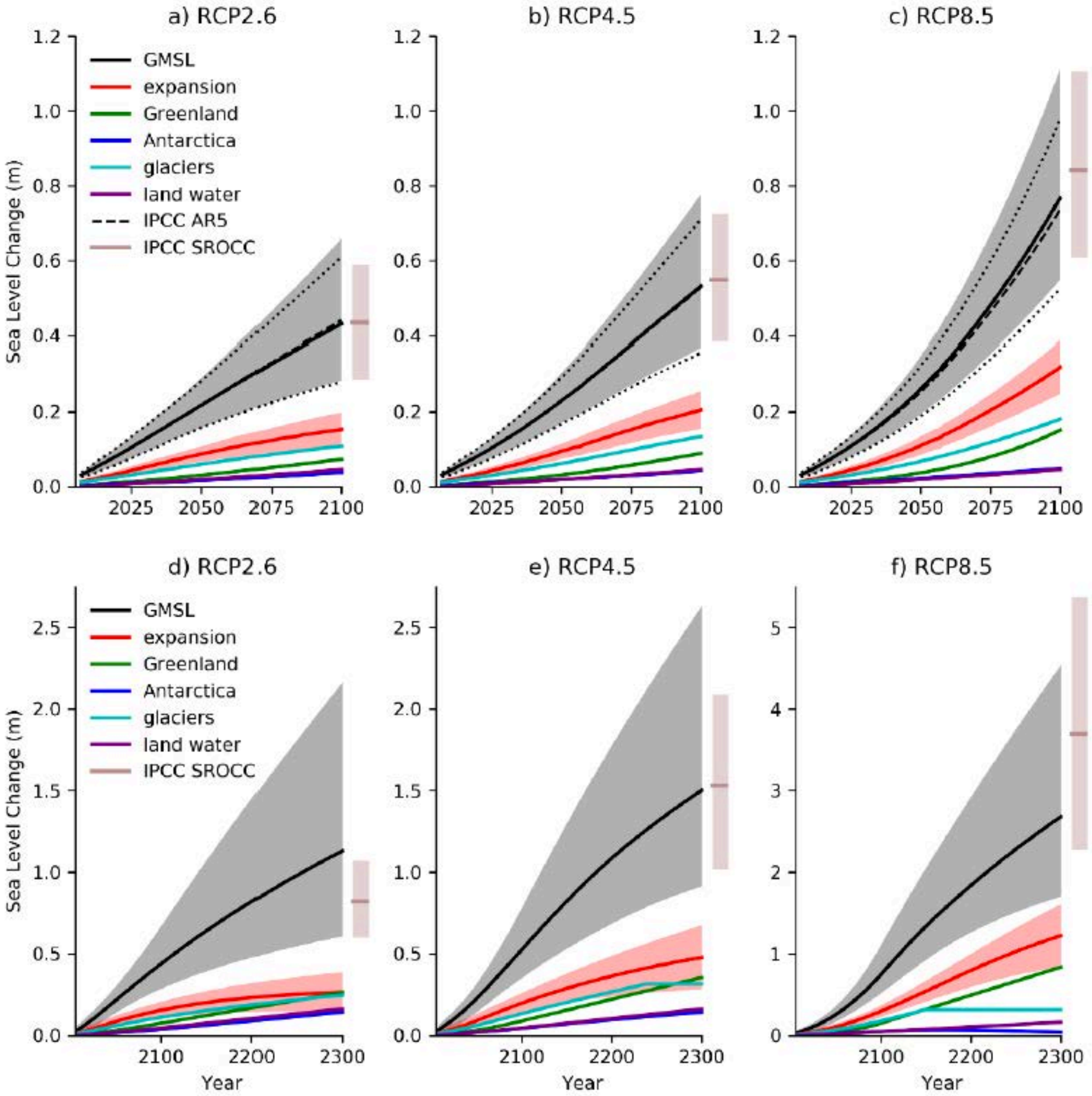
Global glacier loss: 2002-2019

~250 to 350 Gt yr^{-1}



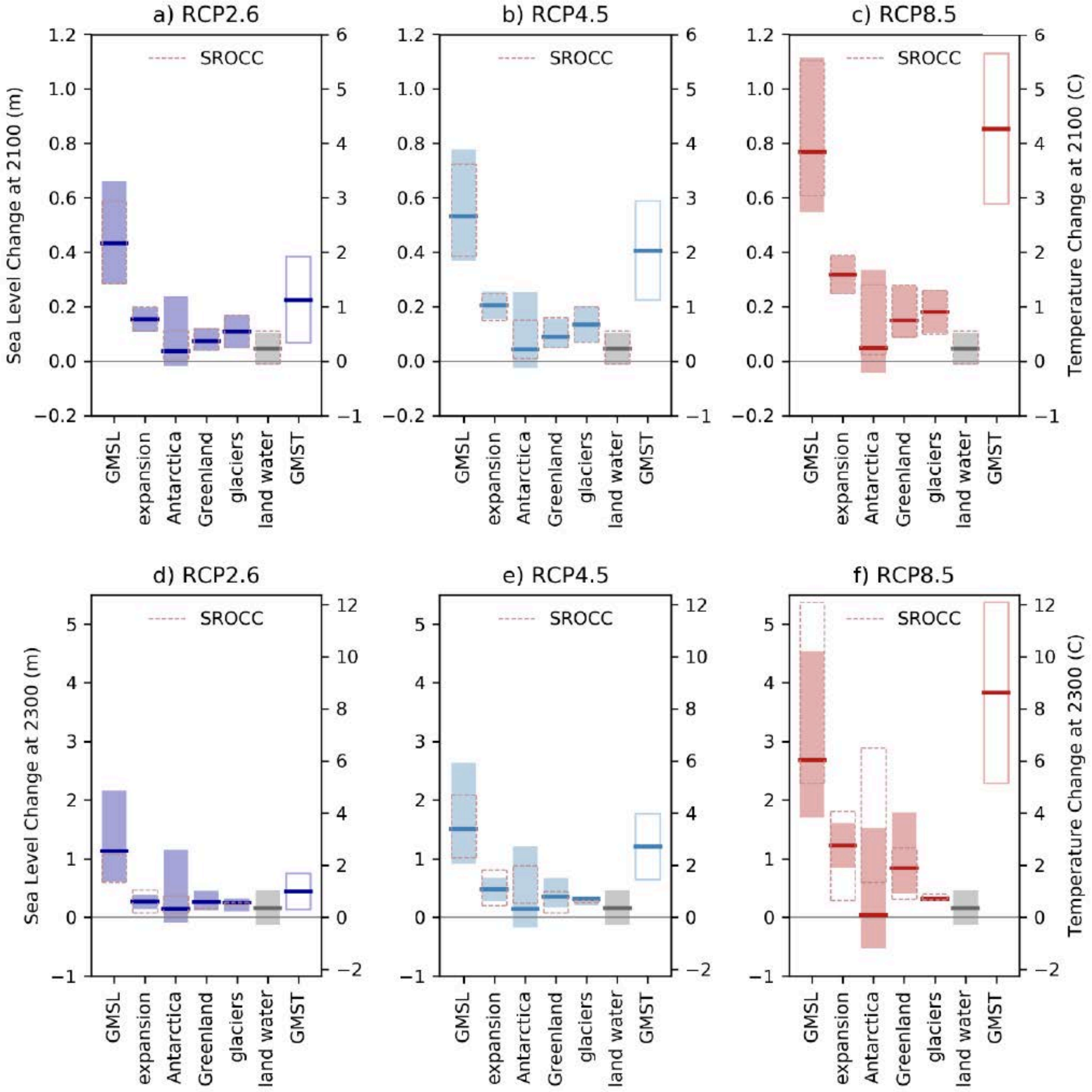
Ciracì et al, 2020
Wouters et al, 2019

How will sea level change, globally and regionally, over the next decade and beyond?



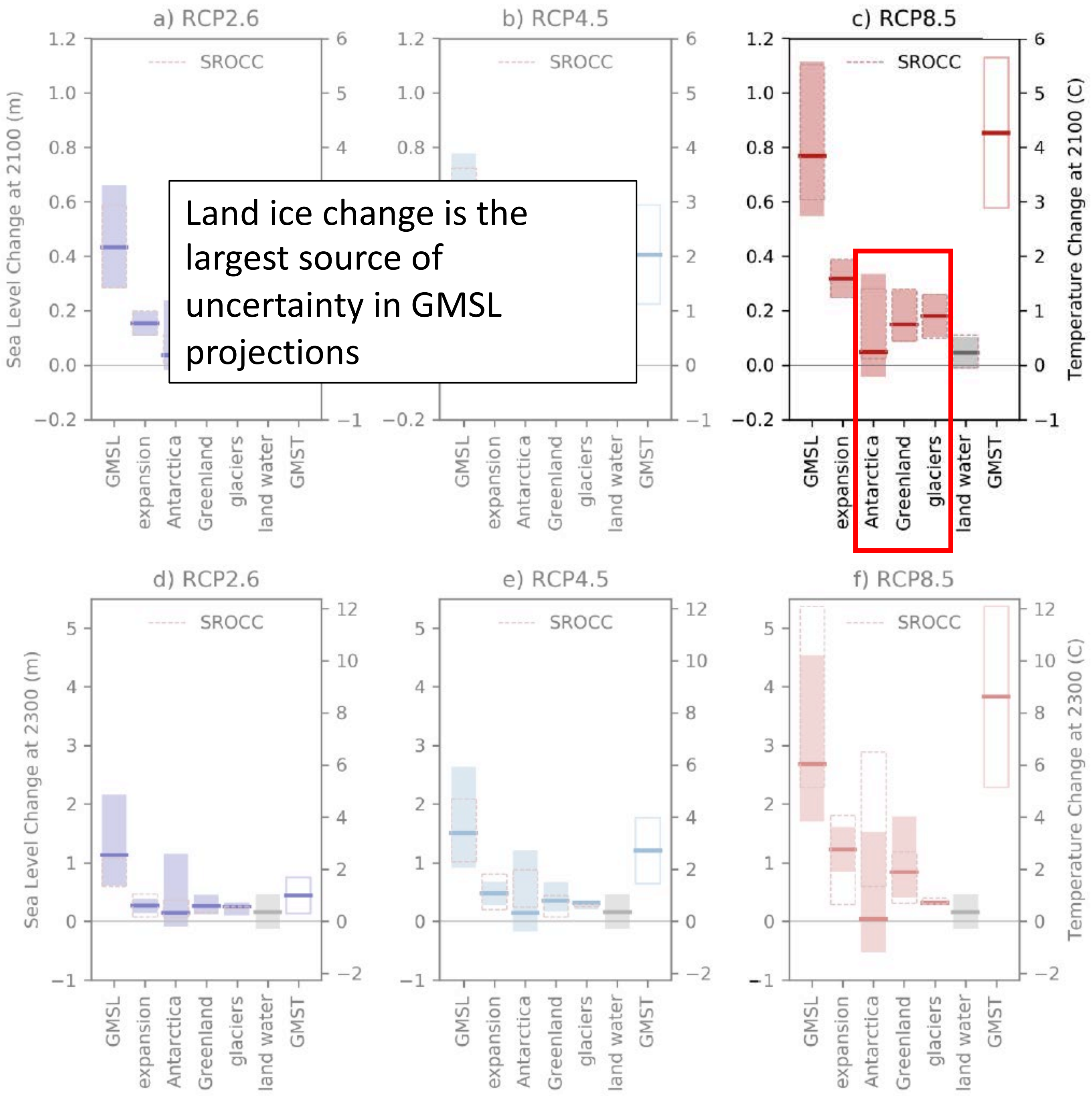
Palmer et al (2020)

Uncertainties in projections



Palmer et al (2020)

Uncertainties in projections



Palmer et al (2020)

What’s needed to make progress ?

- Sea level budget closure is necessary but not sufficient
- Requires advancement in understanding of key time-evolving processes that regulate ice flow, and exchanges of mass and energy at boundaries between ice-and-ocean and ice-and-atmosphere

Alex Gardner, JPL

It’s about improving understanding of key processes

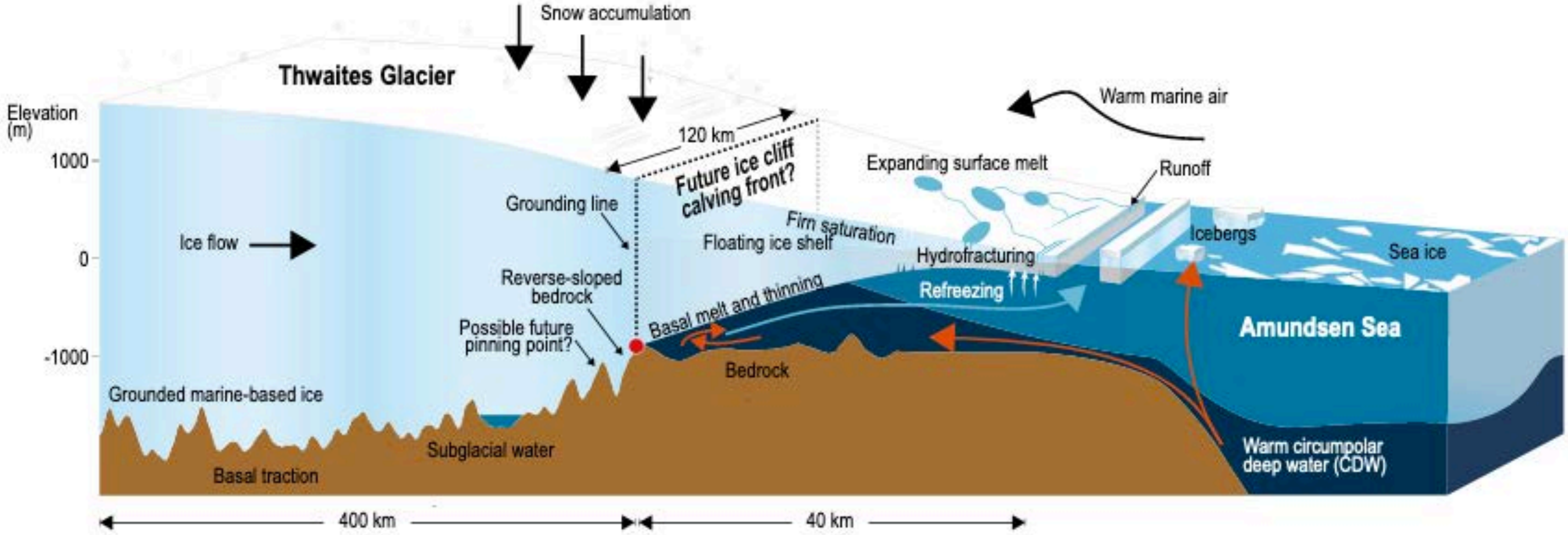


Figure 4.8 | Processes affecting the Thwaites Glacier in the Amundsen Sea sector of Antarctica (adapted from Scambos et al., 2017). The grounding line is currently retreating on reverse-sloped bedrock at a water depth of ~600 m (Joughin et al., 2014; Mouginot et al., 2014). The glacier terminus is ~120 km wide, widens upstream, and is minimally buttressed by a laterally discontinuous ~40 km long ice shelf. The remaining shelf is thinning in response to warm, sub-shelf incursions of circumpolar deep water (CDW), with melt rates up 200 m yr^{-1} near the groundling line in some places (Milillo et al., 2019). The bathymetry upstream of the grounding zone is complex, but it generally slopes downward into a deep basin, up to 2000 m below sea level under the centre of the West Antarctic Ice Sheet (WAIS) (far left), making the glacier vulnerable to marine ice sheet instabilities (Cross-Chapter Box 8 in Chapter 3).

SROCC

Key glacier process that STV can play a role in refining our understanding

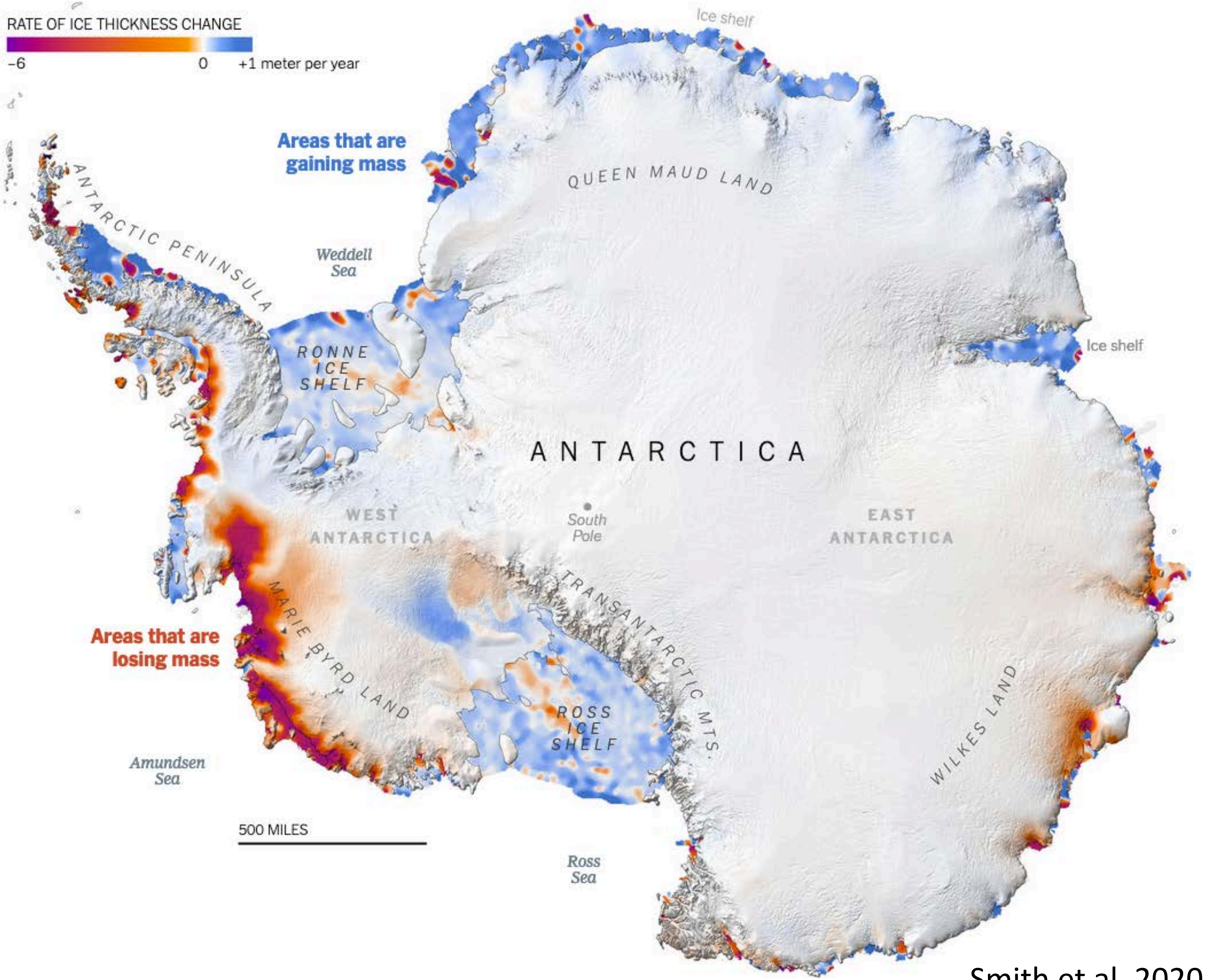
- Glacier sliding
- Surface mass balance
- Ice shelf and glacier calving
- Ice shelf melting by ocean
- Pre-existing ice sheet imbalance
- Grounding zone mechanics
- Shear margin mechanics
- Hydrofracture
- Bedrock topography
- Ice flexure
- Ice fracture
- Basal hydrology

Alex Gardner, JPL

The power of repeat satellite measurements of surface height to reveal process driving glacier change.

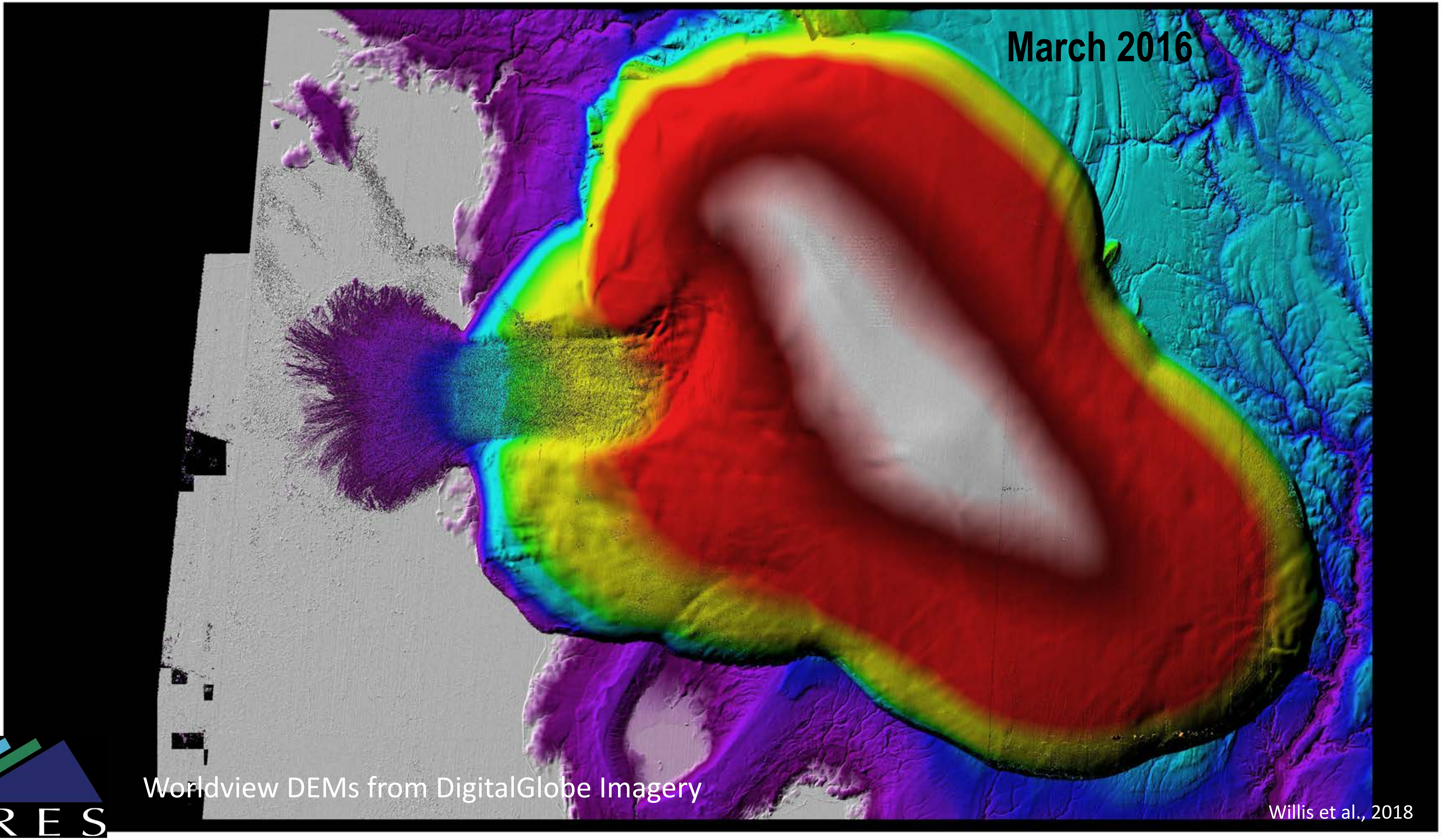
Alex Gardner, JPL

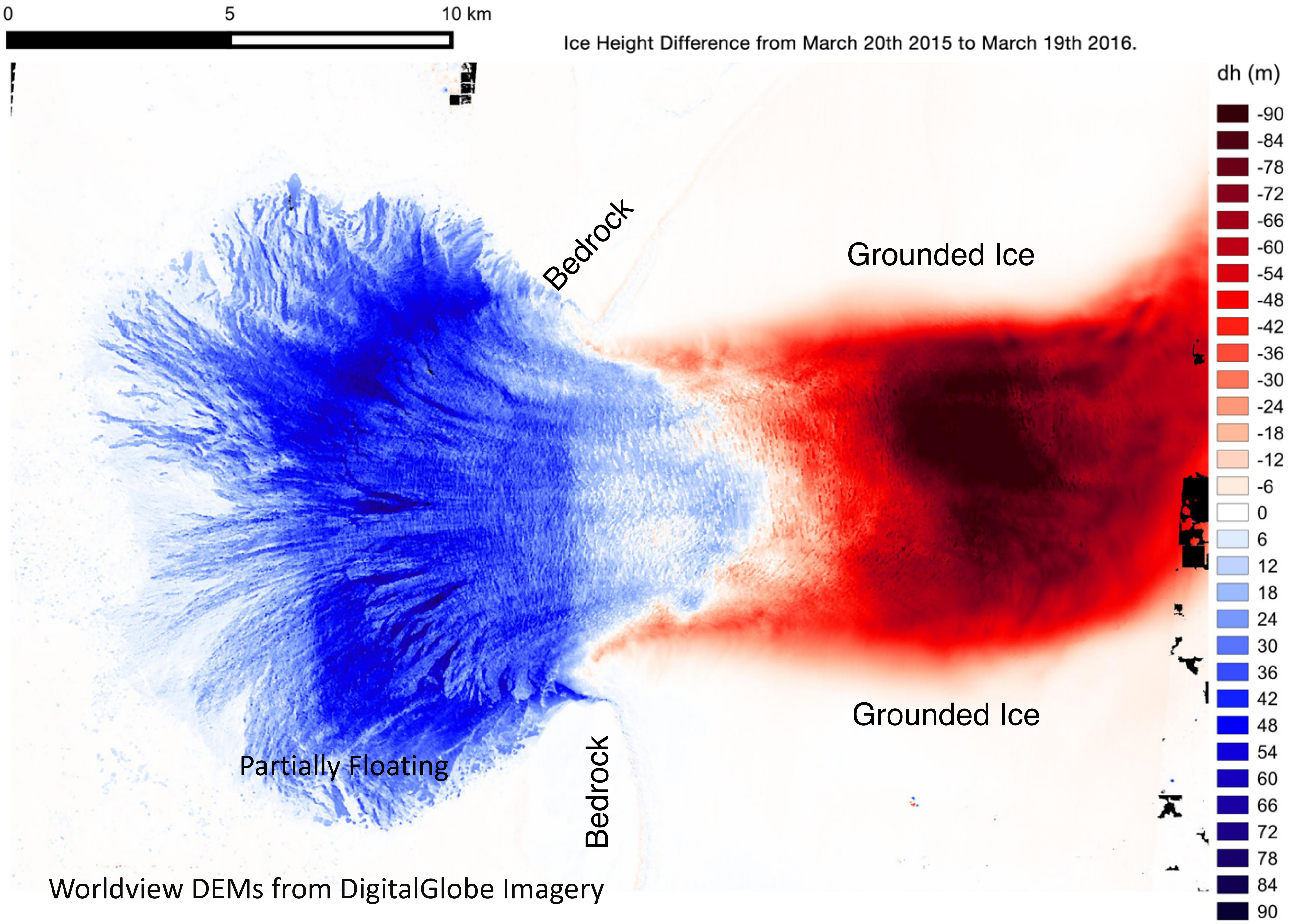
Change in ice sheet topography



Smith et al. 2020

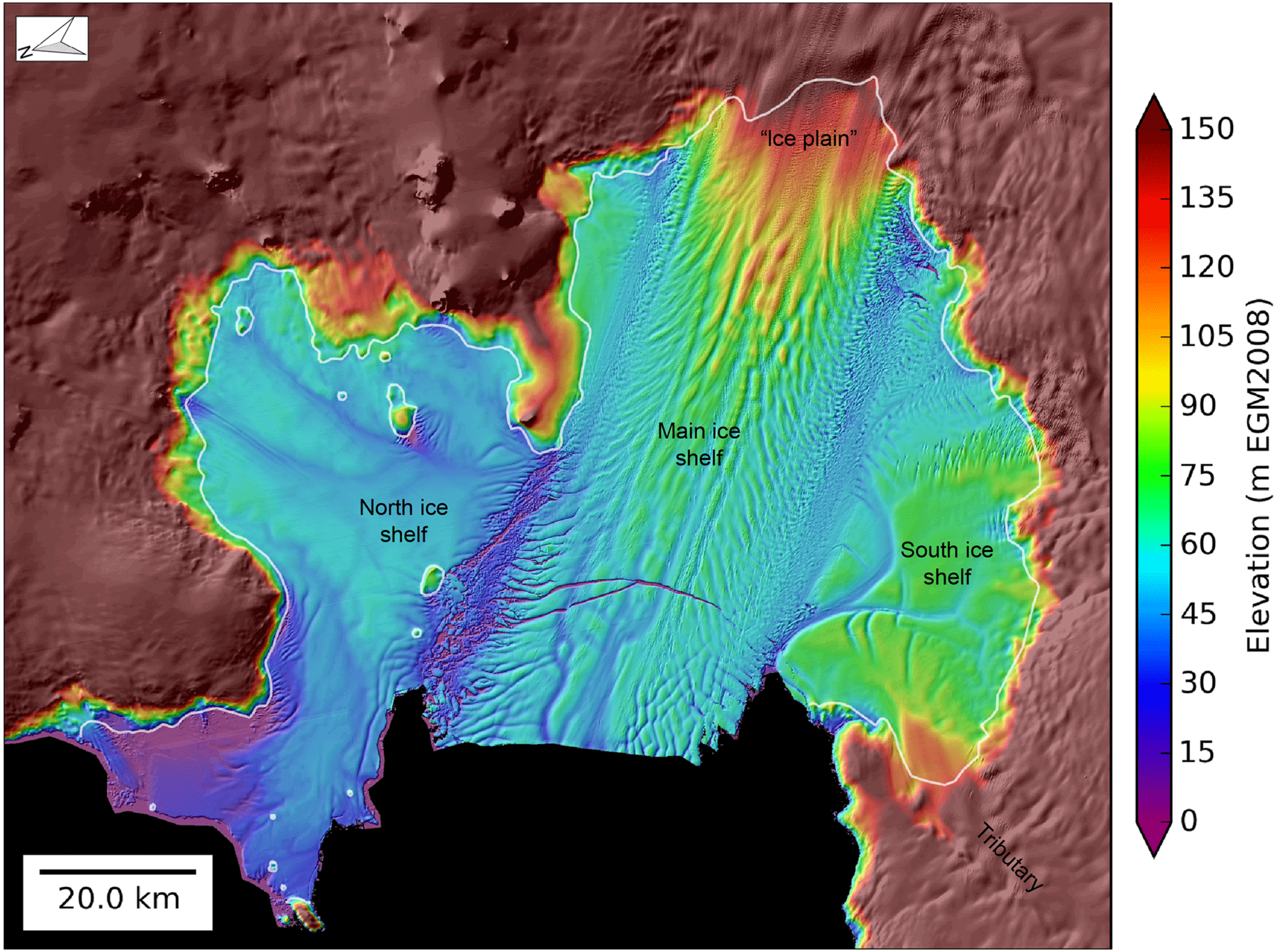
Vavilov Ice Cap





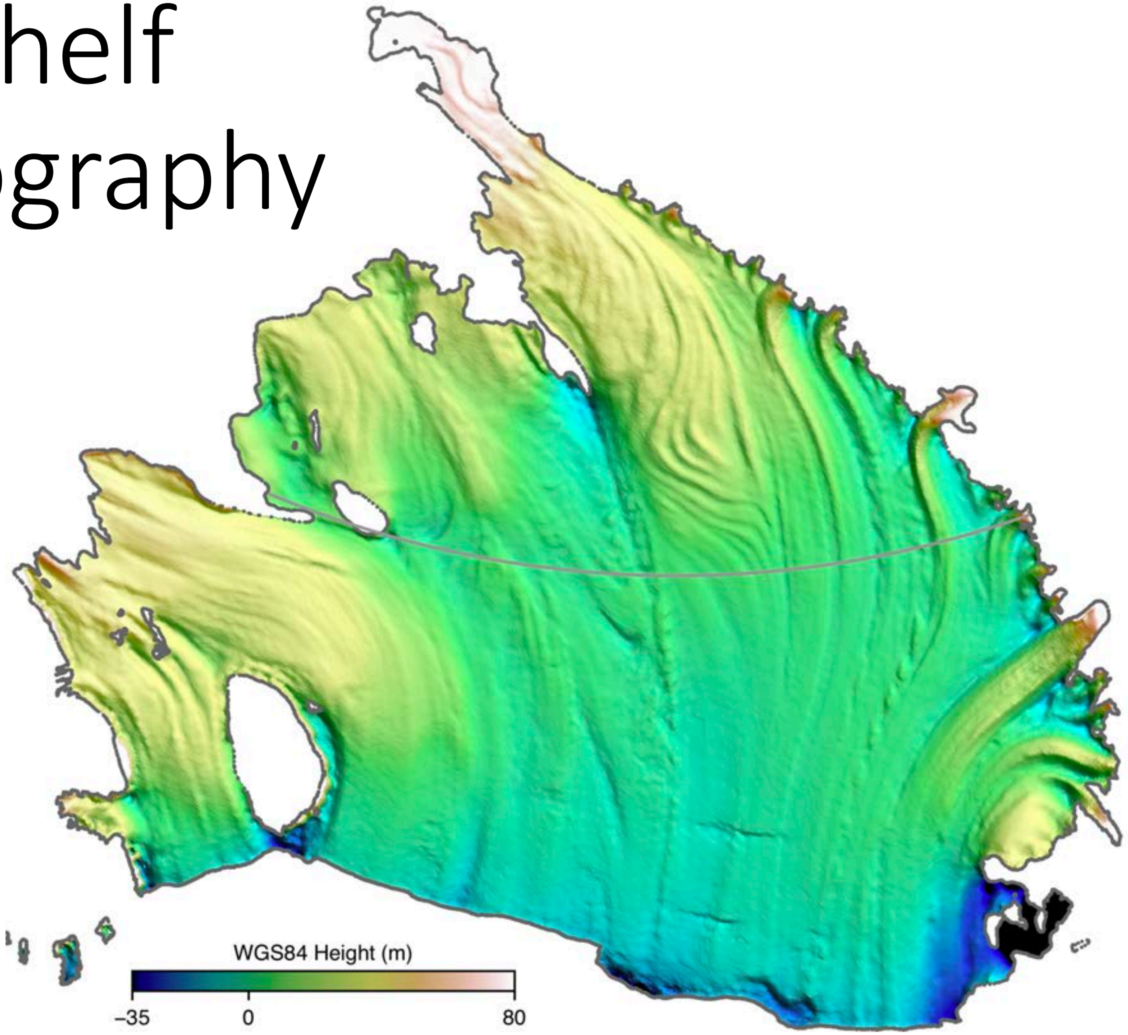
Willis et al., 2018

Ice shelf topography

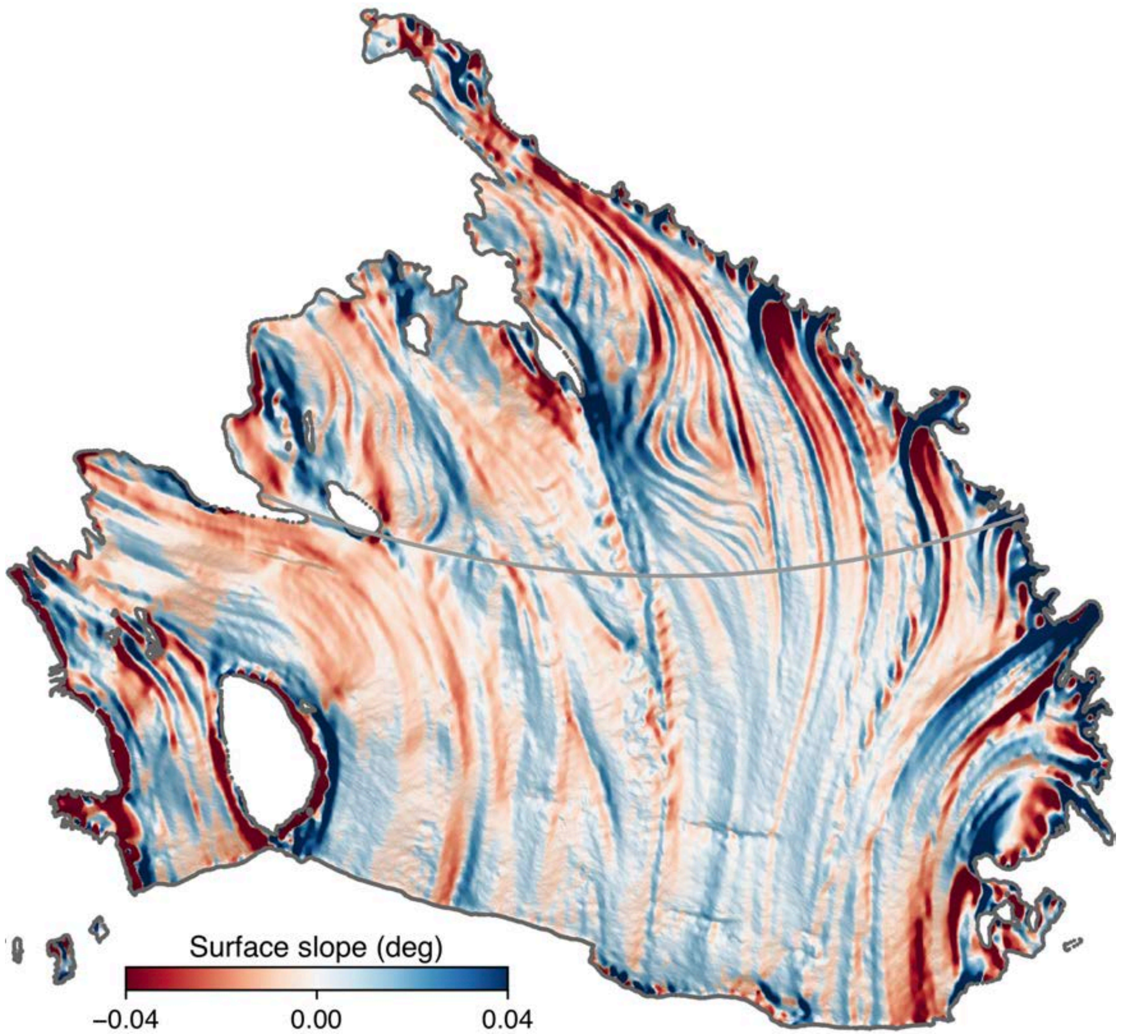


Shean et al., 2019

Ice shelf topography



Thickness

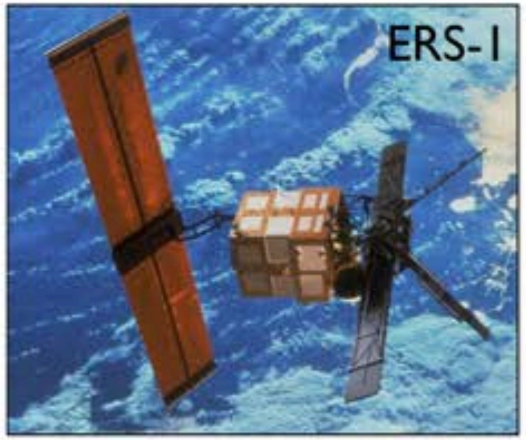


Spatial gradients

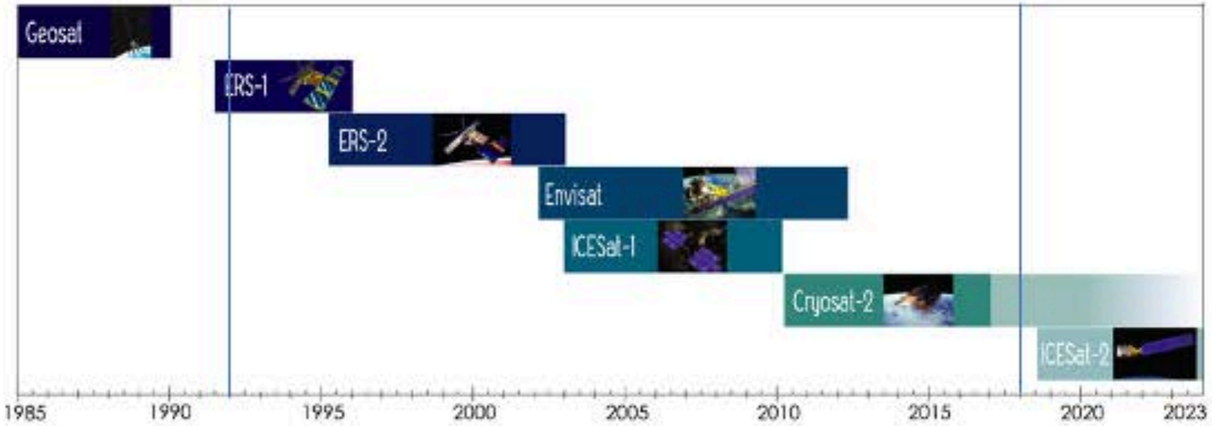
Paolo et al., in prep

Climate record

ESA Radars



NASA Lasers



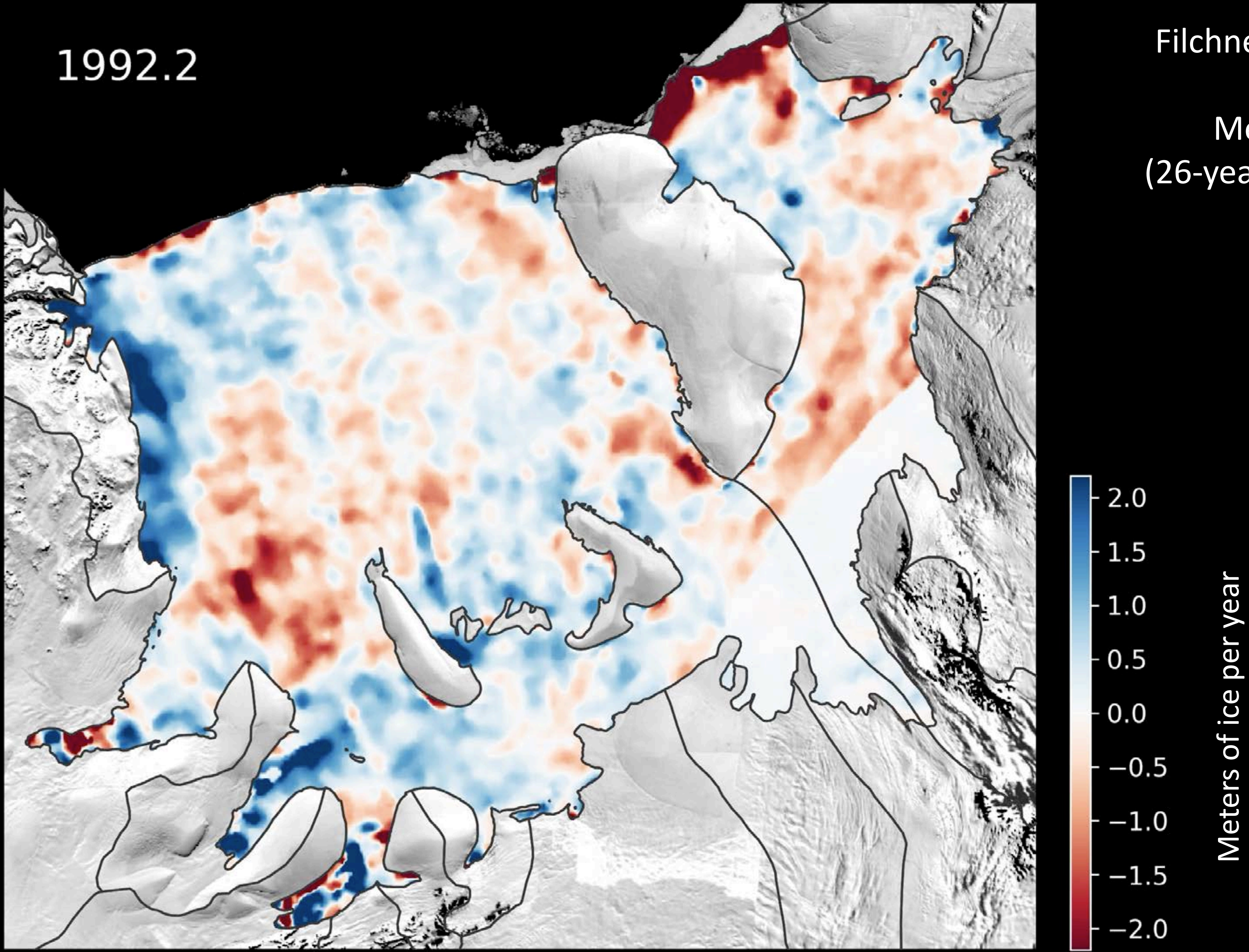
1992 ⟷ 2018

26+ years

Paolo et al., in prep

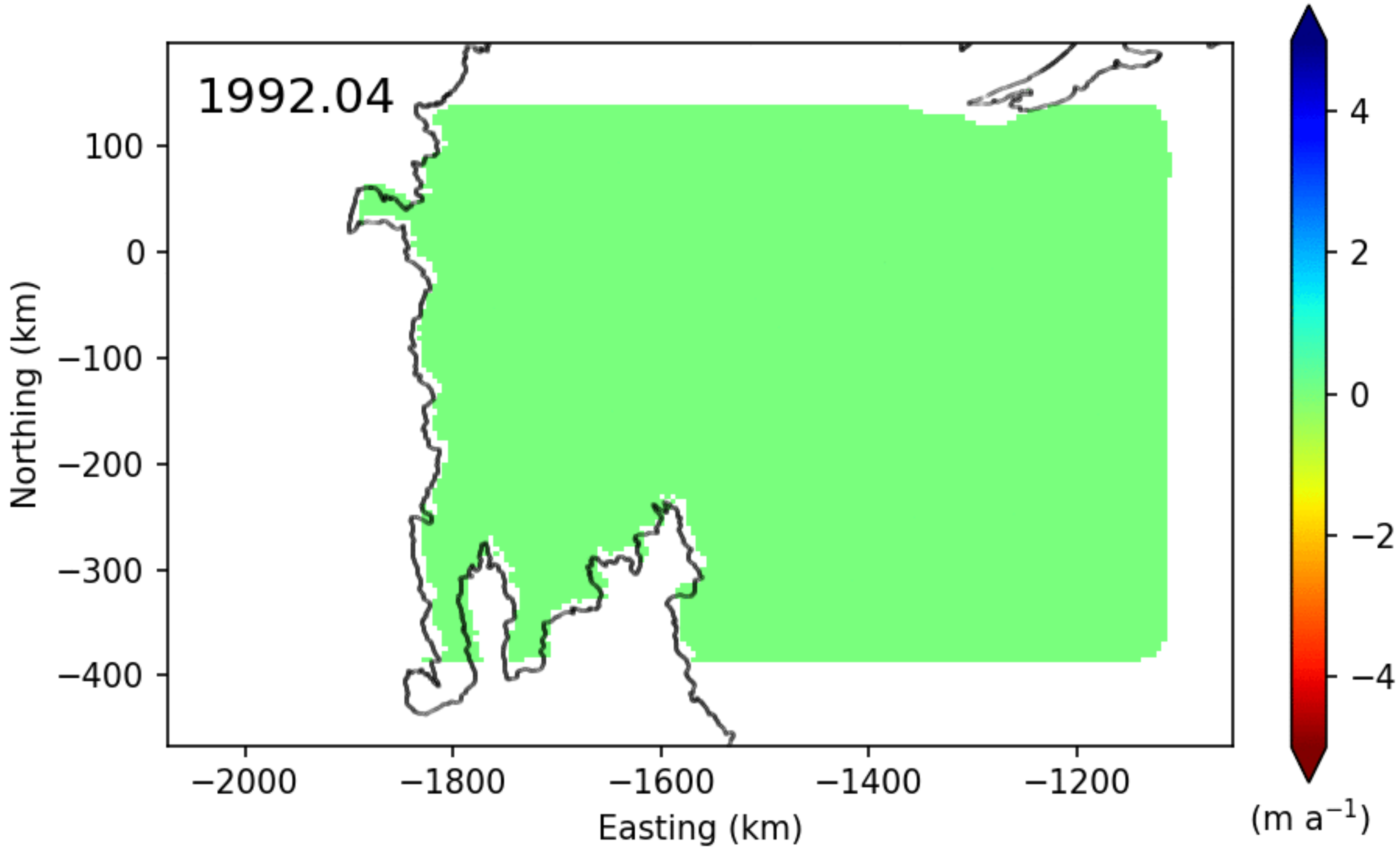
Filchner-Ronne Ice Shelf

Melt rate anomalies
(26-year mean removed)



Paolo et al., in prep

Pine Island catchment



Nilsson et al., in prep

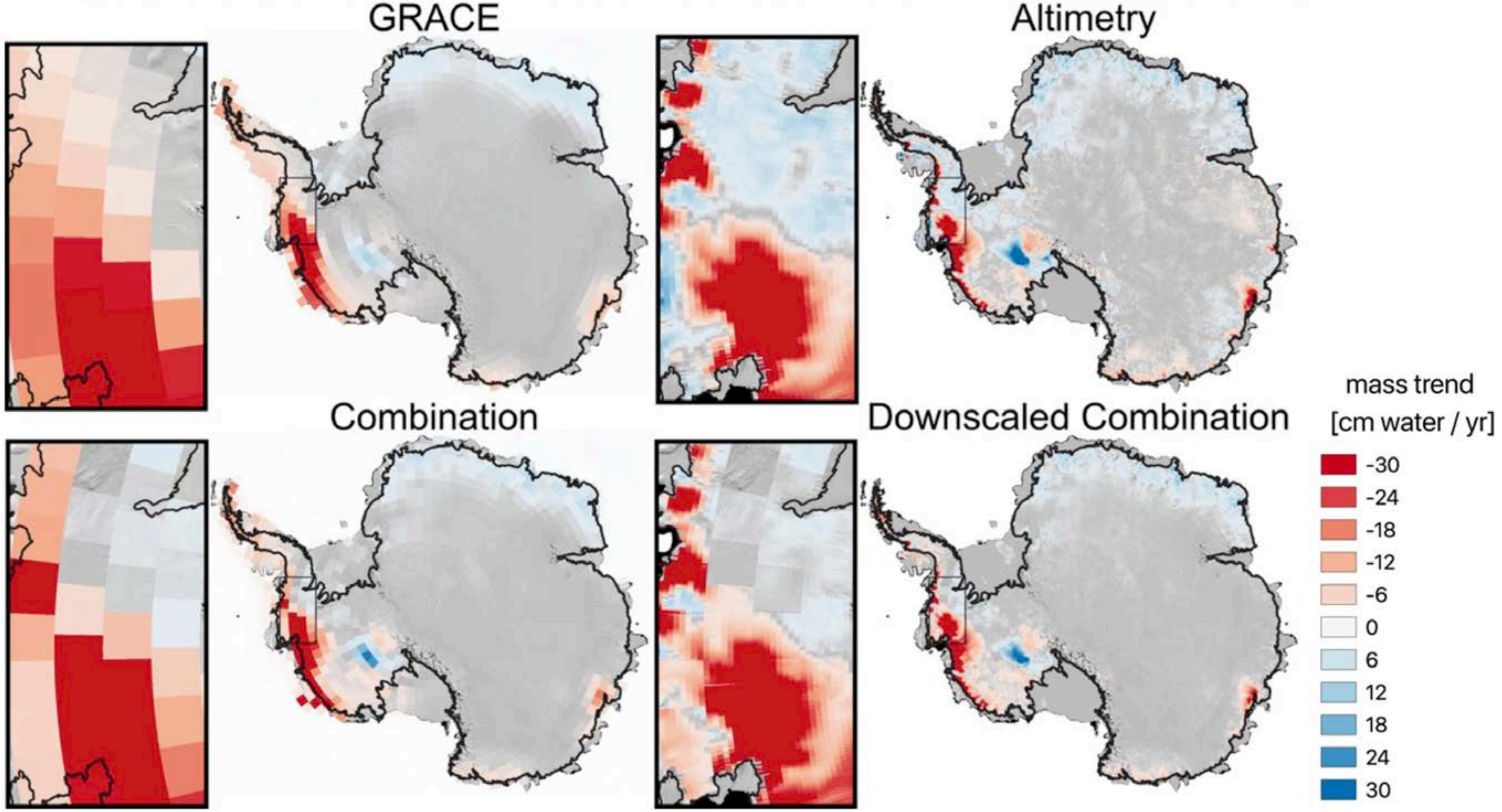
Future of repeat surface elevation measurements from space:

- Data Fusion
- <u>Science</u> driven application of machine learning
- Model inversion

Alex Gardner, JPL

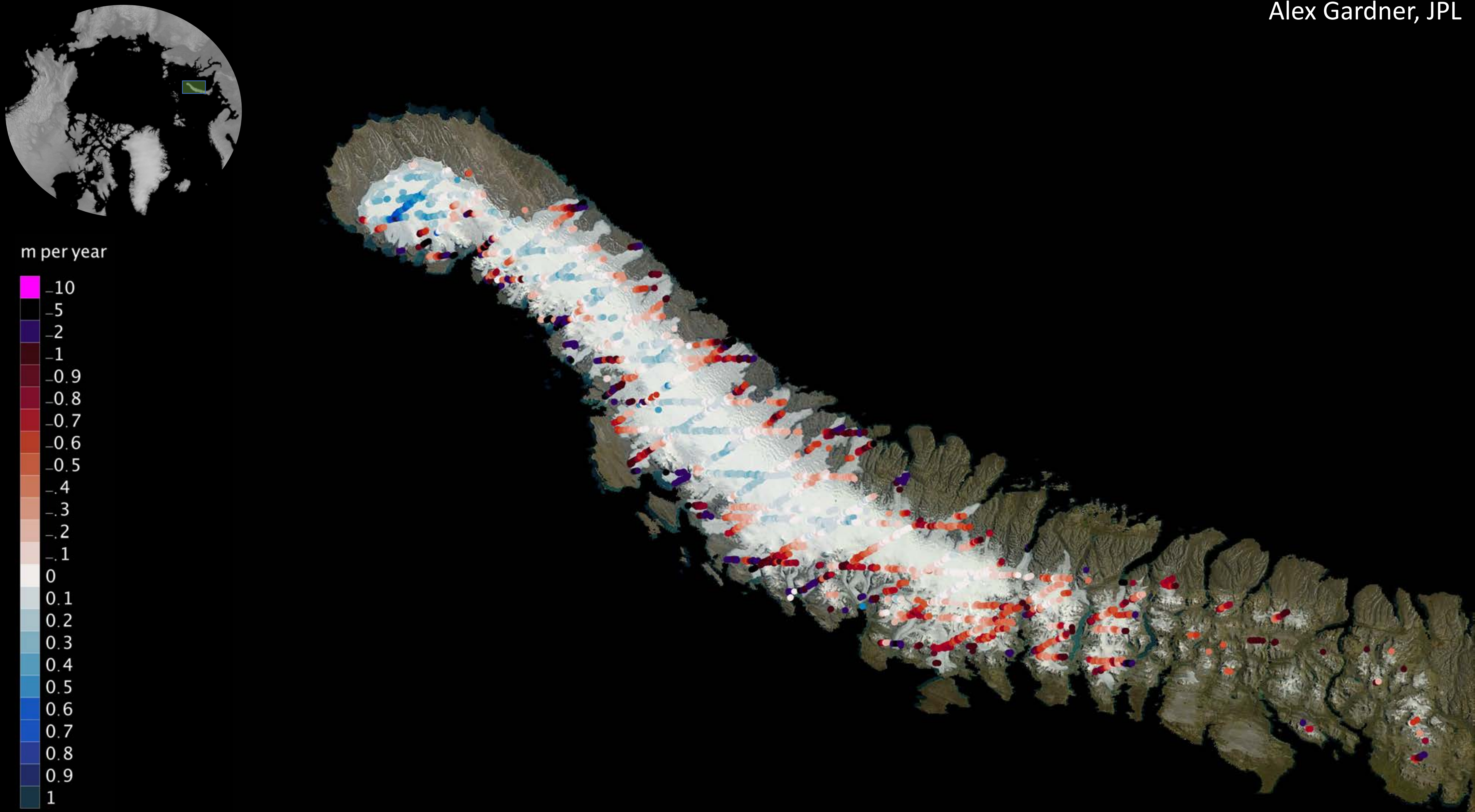
Altimetry-Gravimetry Joint Inversion of Mass Change

David Wiese, Alex Gardner, Nicole-Jeanne Schlegel, Johan Nilsson, Fernando Paolo

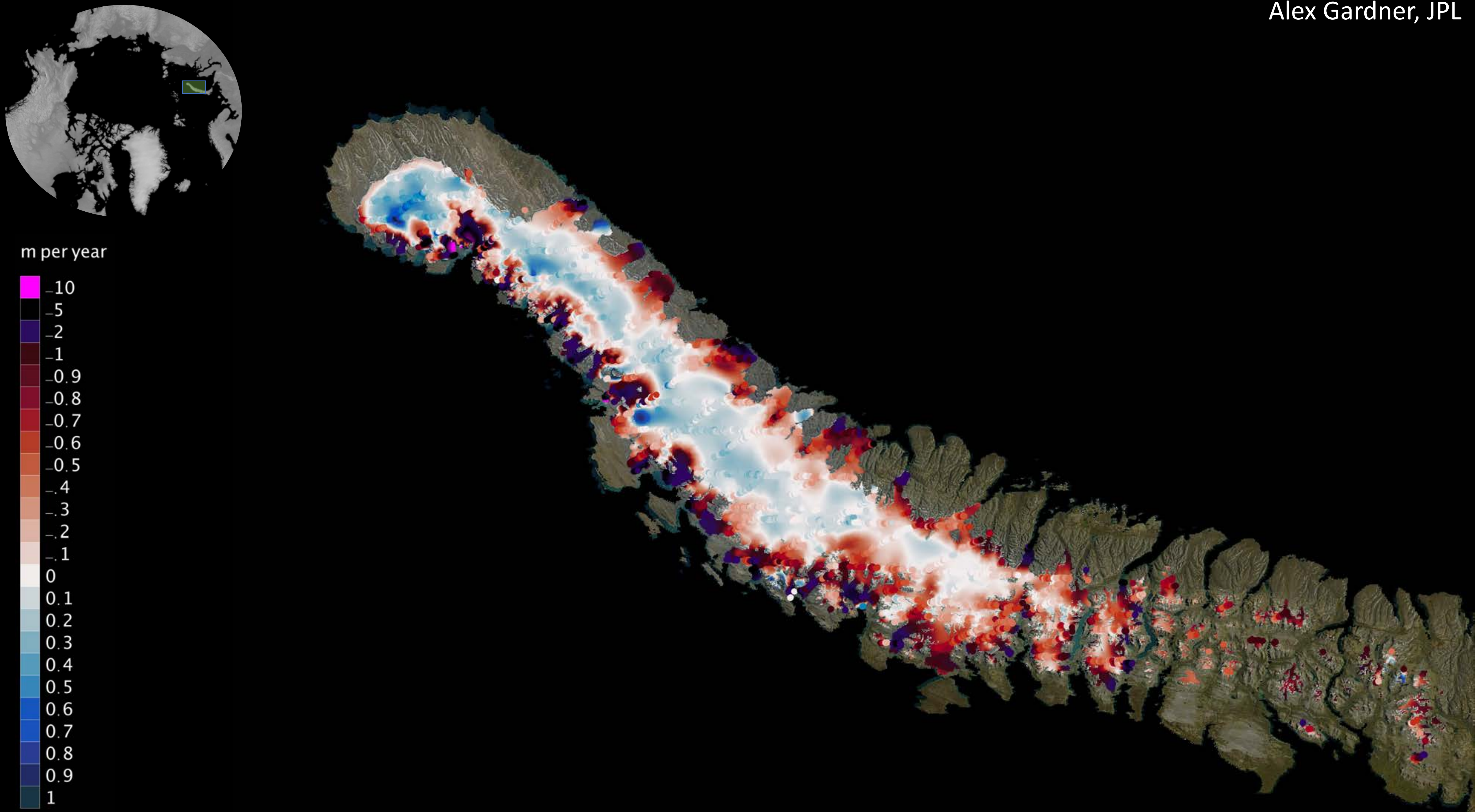


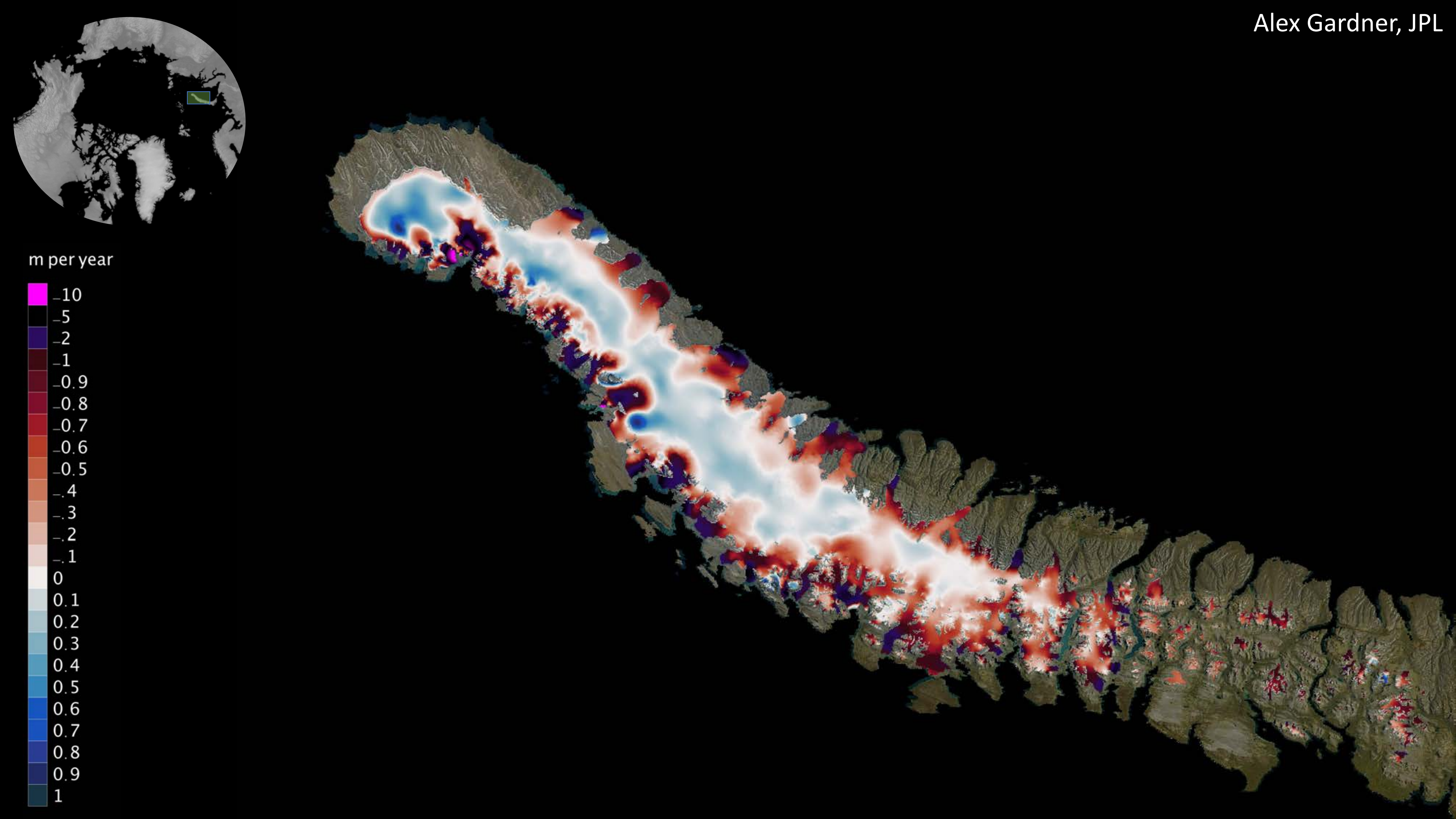
Trend in Antarctic mass from GRACE, Altimetry, joint-inversion, and Downscaled solution [NO FIRN CORRECTION]

Alex Gardner, JPL


m per year
-10
-5
-2
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-.4
-.3
-.2
-.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Alex Gardner, JPL




Alex Gardner, JPL
m per year
-10
-5
-2
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-.4
-.3
-.2
-.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Utilizing timeseries to invert for ice properties

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Earth Surface

RESEARCH ARTICLE

10.1002/2016JF003971

Key Points:
- Remotely sensed data capture the spatiotemporal surface velocity response of an ice stream and ice shelf to forcing by ocean tides
- Velocities are modulated nearly 100 km upstream of the grounding zone at the spring-neap tidal period
- Periodic grounding of the ice shelf causes local stress changes that can propagate far upstream due to

Tidally induced variations in vertical and horizontal motion on Rutford Ice Stream, West Antarctica, inferred from remotely sensed observations

B. M. Minchew[1,2], M. Simons[1], B. Riel[1], and P. Milillo[3,4]

[1]Seismological Laboratory, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA, [2]Now at British Antarctic Survey, Cambridge, UK, [3]School of Engineering, University of Basilicata, Potenza, Italy, [4]Now at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

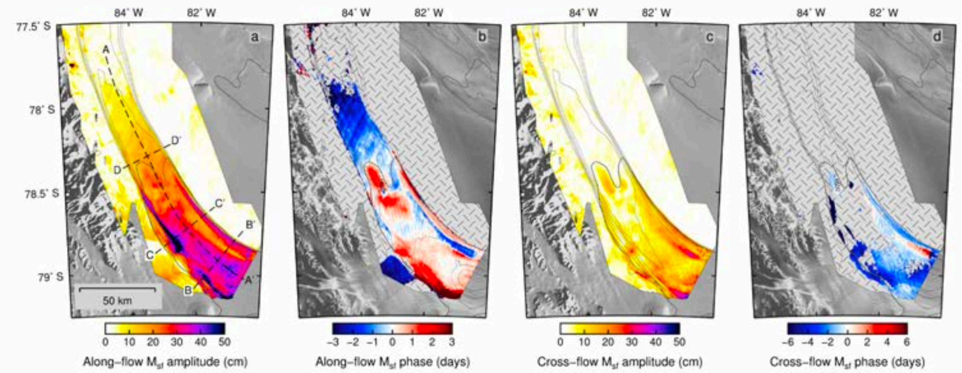


Figure 8. Time-dependent along-flow and cross-flow horizontal velocity components for the M_{sf} (14.77 day) tidal period (Figures 8a–8d). (a) Along-flow amplitude with contour lines showing horizontal secular speed in 0.2 m/d increments. (b) Along-flow phase relative to the median along-flow M_{sf} phase over the ice shelf. Contour lines are bathymetry below −1200 m from Bedmap2 in 200 m increments. Areas with small amplitude and horizontal secular velocity are crosshatched for clarity. (c–d) Same as Figures 8a and 8b but for cross-flow variability. Phase values in Figure 8d are referenced to the median along-flow M_{sf} phase over the ice shelf as in Figure 8b. Grounding lines are the same as in Figure 1.

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL082526

Key Points:
- The recent behavior of Pine Island Glacier is reproduced best with regularized Coulomb friction, which works for both hard and soft beds
- Different representations of effective pressure in similar regularized Coulomb friction laws can produce vastly different behavior
- Relative to many commonly used friction laws, Coulomb friction laws have the potential to improve projections of future sea-level rise

Regularized Coulomb Friction Laws for Ice Sheet Sliding: Application to Pine Island Glacier, Antarctica

Ian Joughin[1], Benjamin E. Smith[1], and Christian G. Schoof[2]

[1]Polar Science Center, Applied Physics Lab, University of Washington, Seattle, WA, USA, [2]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, British Columbia, Canada

Abstract The choice of the best basal friction law to use in ice-sheet models remains a source of uncertainty in projections of sea level. The parameters in commonly used friction laws can produce a broad range of behavior and are poorly constrained. Here we use a time series of elevation and speed data to examine the simulated transient response of Pine Island Glacier, Antarctica, to a loss of basal traction as its grounding line retreats. We evaluate a variety of friction laws, which produces a diversity of

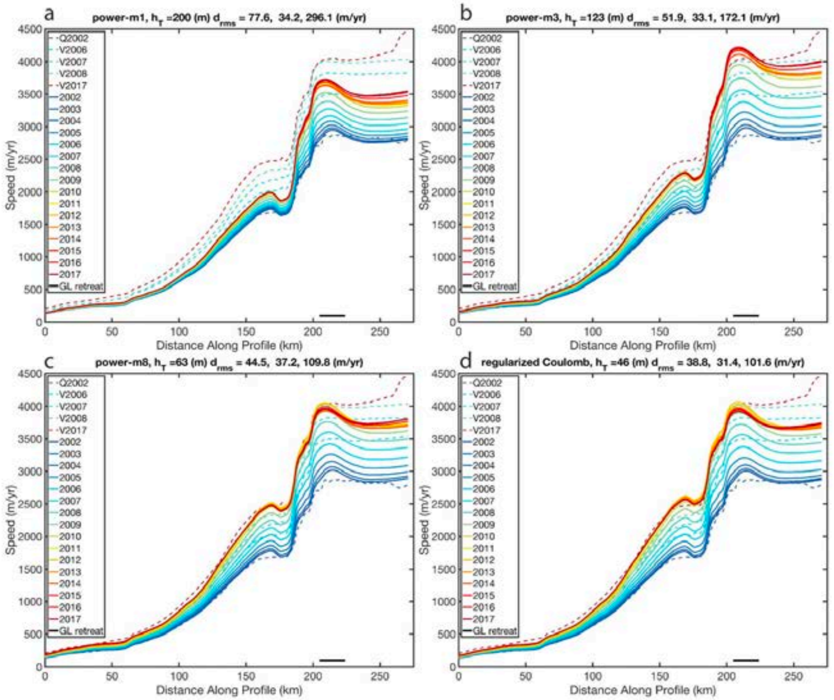


Figure 3. Modeled response to ungrounding from 2002 to 2017 for various friction laws. Results with (a) $m = 1$ and $h_T = 140$, (b) $m = 3$ and $h_T = 75$, (c) $m = 8$ and $h_T = 43$, and (d) regularized Coulomb friction with $m = 3$, $u_o = 300$ m/year, and $h_T = 30$ along the profile shown in Figure 2. Observed velocities (V2006, V2007, V2008, and V2017) as well quasi 2002 (Q2002) velocity are also shown. Each panel includes the model and data differences for 2017, d_{rms} = avg

JPL

Ice sheets are predictable but progress in understanding needs to accelerate at a rate faster than the ice sheets themselves !!!

Alex Gardner, JPL

"I contend that a major disaster—a rapid 5-meter rise in sea level caused by deglaciation of West Antarctica—may be imminent or in progress after atmospheric CO2 content has only doubled" Mercer, 1978. Nature

Fig. 3 *a*, Antarctic ice cover today, and *b*, after a 5–10 °C warming.

Mercer, 1978

It is our job to articulate the next generation of surface topography measurement needs that will lead to rapid advances in our understanding of land ice processes that are necessary to refine projections of sea level chnage

Alex Gardner, JPL

Land Ice measurement needs

Can be broken down into four target surfaces:

1. Fast Moving portions of Ice Sheets and Ice Caps
2. Slow Moving portions of Ice Sheets and Ice Caps
3. Ice Shelves
4. Mountain glaciers

Alex Gardner, JPL

Measurement needs

For each surface we need to define

1. Spatial scales
2. Temporal repeat
3. Measurement accuracy and precision

Also need to think about **applications** needs

- Sea ice mapping and classification
- Ice bergs
- May have unique latency and rapid response requirements

Alex Gardner, JPL

Altimetry and ice-covered Polar oceans

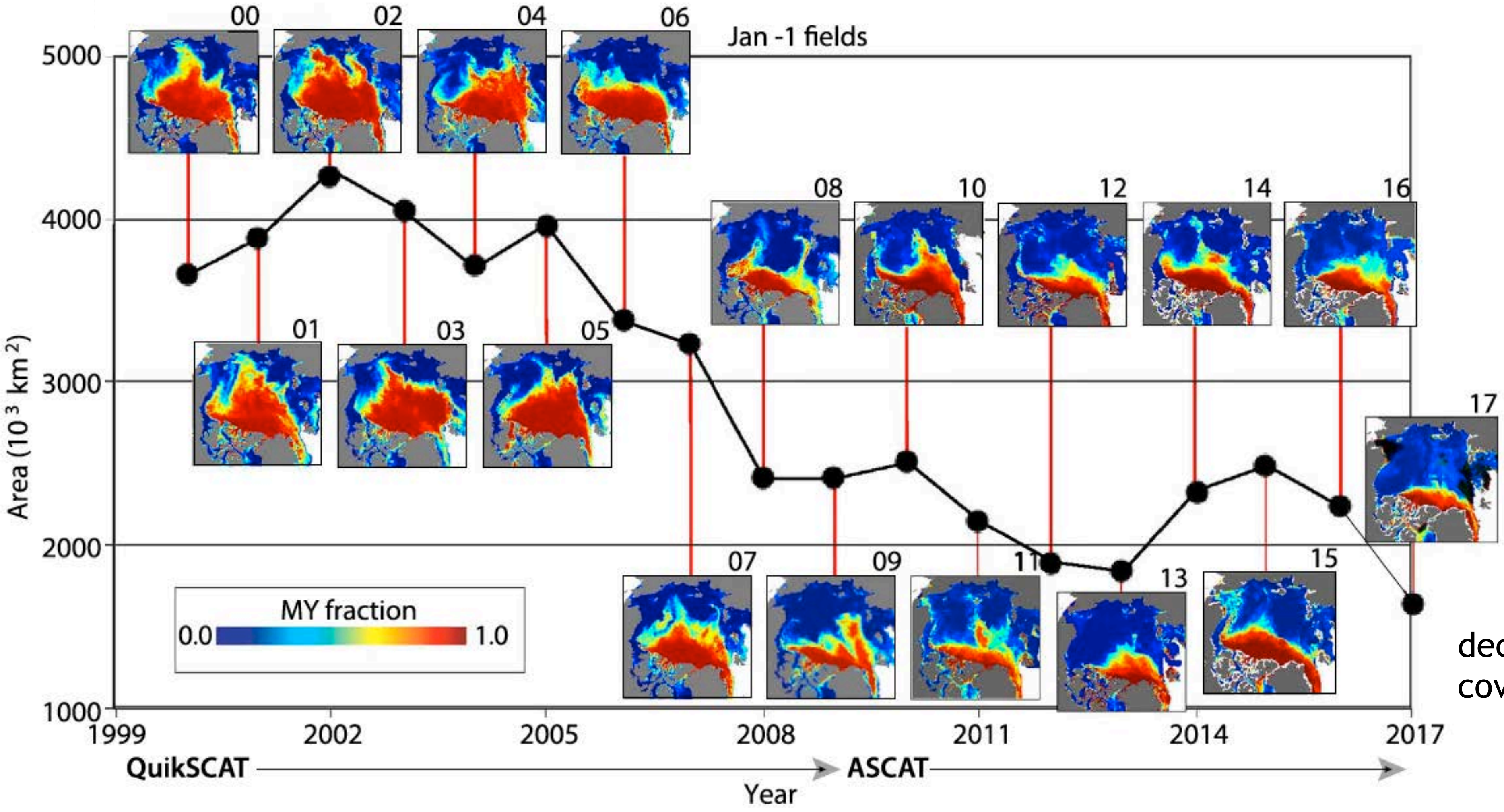
Ron Kwok
Polar Science Center
Applied Physics Laboratory
University of Washington
Seattle, WA

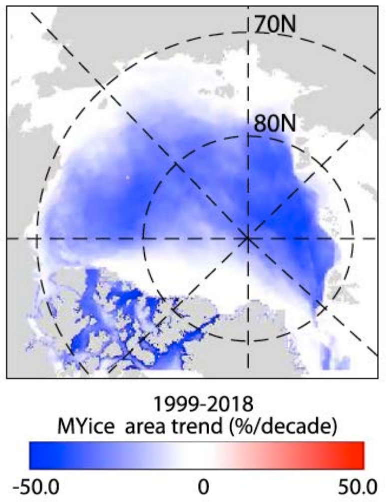
AIR • SEA • ICE
Polar Science Center
Applied Physics Laboratory · University of Washington

Topics

- Arctic Ocean ice thickness record (1960s – present)
- Sea ice freeboard, thickness, roughness
- Dynamic topography of the ice-covered oceans

Decline in multiyear sea ice coverage: 1999-2017



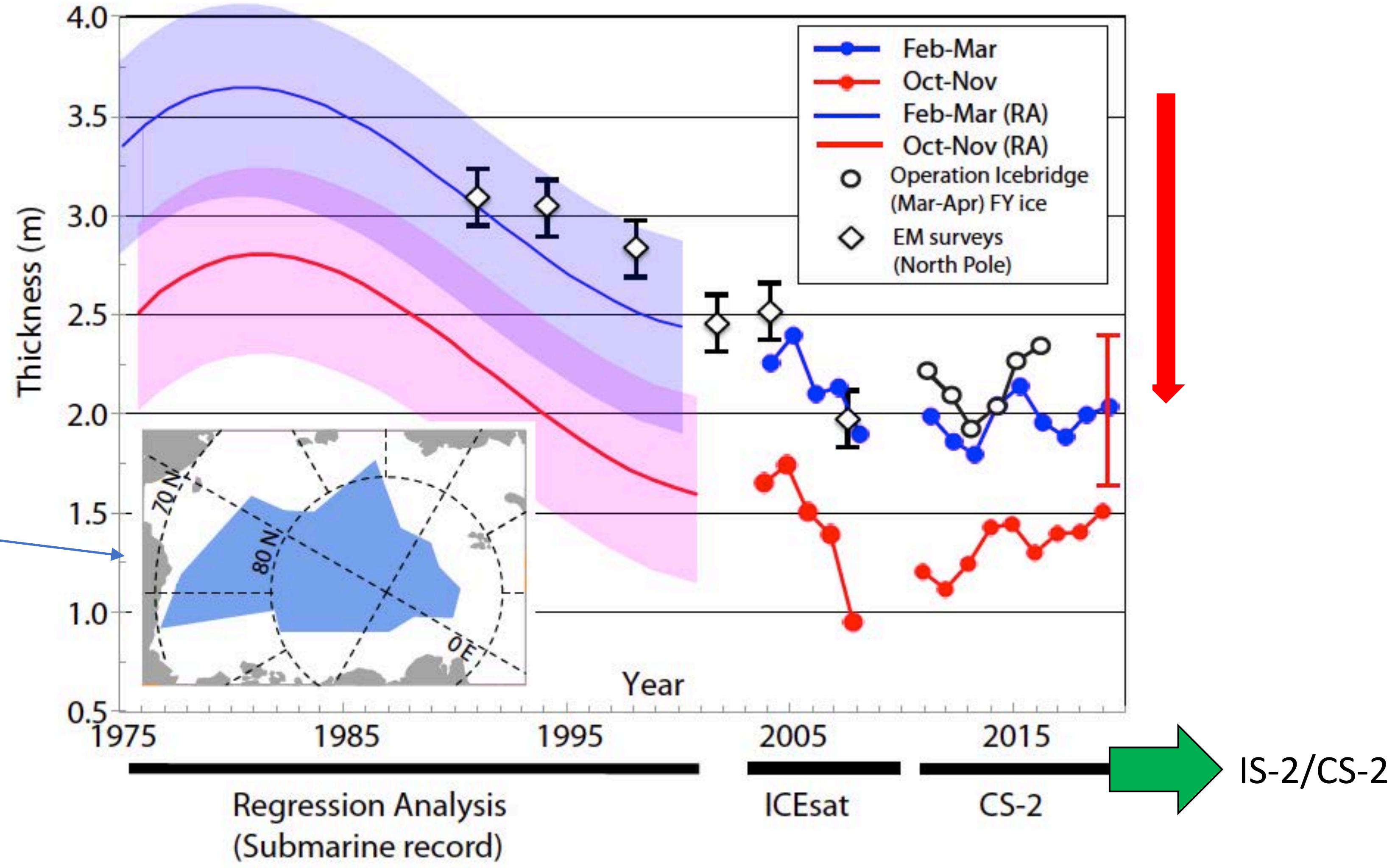


decrease of >50%
covering 1/3 of Arctic Basin

Polyakov et al. 2012, Kwok, 2018

Decline in sea ice thickness (Central Arctic Ocean): (Submarine, AEM, CS-2, Operation IceBridge, and ICESat)

Note:
Ice thickness is within this polygon



CryoSat-2 altimetry data are from ESA' s data portal (URL: https://earth.esa.int)

Decline in Arctic sea ice volume
Satellite era

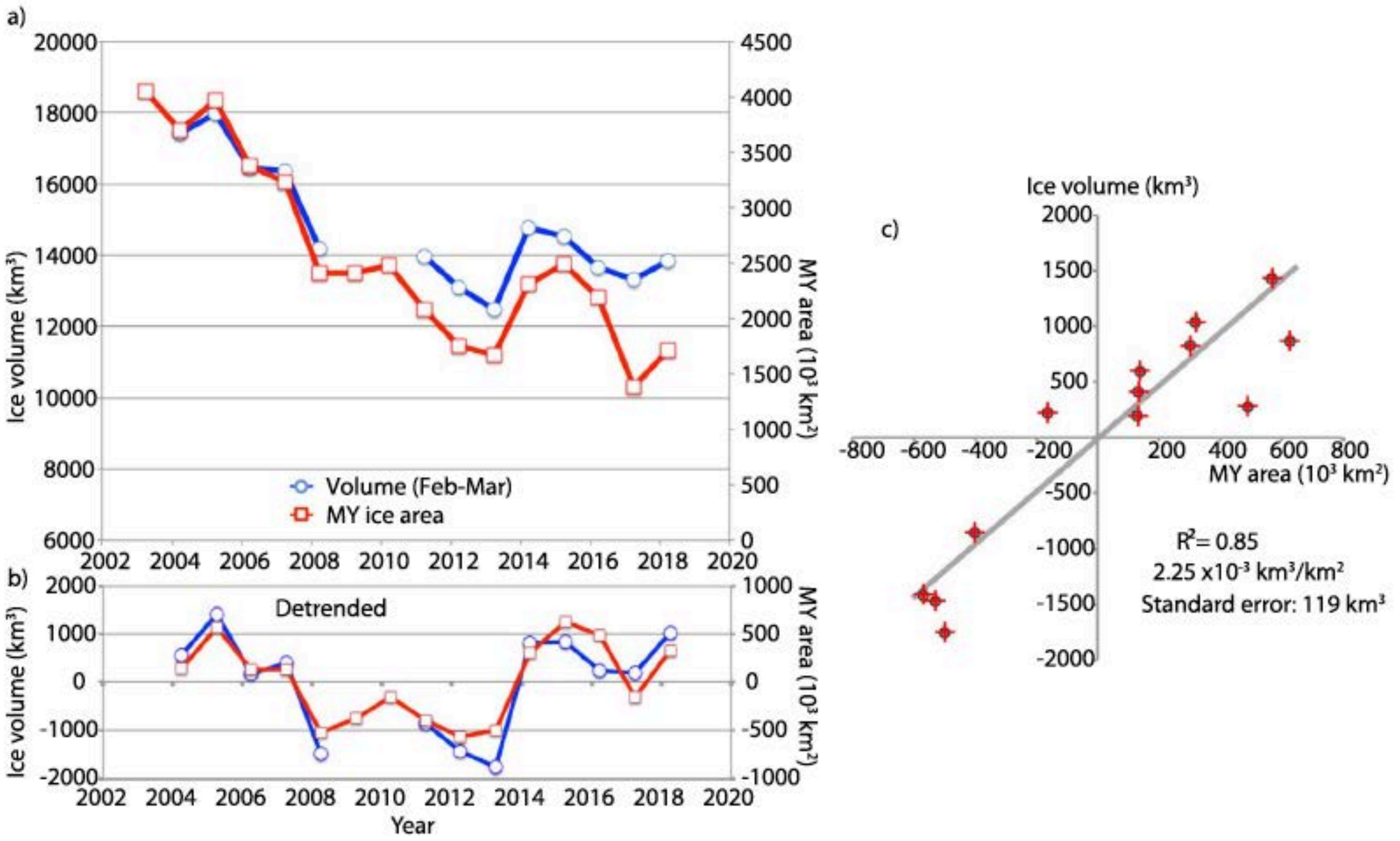
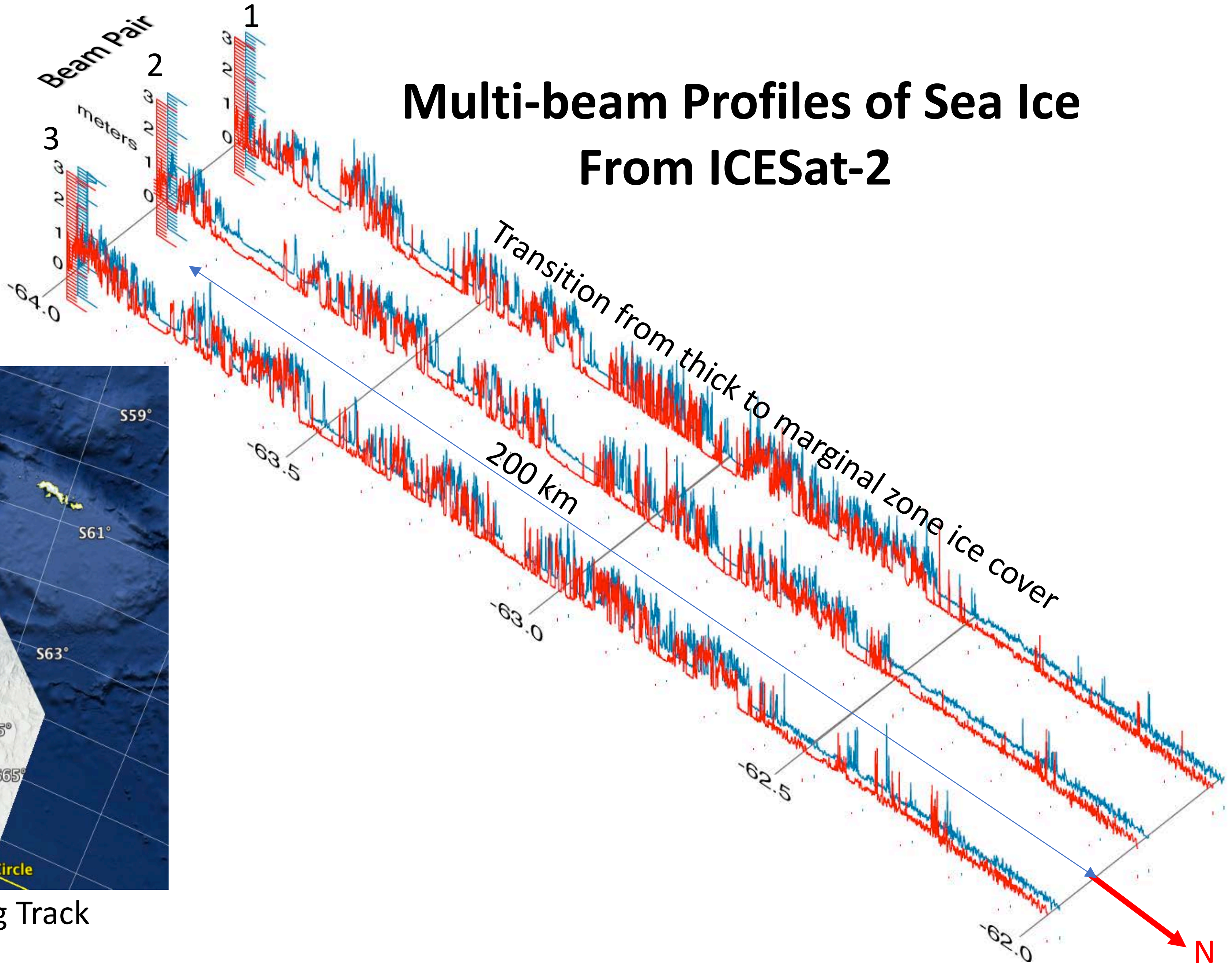
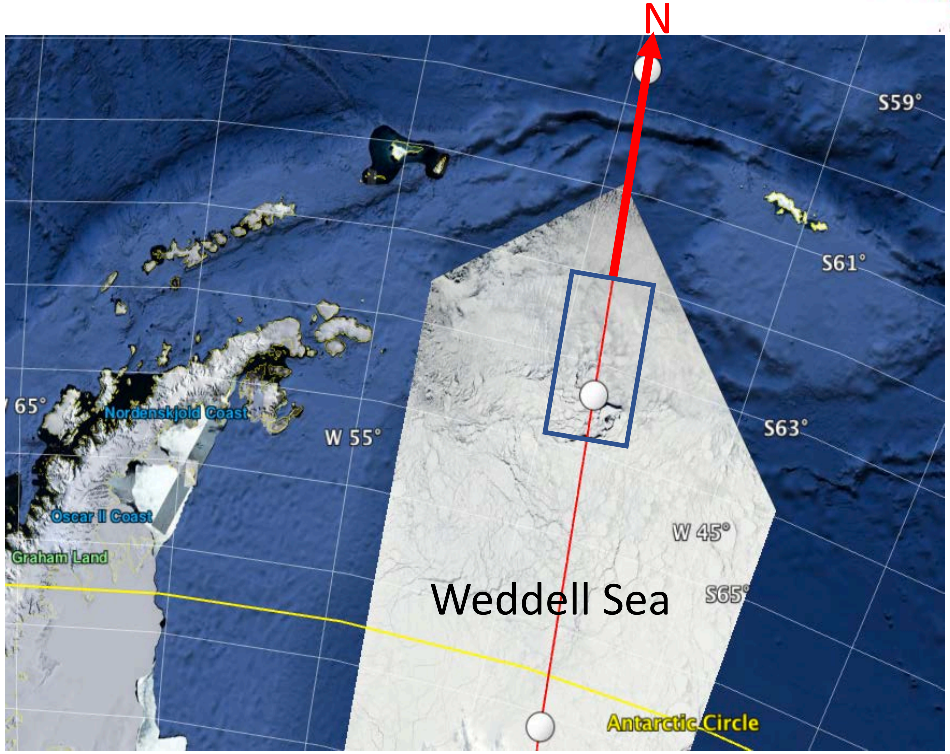


Figure 5. Coupled variability of Arctic Ocean sea ice volume and multiyear sea ice (MYI) coverage. (a) Time-varying sea ice volume (from figure 3) and MYI coverage (from figure 4) in winter (2003–2018). (b) Detrended time series of (a). (c) Scatterplot of detrended ice volume and MYI coverage.

Multi-beam Profiles of Sea Ice From ICESat-2





October 17, 2018 – Ascending Track

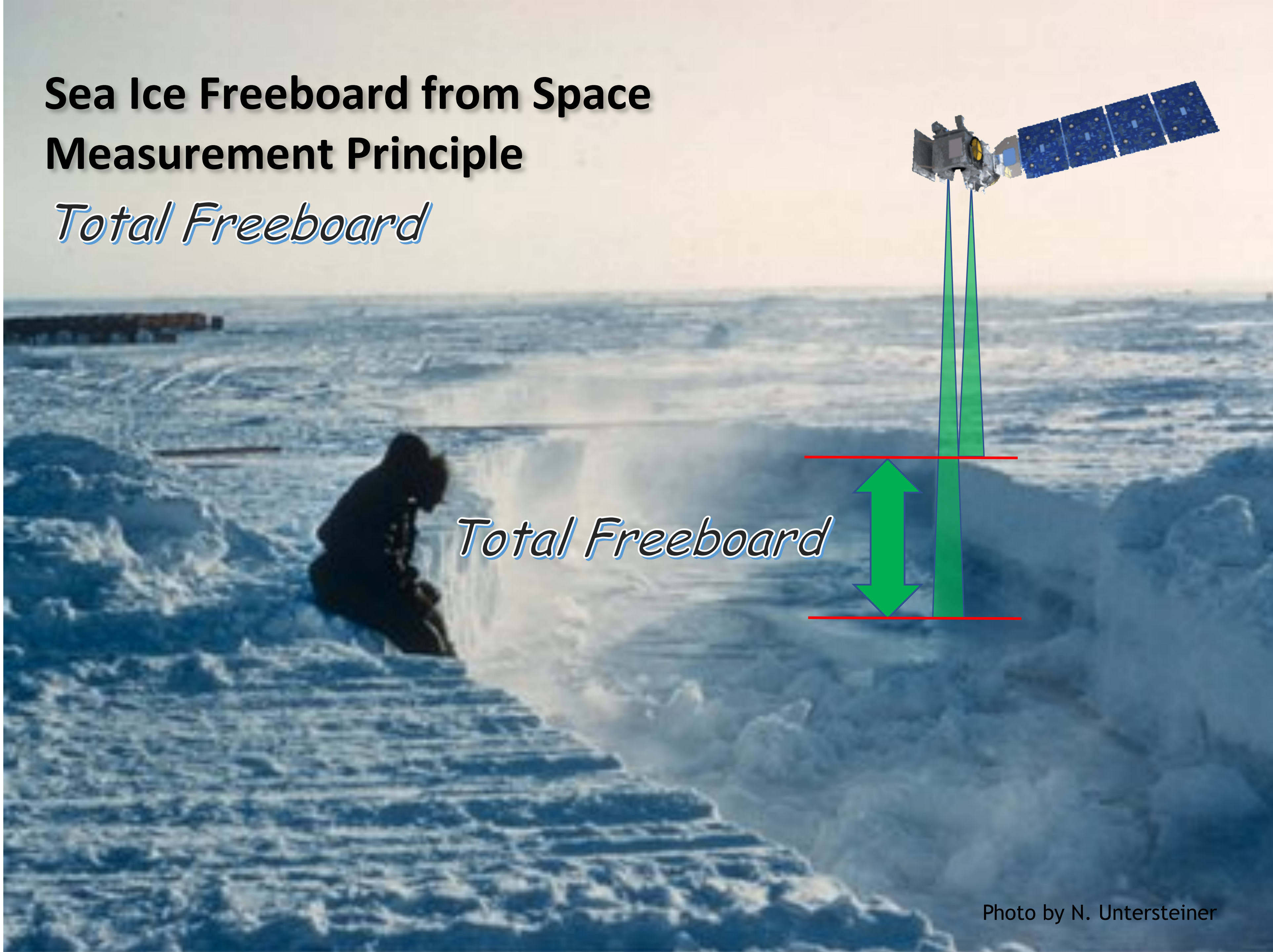
Key Science Objectives: Polar Oceans

- Arctic
  - Monitoring changes in sea ice thickness/volume
  - Short term forecasts to climate projections/model improvements
  - Dynamic topography
- Antarctic (Important focus)
  - Monitoring changes in sea ice thickness/volume
    - Limited retrievals and understanding of approaches
  - Climate projections/model improvements
  - Dynamic topography

Altimetry of the Polar Oceans

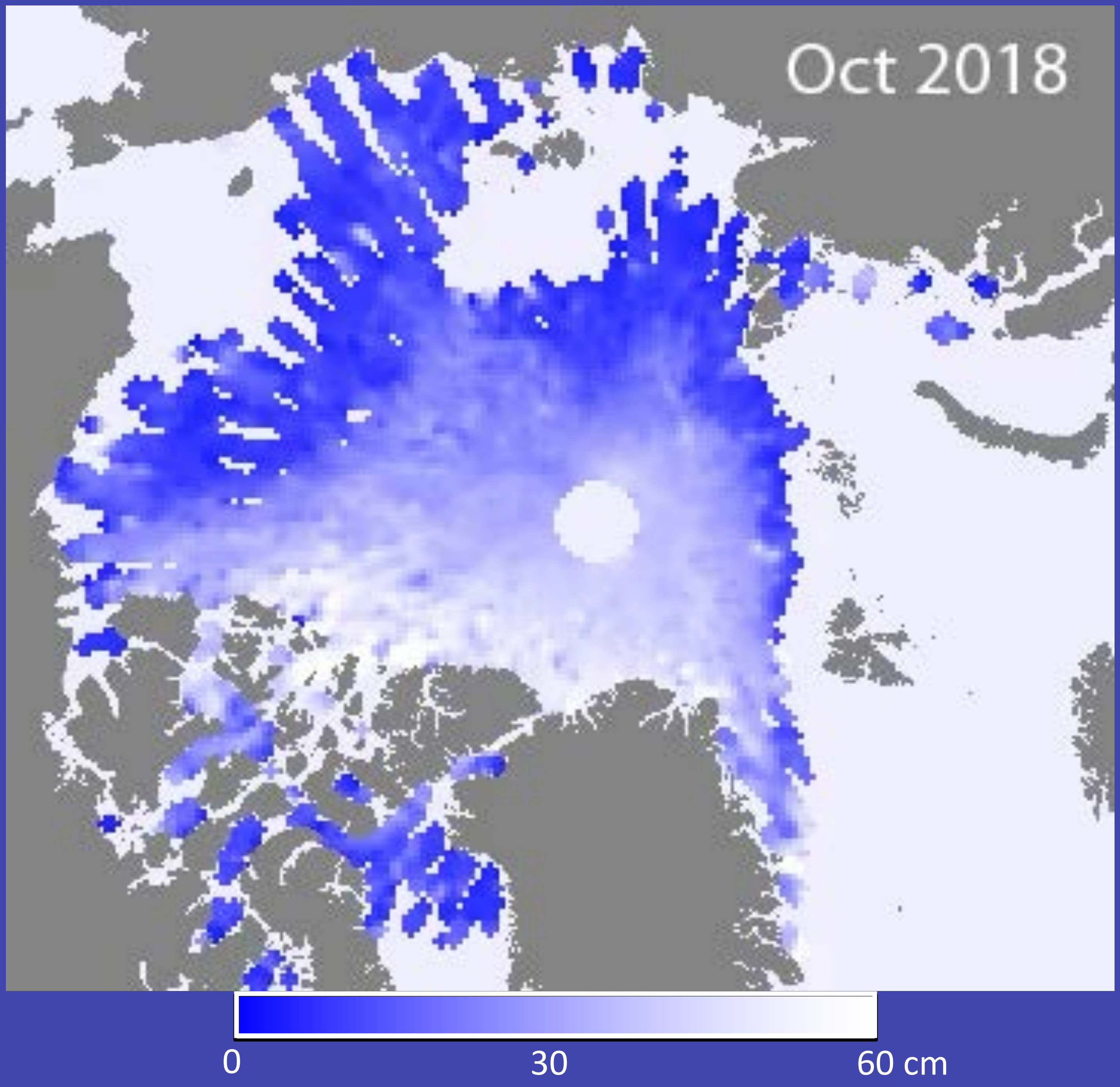
Altimetry of the Polar Oceans

Sea Ice Freeboard from Space
Measurement Principle

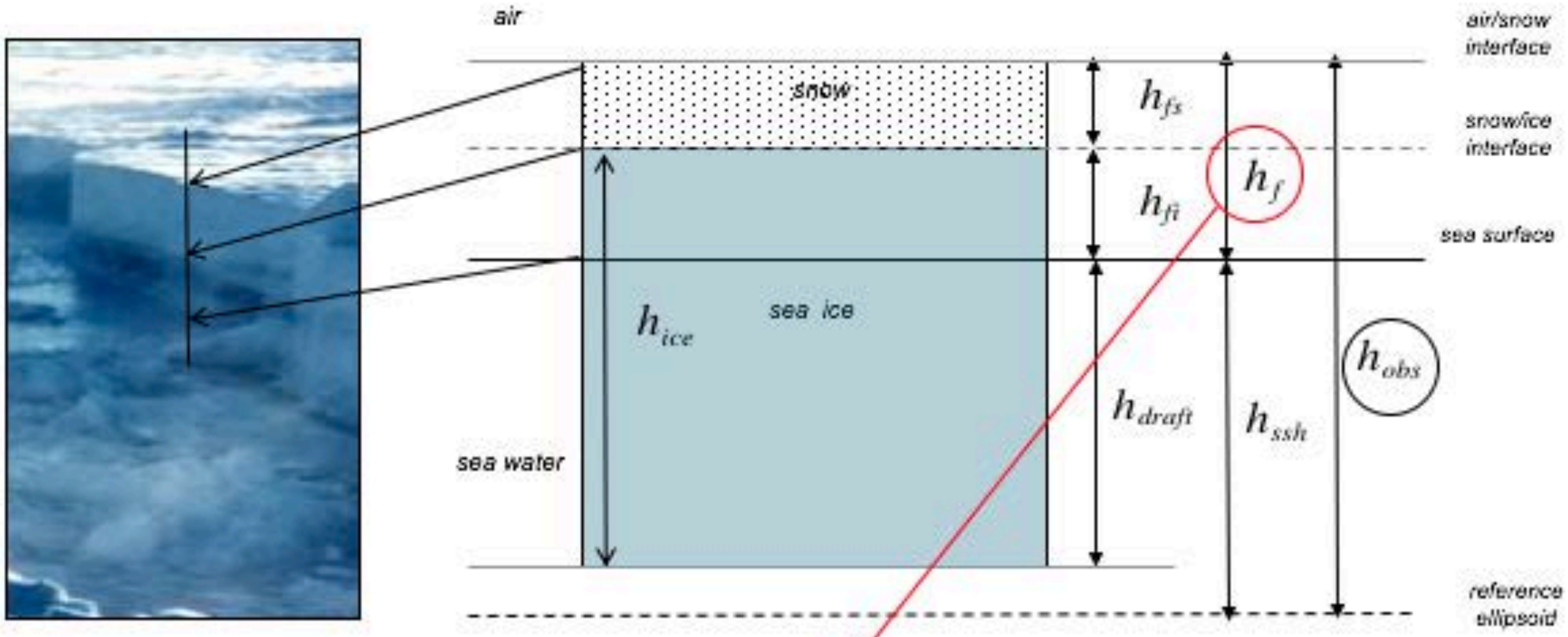


ICESat-2

ICE, CLOUD, AND LAND ELEVATION SATELLITE-2



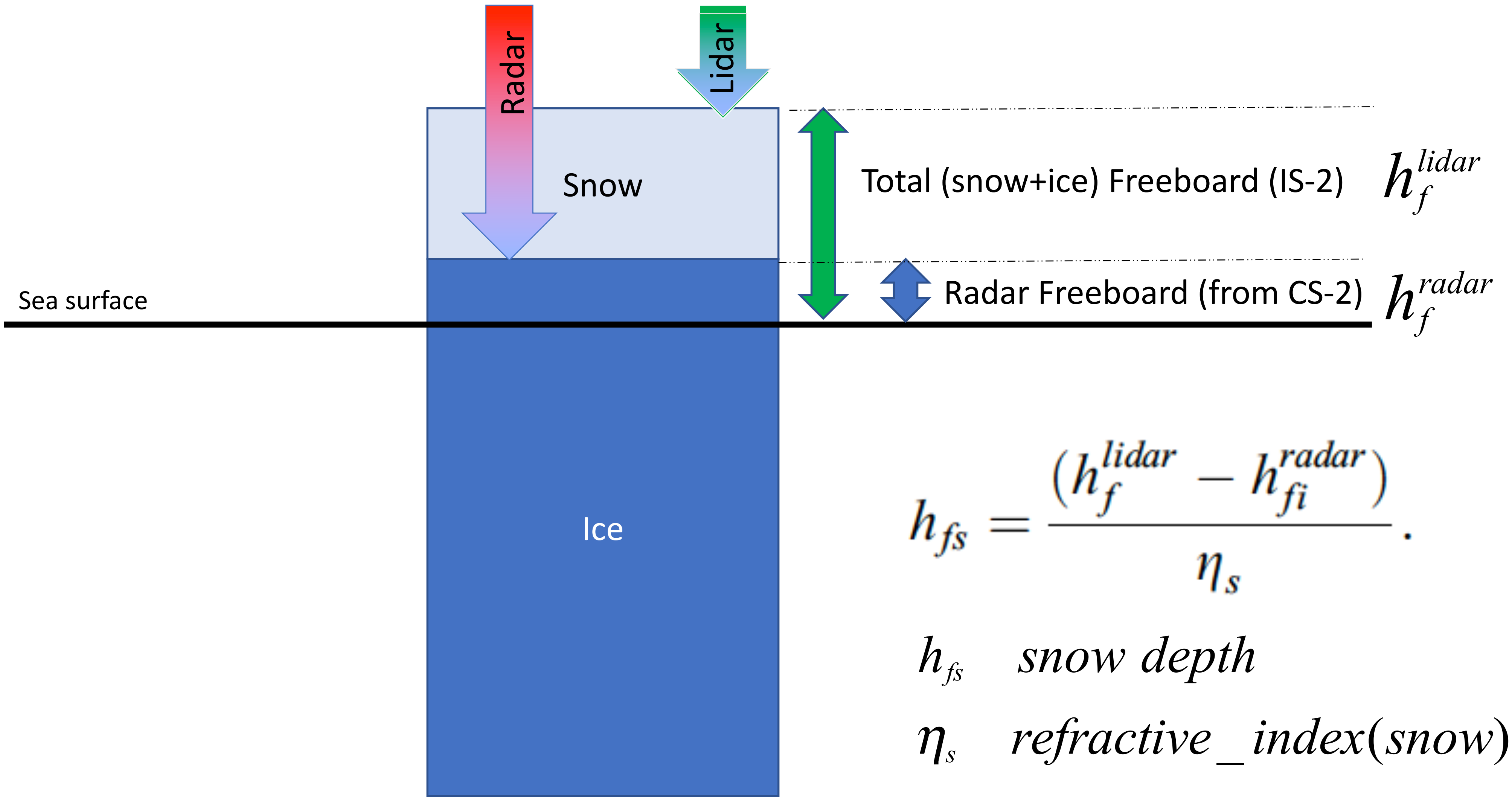
Sea Ice Thickness from Lidars



$$h_f = h_{fs} + h_{fi}$$

$$h_{ice} = \frac{\rho_w}{\rho_w - \rho_i} h_f - \left(\frac{\rho_w - \rho_s}{\rho_w - \rho_i}\right) h_{fs}$$

Snow Depth: Measurement Principle

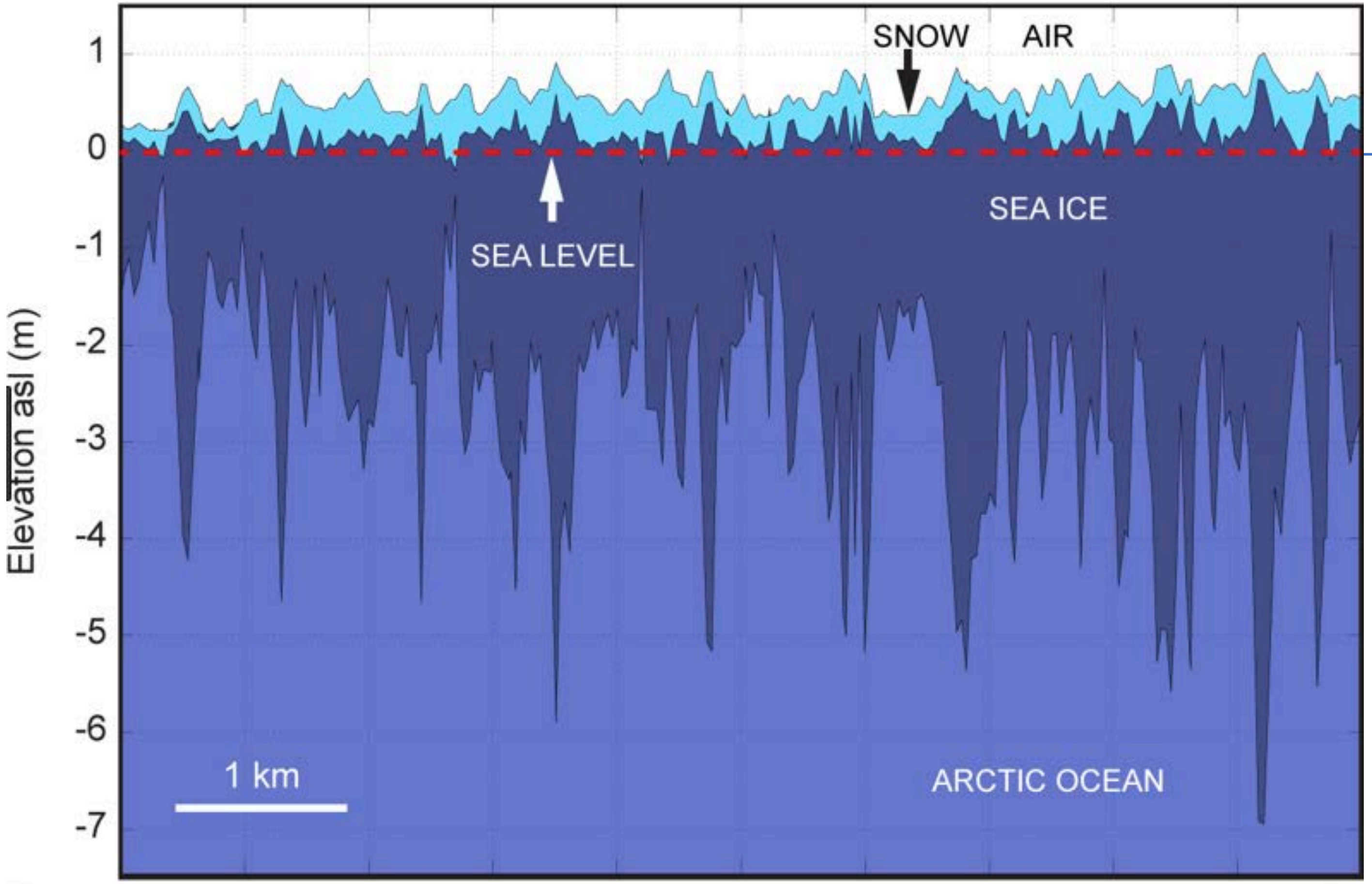


$$h_{fs} = \frac{(h_f^{lidar} - h_{fi}^{radar})}{\eta_s}.$$

h_{fs} *snow depth*

η_s *refractive_index(snow)*

Reconstruction of thickness from freeboard

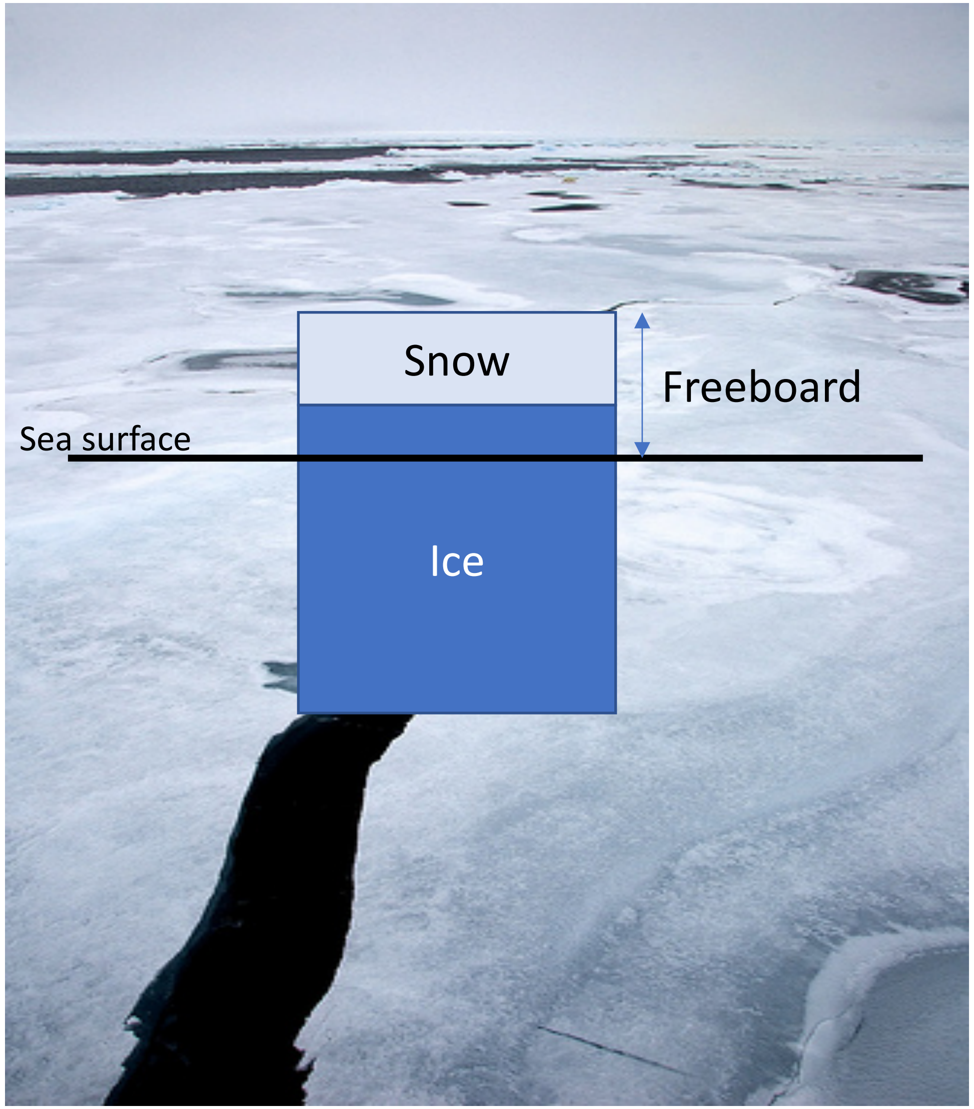


freeboard

draft

graphics from Operation IceBridge:
NASA airborne mission

Sea ice Freeboard Requirements

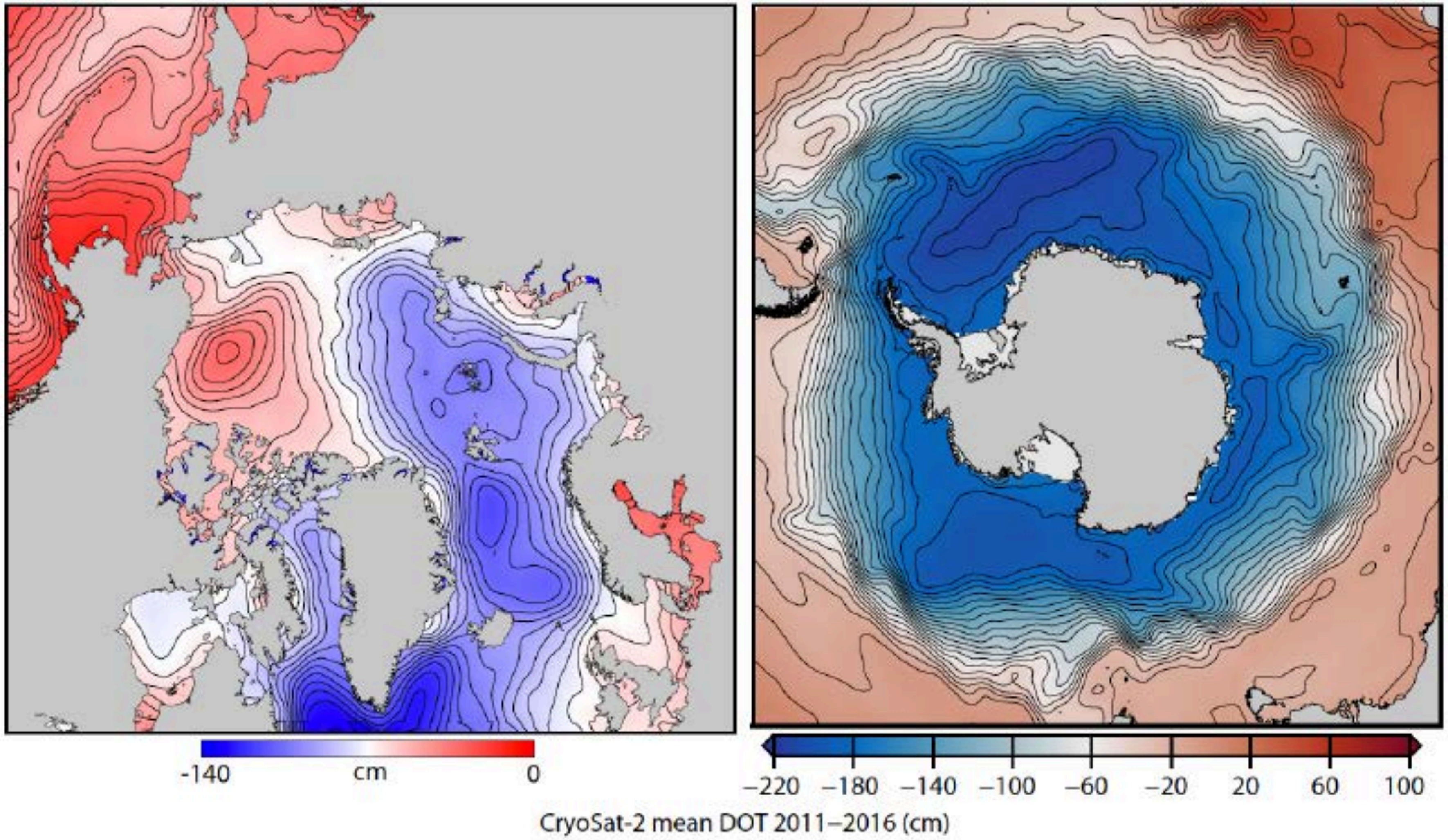


- Provide surface elevations to enable the determination of sea-ice freeboard
- Key requirements
  - Precision
    - for accurate sea surface reference
  - Spot resolution
    - 80% of leads are <50 m wide
  - Coverage
    - Monthly uniform coverage of ice-covered oceans

Science: Polar Oceans

- Arctic
  - Monitoring changes in sea ice thickness/volume
  - Short term forecasts to climate projections/model improvements
  - Dynamic topography
- Antarctic (Important focus)
  - Monitoring changes in sea ice thickness/volume
    - Limited retrievals and understanding of approaches
  - Climate projections/model improvements
  - Dynamic topography
- Snow depth (both oceans)
  - Requires new technology

Topography of the ice-covered oceans



Alex Gardner, JPL

What do we need to rapidly advance the science ?

- **ASPIRATIONAL QUALITY**: What would enable a dramatic advance in cryosphere science objective; that is, what would ideally meet our needs?
- **THRESHOLD QUALITY**: What would enable an important advance, but not dramatic, in cryosphere science objective; that is, what would be a valuable improvement compared to what is now available or is expected to be available in this decade from planned programs or missions?

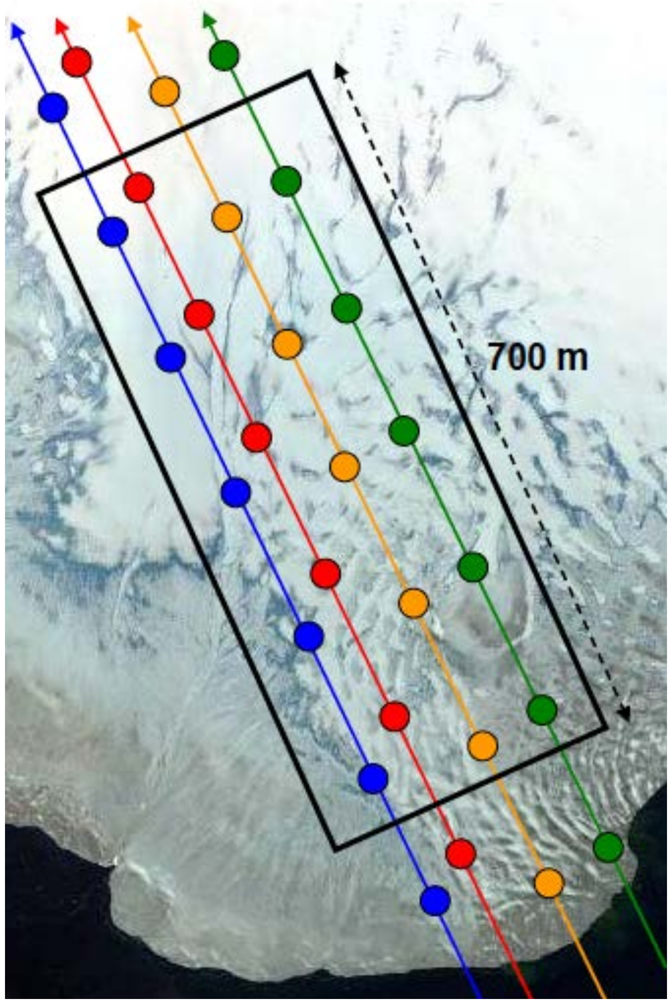
- How do we objectively make these decisions with sufficient traceability?
- Recommendations need to stand up to inter-discipline / inter-observation competition in a resource limited environment. More is always better, unless it leads to nothing.
- It’s our job to see that these observations are realized for the next generation of cryosphere science that will work to answer some of societies most pressing questions.

So, how many measurements do we need?

Example: Observing System *Simulation Experiments* (OSSEs) for glacier volume change

Minimum elevation change sampling required to resolve *regional volume change*

- Select 1000 random samples (with replacement) of decreasing sample size to determine standard error for a range of sample sizes
- Bin measurements of *elevation change* by elevation and weight by hypsometric area

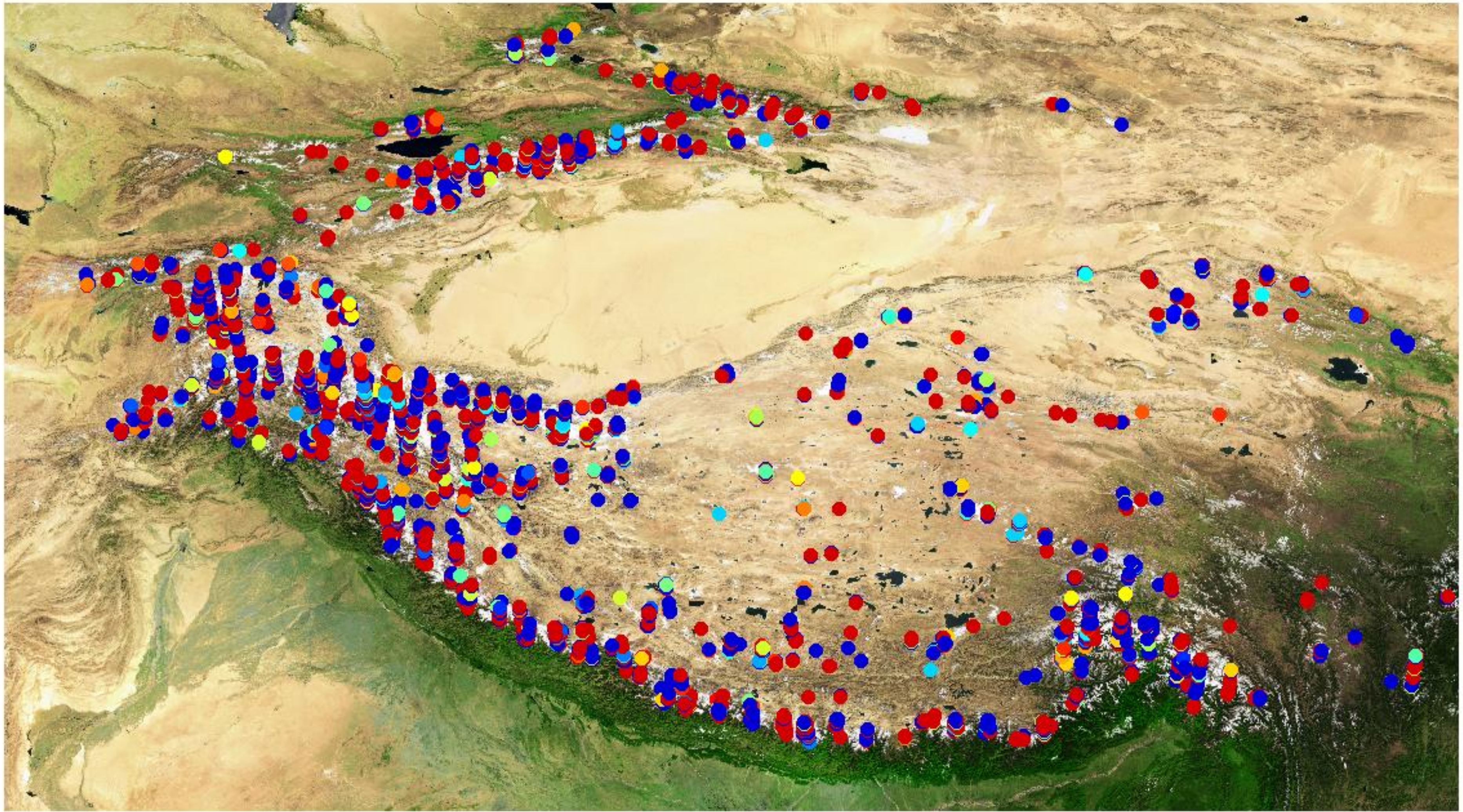


# of spot elevations

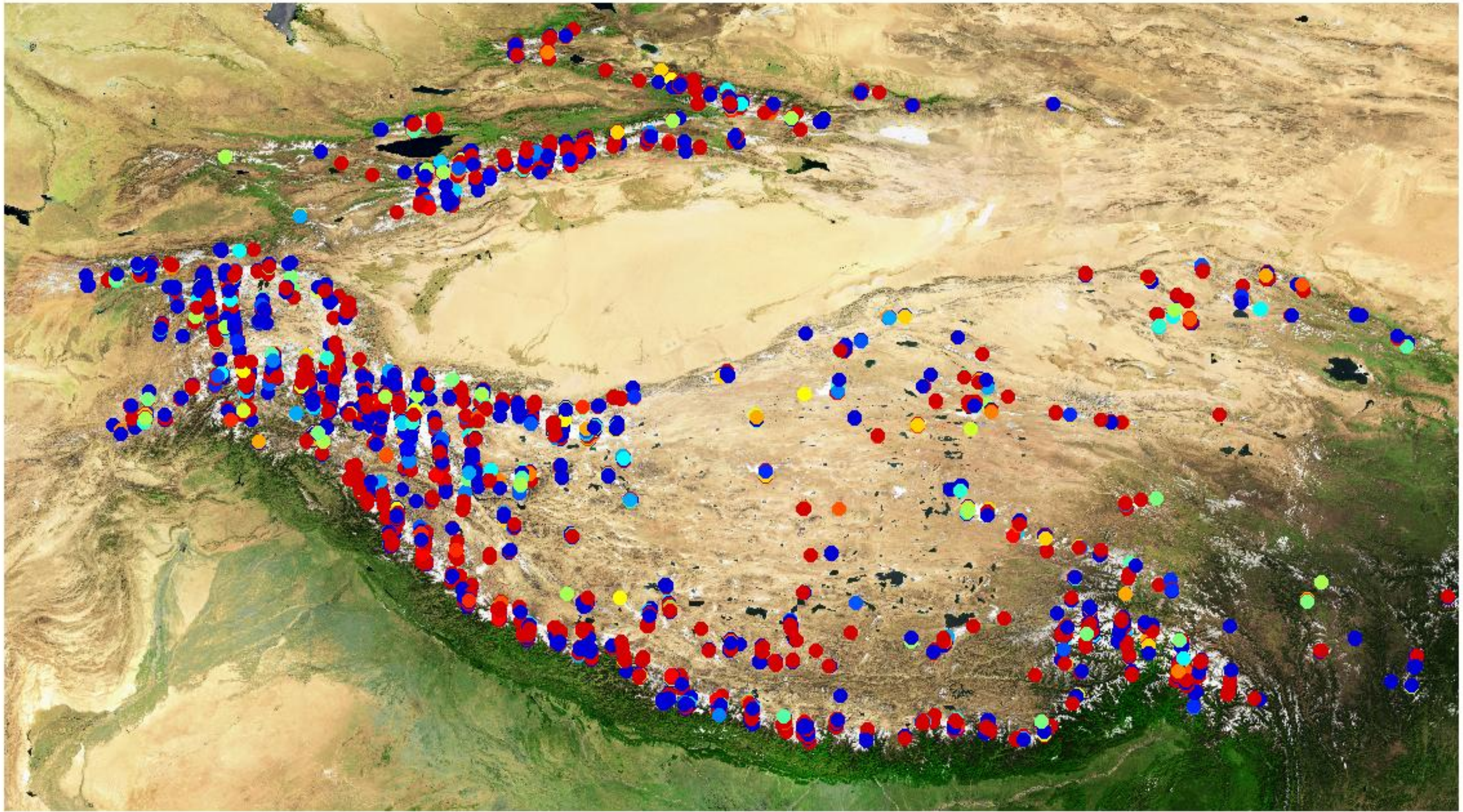
60986

dh/dt

-0.35 ± 1.96 *SE*



# of spot elevations	dh/dt
20000	**-0.35 ± 0.05 m yr^{-1}**

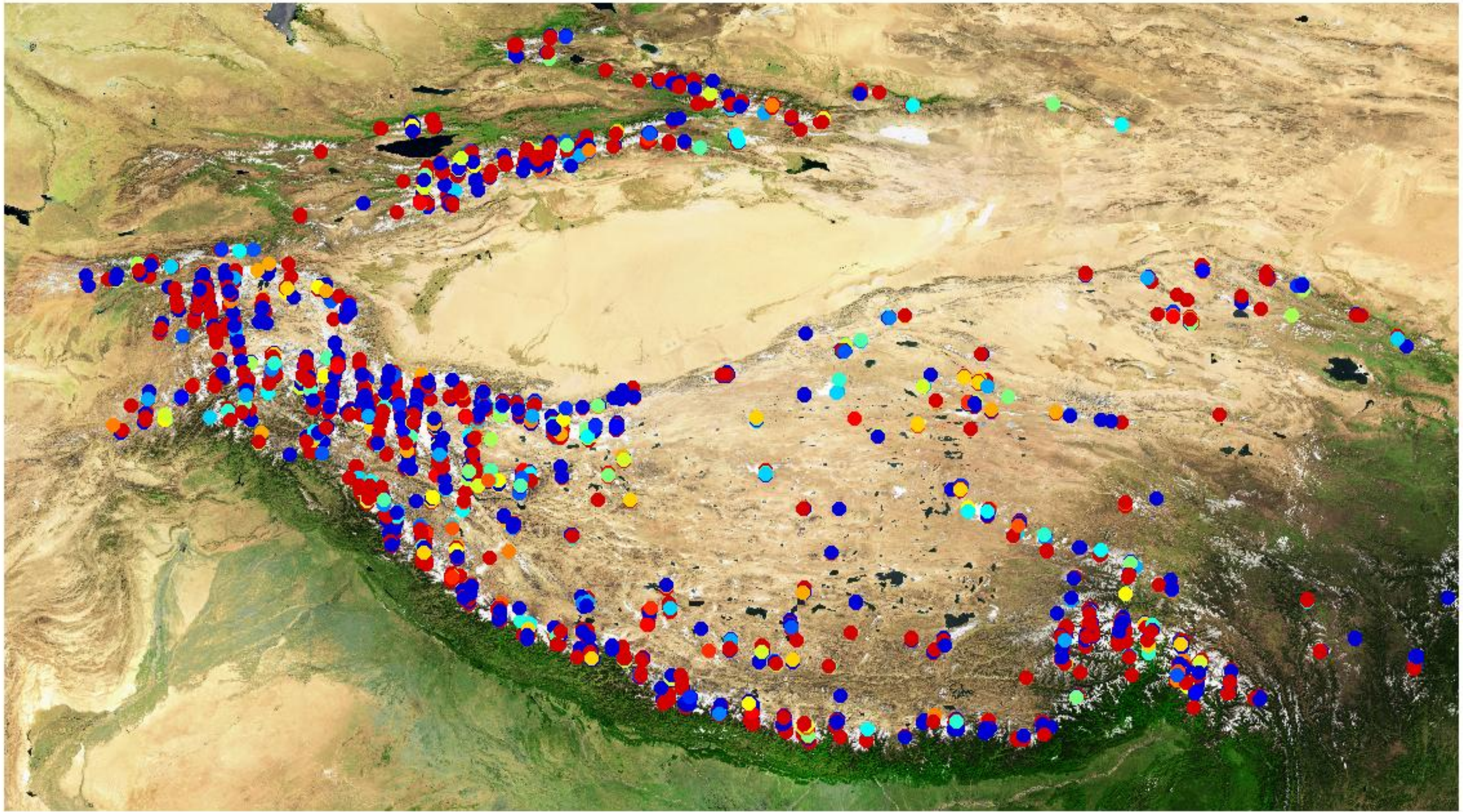


# of spot elevations

10000

dh/dt

-0.35 ± 0.07 m yr^{-1}

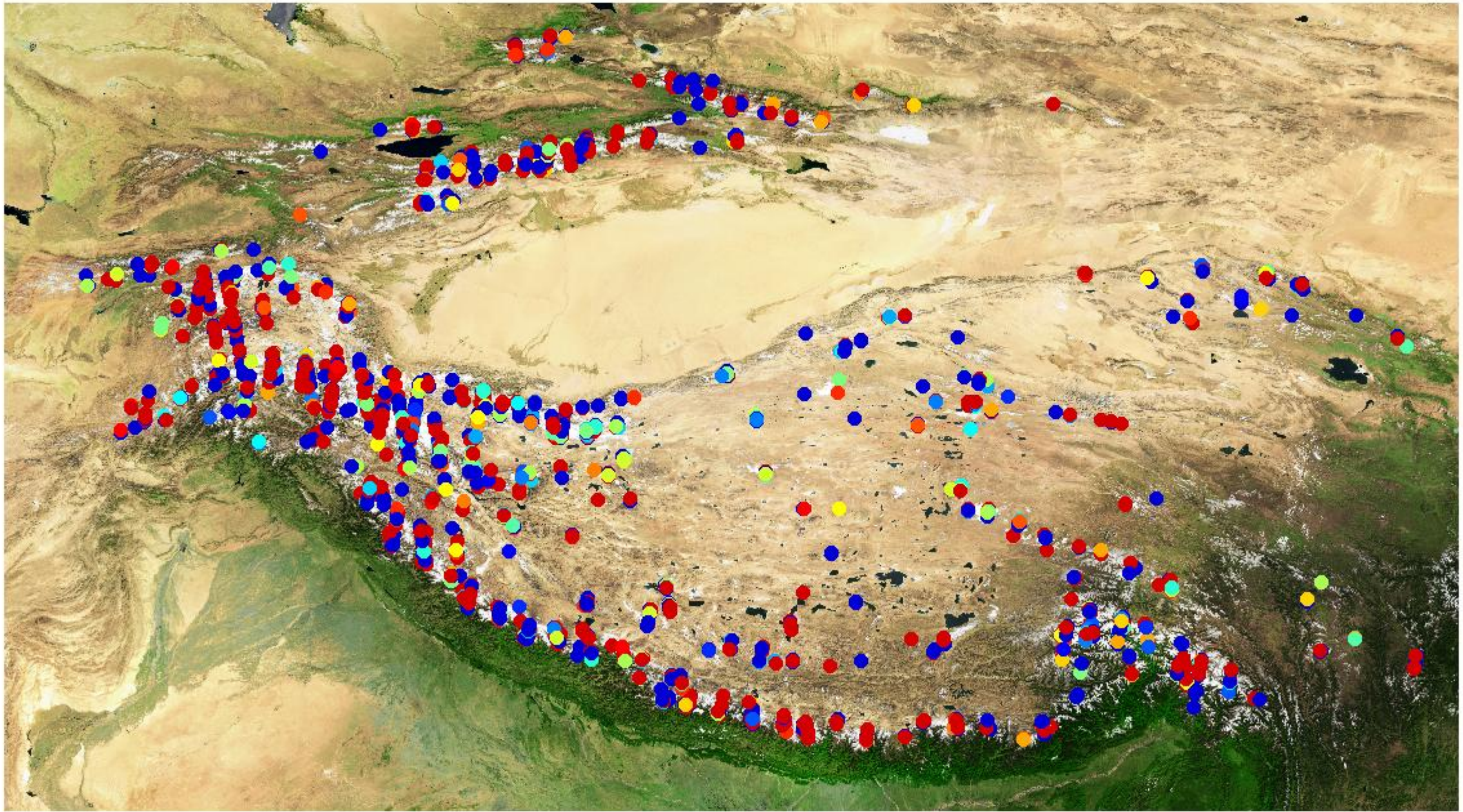


# of spot elevations

5000

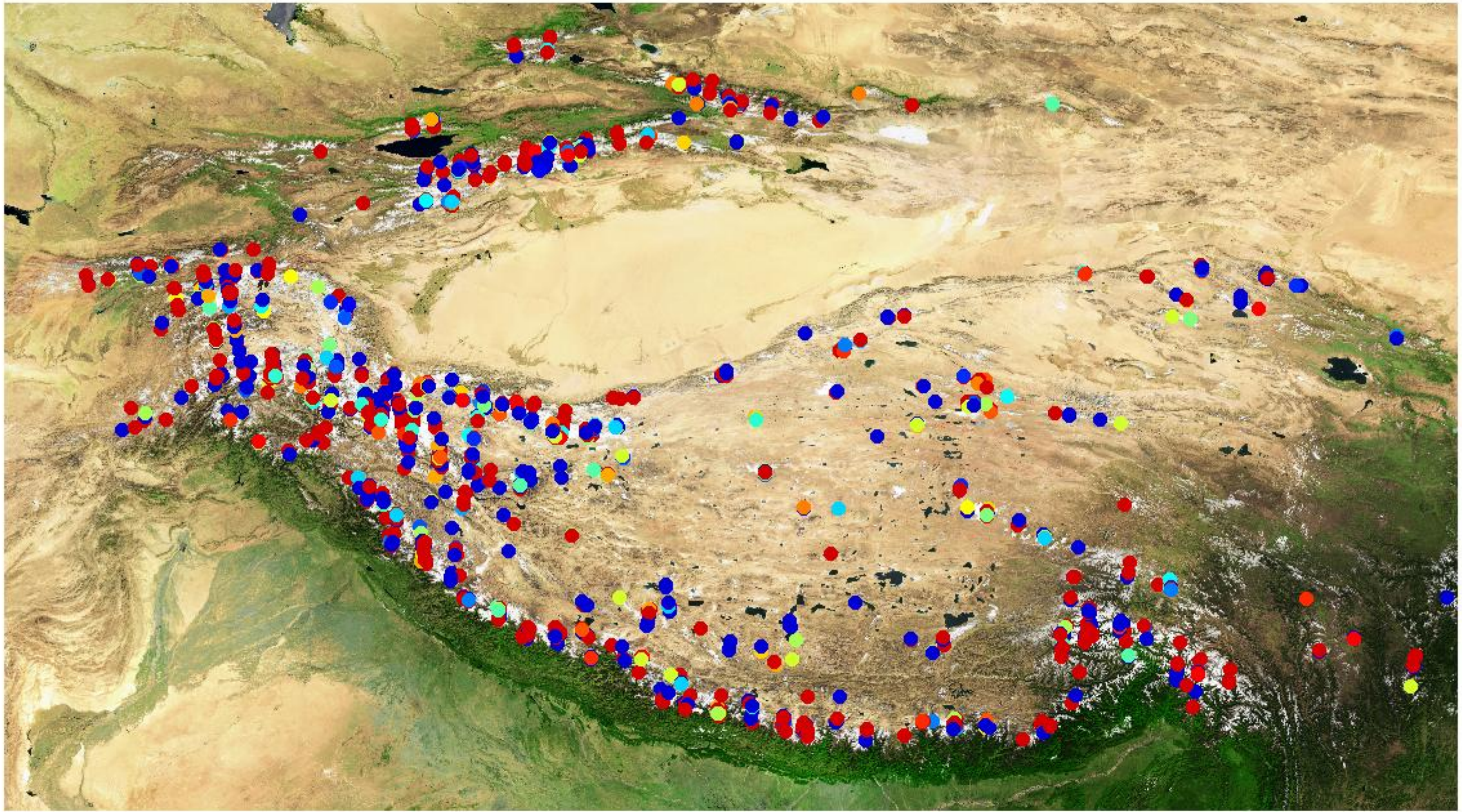
dh/dt

-0.35 ± 0.11 m yr^{-1}



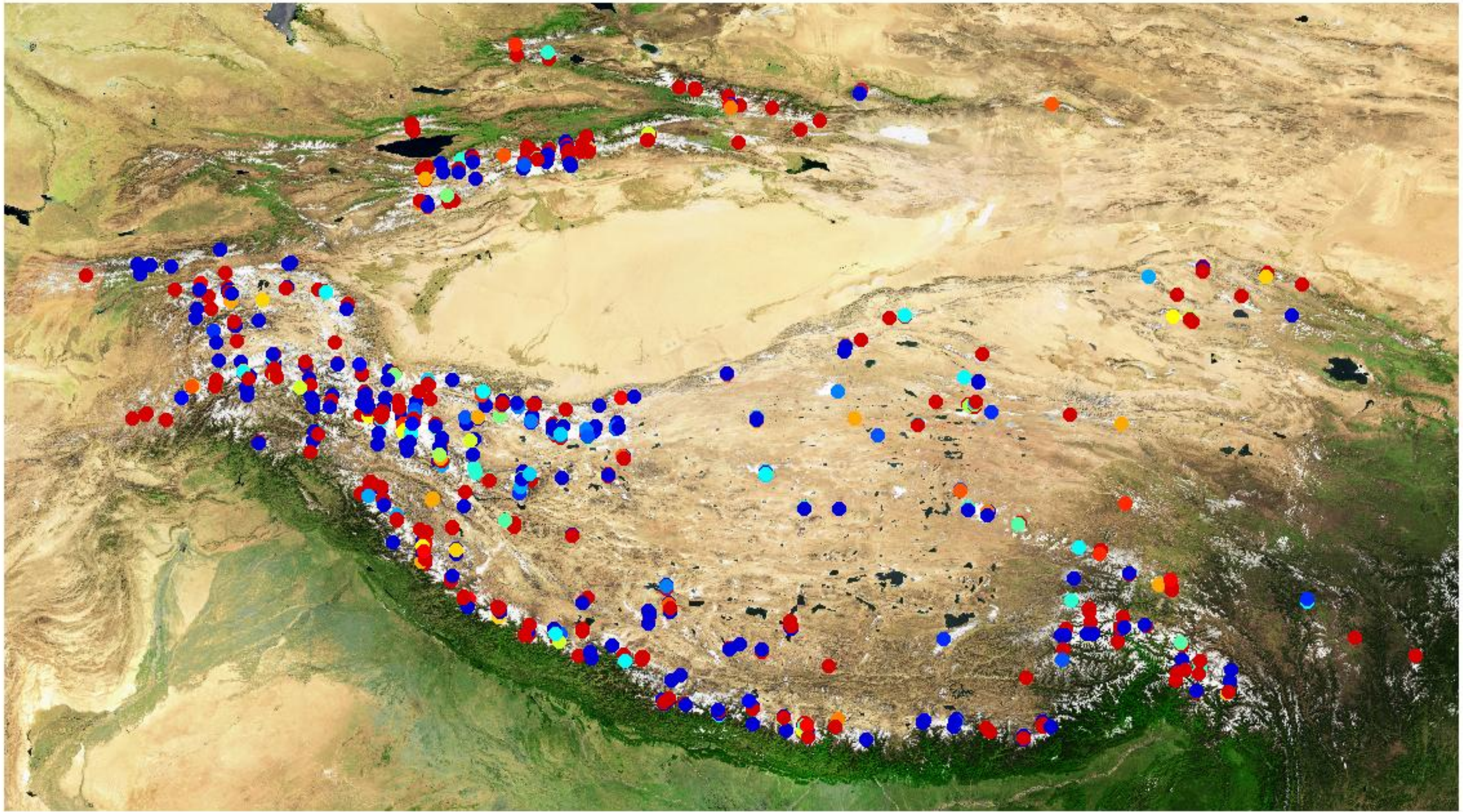
# of spot elevations
2500

dh/dt
-0.35 ± 0.15 m yr^{-1}



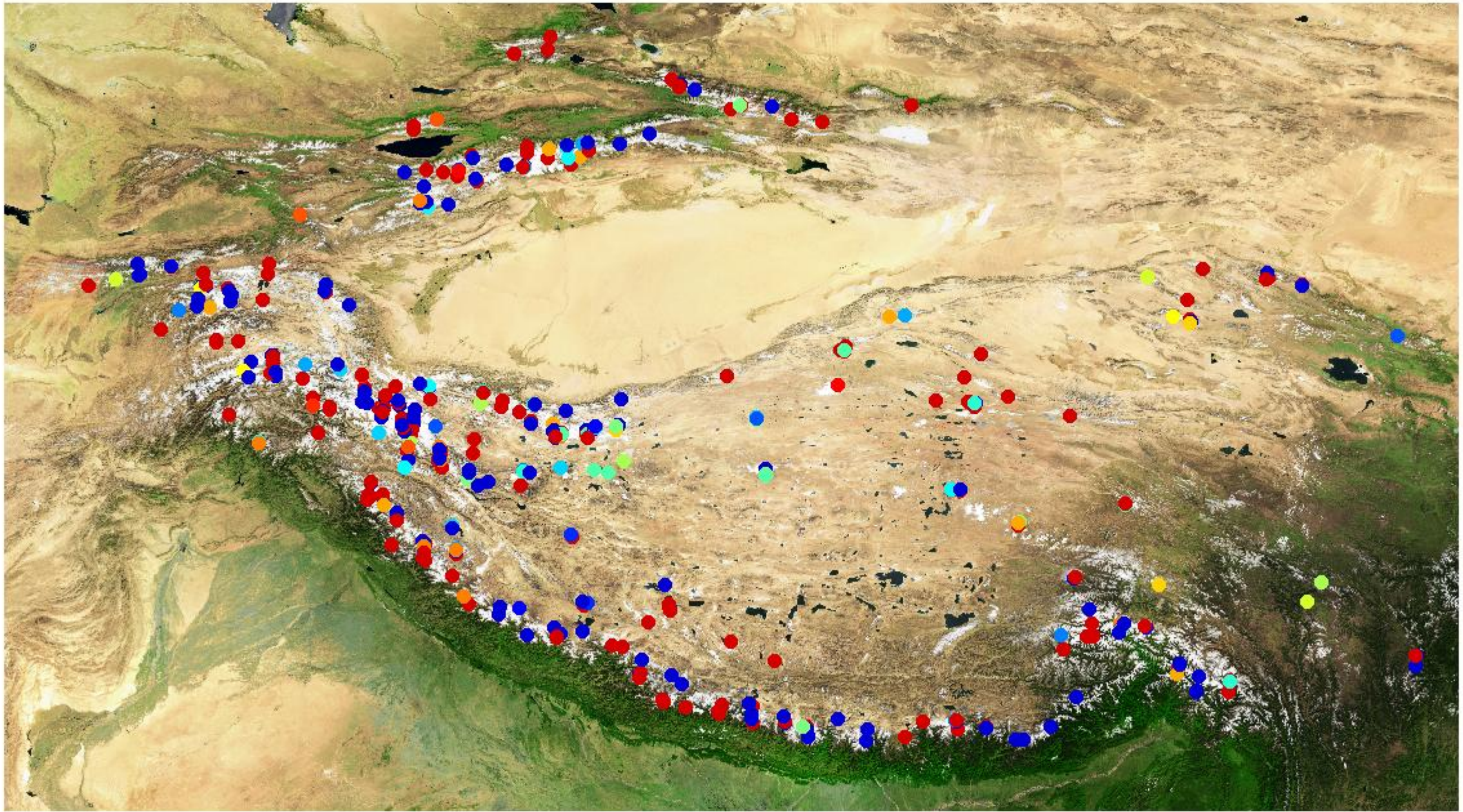
# of spot elevations
1000

dh/dt
-0.35 ± 0.23 m yr^{-1}



# of spot elevations   dh/dt

500   **-0.35 ± 0.32 m yr^{-1}**

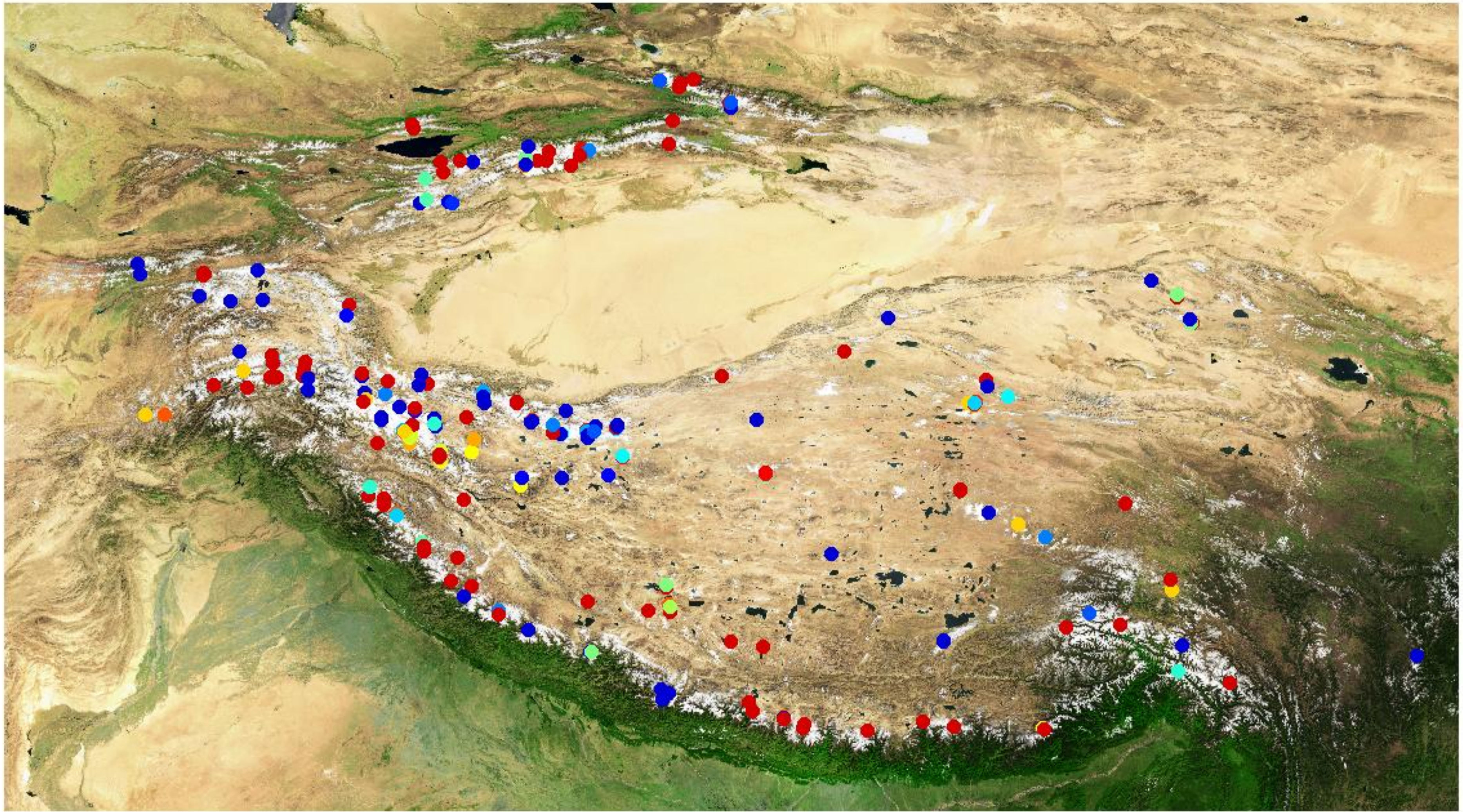


\# of spot elevations

250

dh/dt

-0.35 ± 0.45 m yr^{-1}

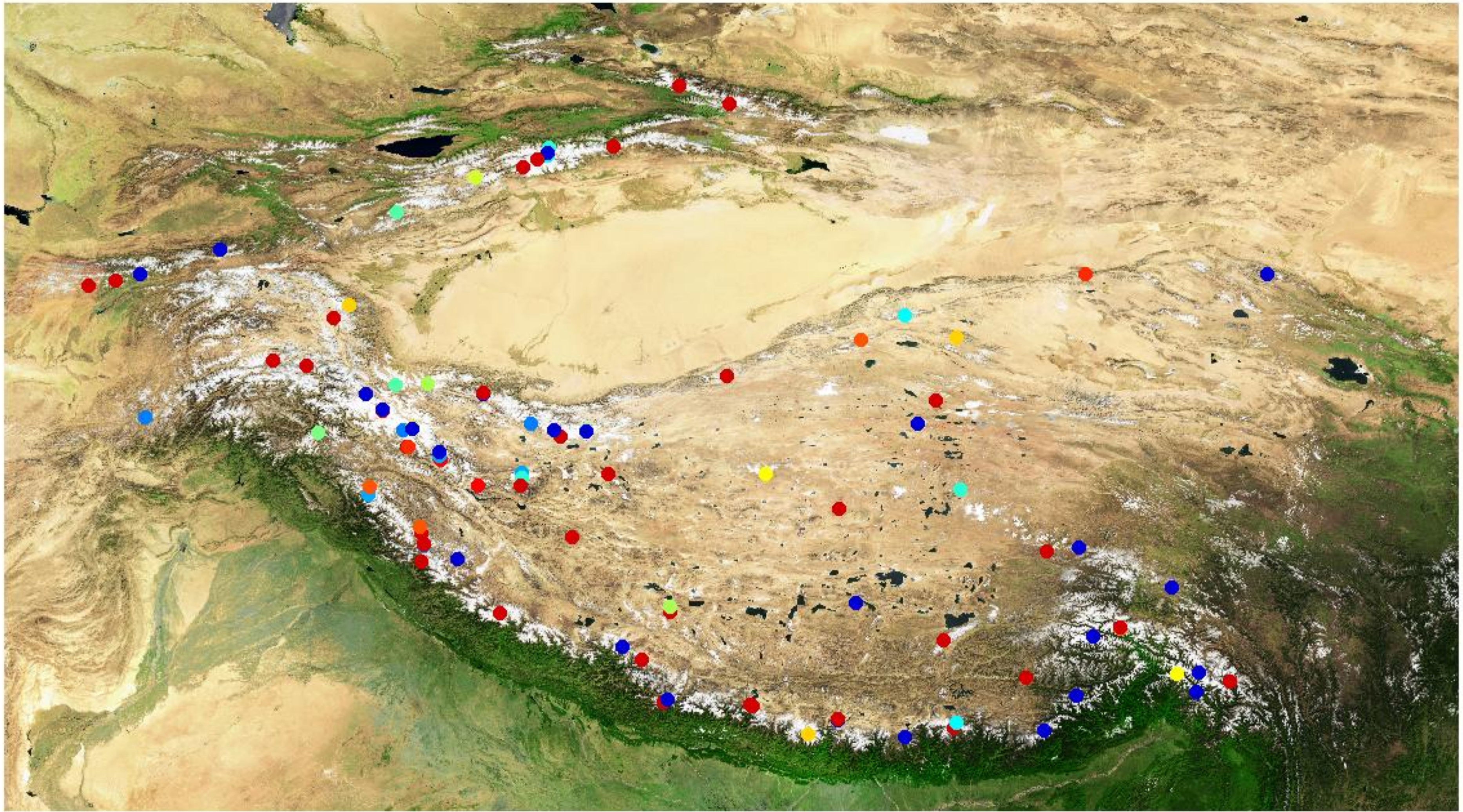


# of spot elevations

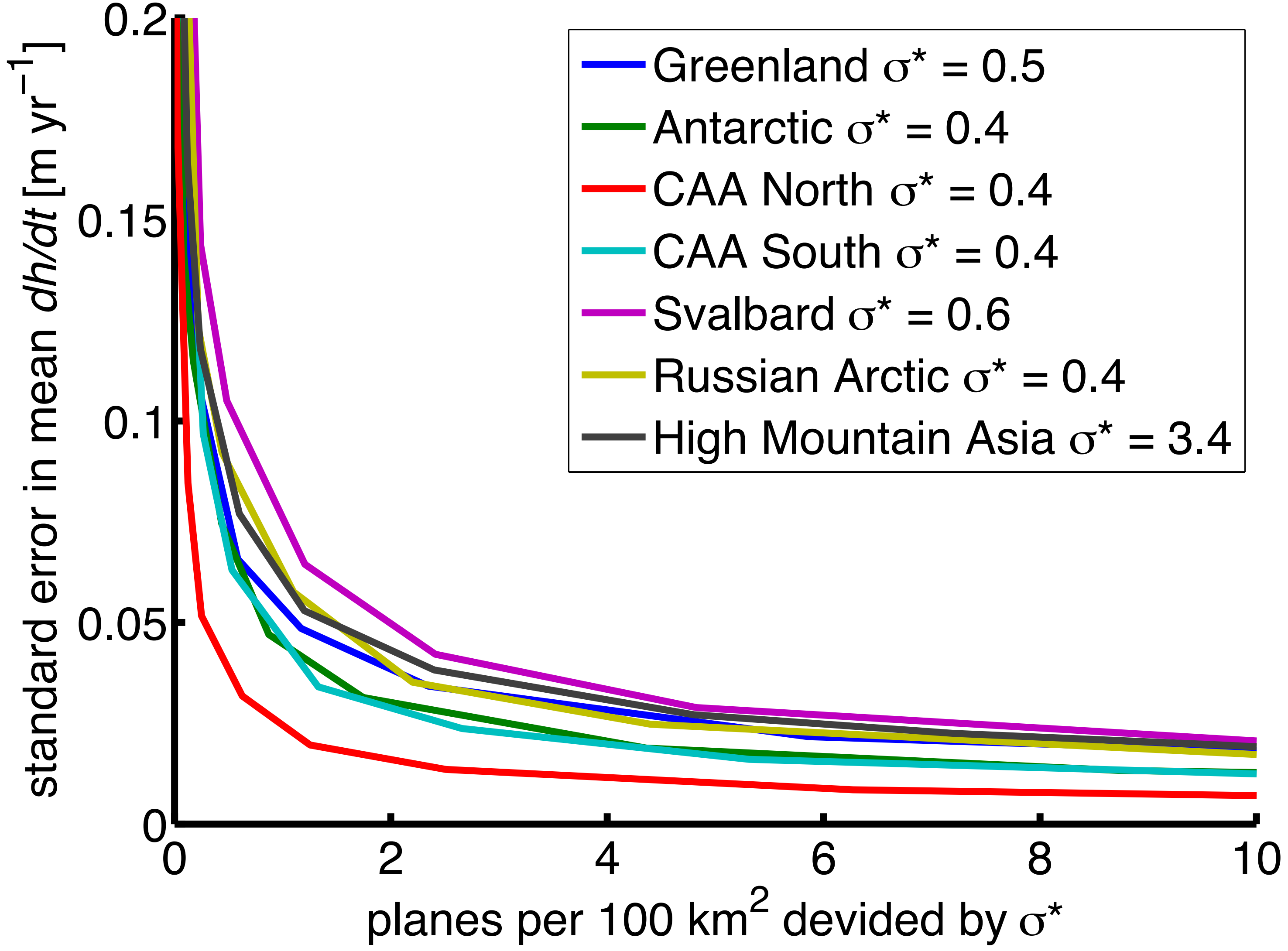
100

dh/dt

-0.35 ± 0.72 m yr^{-1}

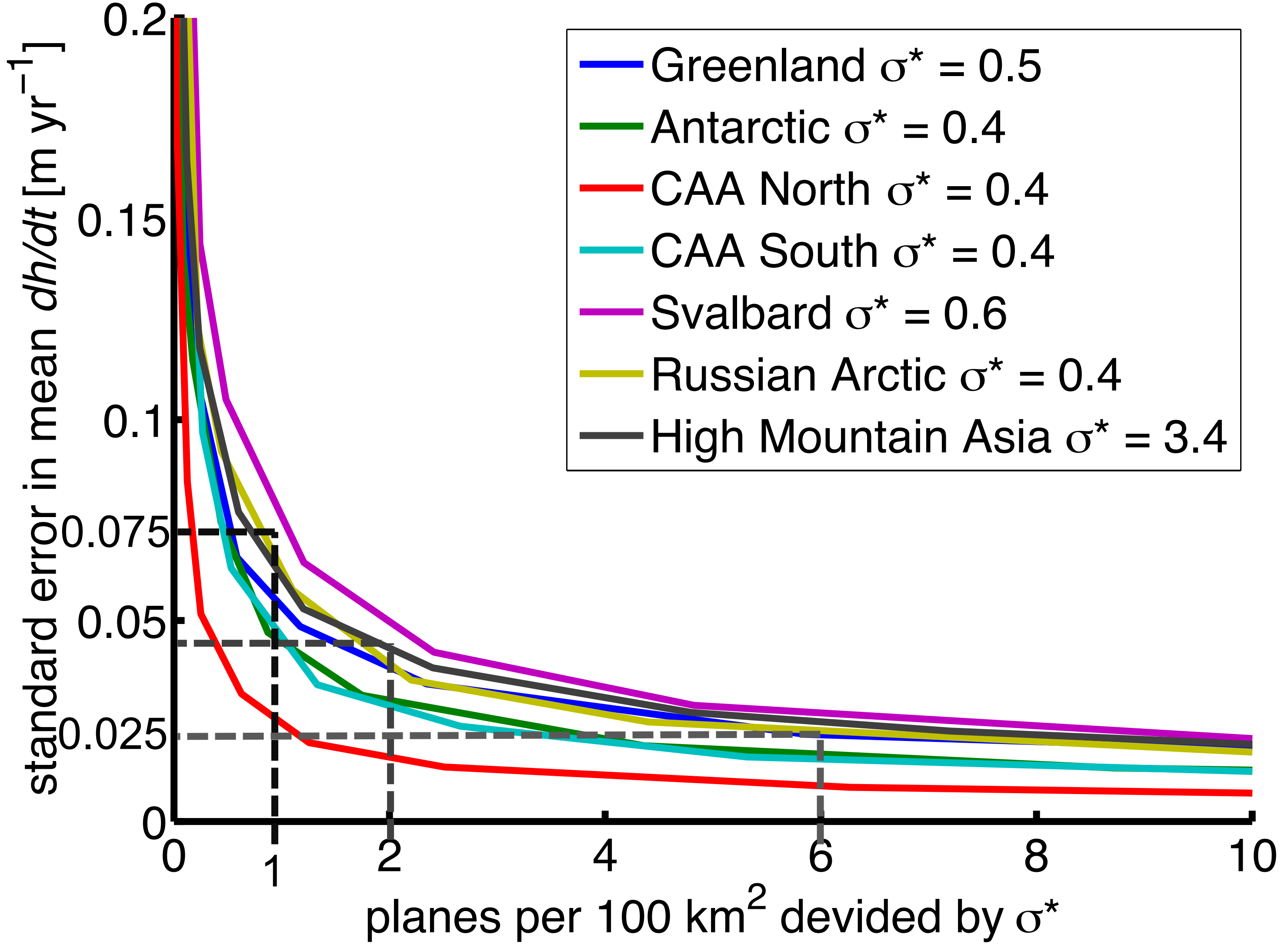


Random Spatial Sampling



σ* = hypsometry weighted standard deviation in *dh*

Random Spatial Sampling



σ* = hypsometry weighted standard deviation in *dh*

Conclusion

- sparse *elevation change* measurements (~2 per 100 km^2) provide accurate *elevation changes*
- Measurements must have representative spatial distribution

Other ways to justify needs

- Peer-reviewed literature
- Community white papers
- National and international reports:
  - Special Report on the Ocean and Cryosphere in a Changing Climate
  - IPCC AR5
- Identify needs for future OSSE experiments or small studies to make objective / tracible recommendations

Summary of key whitepapers submitted to DS

- 6 of 151 RFIs directly pertain to STV Cryo

28	Glacial Acceleration - Reduction of Uncertainty in Sea-Level-Rise Assessment	Paper motivated by the need to understand glacial acceleration which is a main source of uncertainty in sea-level change assessment. Observables: High-res surface height. Possible Measurement Approach: Swath or multi-beam altimetry in several frequencies. Links of thought: ice -ocean-atmosphere, beyond-ICEsat2, observation suite Themes I, IV, V
49	Lidar-Optical Fusion for High-resolution Measurements of Ice and Vegetation Change	This proposal outlines measurement requirements for cryosphere and ecosystem science objectives using a combination of lidar and optical measurements from a single space-based observatory.
57	Monitoring ice sheets and sea ice: The need for satellite altimetry data in the coming decades.	Here we describe a set of science goals for understanding changes in ice sheets and sea ice, and describe a set of measurements that will meet these goals. We propose that laser altimetry measurements provide the best chance to meet these goals and conclude that the heritage of NASA technology will make this mission reliable and affordable.

Summary of key whitepapers submitted to DS: Land Ice

67	Quantifying Mass Change Components of Land Ice and Sea Ice	The cryospheric community advocates for a multi-sensor mission that includes a Lidar capable of precise topographic and bathymetric mapping and a wide-bandwidth dual-frequency radar to reduced uncertainties in future ice mass loss and sea level rise.
78	Linkages of salinity with ocean circulation, water cycle, and climate variability	This white paper addresses the enhancement of capability for space-based measurements of global sea surface salinity (SSS) and sea ice thickness to study the linkages of ocean circulation with the water cycle and climate variability, as well as to facilitate biogeochemistry research.
136	Understanding glaciers and ice sheets response to changes in atmosphere and ocean conditions	Desired geophysical observations for improving understanding of glacier and ice sheet processes relevant to improving projections of sea level change. The three key variables identified are repeat measurements of surface velocity, gravity and elevation.

Summary of key whitepapers submitted to DS: Land Ice

Glacier and ice sheet monitoring: Data needed for cutting edge science in the next decades.

Benjamin Smith, University of Washington Applied Physics Lab
Kelly Brunt, Earth System Science Interdisciplinary Center, University of Maryland
Bea Csatho, University at Buffalo Department of geology
Helen Fricker, Scripps Institution of Oceanography
Alex Gardner, NASA Jet Propulsion Laboratory
Thomas Neumann, NASA Goddard Space Flight Center

	Measurement goals	Unique challenges	Measurement priorities
Glaciers	-Current trend magnitudes -Process model constraints	Small spatial scales Strong atmospheric signals need downscaled data	-Fine-scale altimetry / photogrammetry -Understanding of SMB processes such as surface reflectance
Coastal ice sheets and outlet glaciers	-Process-based modeling -Ablation rates	-Processes operate on short temporal and spatial scales	-Altimetry / photogrammetry with sub-seasonal temporal resolution -Seasonal velocity measurements
Interior ice sheets	-Estimating present and recent-past mass balance -Inland propagation of coastal changes	-High precision requirements -Large signals due to accumulation and densification variability	-Long-term laser-altimetry measurements -Accurate firn and SMB modeling -Mission-to-mission radar altimetry calibration
Ice shelves	-Estimates of ocean and atmospheric forcing -Changes in marginal forcing	-Hydrostatic compensation reduces signal -Large sensitivity to firn-model processes -Advection of small-scale features	-Long-term altimetry time series -Accurate firn and SMB modeling -Velocity mapping

Smith et al. 2017

Summary of key white papers submitted to DS: Sea Ice

Observing the Arctic Ocean Sea Ice Cover: 2017-2027

R. Kwok[1], J. C. Comiso[2], T. Markus[2], A. Schweiger[3], M. C. Serreze[4], J. C. Stroeve[4]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[2]NASA/Goddard Space Flight Center, Greenbelt, MD
[3]Polar Science Center, University of Washington, Seattle, WA
[4]National Snow and Ice Data Center, University of Colorado, Boulder, CO

Summary of key whitepapers submitted to DS: Sea Ice

Key Questions:

- How predictable are different aspects of the Arctic sea ice cover, and what is needed to improve predictability at the local and regional scale to facilitate planning, mitigation, and adaptation? Improvements in model physics and specification of initial state. While there are intrinsic limitations on Arctic sea ice predictability, some appear to reside in the initial ice/ocean state and in the longer-term trend; the initial states (e.g. thickness, snow depth, etc.) affect the potential trajectories in the evolution of ice coverage.
- What are the critical linkages between the Arctic system and the larger Arctic and global systems? Although efforts are under way to better understand the role of Arctic sea ice in this broader context, progress has been limited by the lack of coordinated observations of sea ice and associated forcing parameters (atmosphere and ocean) at appropriate time and space scales.

Kwok et al. 2017

Key Sea Ice Parameters

Ice thickness distribution. Beyond 2021, there are currently no plans for another altimeter suitable for fully mapping Arctic sea ice thickness. This is an important consideration.

Coordinated observations: motion and thickness. Satellite retrievals of sea ice thickness and motion are typically acquired independently with little consideration of the close links between thermodynamic and dynamic processes that control ice conditions, which must be treated realistically to improve predictive models.

Kwok et al. 2017

Conclusion

- White papers are very high-level and provide little guidance on specifics of measurement needs
- It is the job of the STV to refine the description of these identified needs

Simplified Cryo STV SATM

Area of Interest	Coverage (%)	Horizontal Resolution [m]	Repeat Accuracy (vertical) [m]	Repeat Frequency [days]	Latency [days]
Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)	100% 80%	1-5 m 10 m 50m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
Slow Moving portions of Ice Sheets and Ice Caps (interior ice)	80% 50%	1-5 m 200 m 500 m	0.1 m 0.005 m 0.01 m	90 days 30 days 90 days	10 days 30 days
Antarctic and Greenland Ice Shelves	100% 75%	1-5 m 10 m 50 m	0.1 m 0.005 m 0.01 m	90 days 5 days 10 days	10 days 30 days
All mountain glaciers larger than 50 km^2	100% 50%	1-5 m 10 m 25 m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
Static Land Ice DEM	100% 90%	1 m 5 m	0.5 m 1 m	N/A	N/A
Arctic and Southern Ocean Sea Ice Cover	100% 50%	100 m 500 m	0.01 m 0.02 m	5 days 10 days	10 days 30 days

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold

Fast Outlet Glaciers

Area of Interest	Coverage (%)	Horizontal Resolution [m]	Repeat Accuracy (vertical) [m]	Repeat Frequency [days]	Latency [days]
Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)	100% 80%	1-5 m 10 m 50m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
Slow Moving portions of Ice Sheets and Ice Caps (interior ice)	80% 50%	1-5 m 200 m 500 m	0.1 m 0.005 m 0.01 m	90 days 30 days 90 days	10 days 30 days
Antarctic and Greenland Ice Shelves	100% 75%	1-5 m 10 m 50 m	0.1 m 0.005 m 0.01 m	90 days 5 days 10 days	10 days 30 days
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Static Land Ice DEM	100% 90%	1 m 5 m	0.5 m 1 m	N/A	N/A
Arctic and Southern Ocean Sea Ice Cover	100% 50%	100 m 500 m	0.01 m 0.02 m	5 days 10 days	10 days 30 days

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold

Slow Moving Ice Sheet

Area of Interest	Coverage (%)	Horizontal Resolution [m]	Repeat Accuracy (vertical) [m]	Repeat Frequency [days]	Latency [days]
Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)	100% 80%	1-5 m 10 m 50m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
Slow Moving portions of Ice Sheets and Ice Caps (interior ice)	80% 50%	1-5 m 200 m 500 m	0.1 m 0.005 m 0.01 m	90 days 30 days 90 days	10 days 30 days
Antarctic and Greenland Ice Shelves	100% 75%	1-5 m 10 m 50 m	0.1 m 0.005 m 0.01 m	90 days 5 days 10 days	10 days 30 days
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Static Land Ice DEM	100% 90%	1 m 5 m	0.5 m 1 m	N/A	N/A
Arctic and Southern Ocean Sea Ice Cover	100% 50%	100 m 500 m	0.01 m 0.02 m	5 days 10 days	10 days 30 days

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold

Ice Shelves

Area of Interest	Coverage (%)	Horizontal Resolution [m]	Repeat Accuracy (vertical) [m]	Repeat Frequency [days]	Latency [days]
Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)	100% 80%	1-5 m 10 m 50m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
Slow Moving portions of Ice Sheets and Ice Caps (interior ice)	80% 50%	1-5 m 200 m 500 m	0.1 m 0.005 m 0.01 m	90 days 30 days 90 days	10 days 30 days
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Static Land Ice DEM	100% 90%	1 m 5 m	0.5 m 1 m	N/A	N/A
Arctic and Southern Ocean Sea Ice Cover	100% 50%	100 m 500 m	0.01 m 0.02 m	5 days 10 days	10 days 30 days

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold

Mountain Glaciers

Area of Interest	Coverage (%)	Horizontal Resolution [m]	Repeat Accuracy (vertical) [m]	Repeat Frequency [days]	Latency [days]
Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)	100% 80%	1-5 m 10 m 50m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
Slow Moving portions of Ice Sheets and Ice Caps (interior ice)	80% 50%	1-5 m 200 m 500 m	0.1 m 0.005 m 0.01 m	90 days 30 days 90 days	10 days 30 days
Antarctic and Greenland Ice Shelves	100% 75%	1-5 m 10 m 50 m	0.1 m 0.005 m 0.01 m	90 days 5 days 10 days	10 days 30 days
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Static Land Ice DEM	100% 90%	1 m 5 m	0.5 m 1 m	N/A	N/A
Arctic and Southern Ocean Sea Ice Cover	100% 50%	100 m 500 m	0.01 m 0.02 m	5 days 10 days	10 days 30 days

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold

Static DEM

Area of Interest	Coverage (%)	Horizontal Resolution [m]	Repeat Accuracy (vertical) [m]	Repeat Frequency [days]	Latency [days]
Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)	100% 80%	1-5 m 10 m 50m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
Slow Moving portions of Ice Sheets and Ice Caps (interior ice)	80% 50%	1-5 m 200 m 500 m	0.1 m 0.005 m 0.01 m	90 days 30 days 90 days	10 days 30 days
Antarctic and Greenland Ice Shelves	100% 75%	1-5 m 10 m 50 m	0.1 m 0.005 m 0.01 m	90 days 5 days 10 days	10 days 30 days
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Arctic and Southern Ocean Sea Ice Cover	100% 50%	100 m 500 m	0.01 m 0.02 m	5 days 10 days	10 days 30 days

(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold

Sea Ice

Area of Interest	Coverage (%)	Horizontal Resolution [m]	Repeat Accuracy (vertical) [m]	Repeat Frequency [days]	Latency [days]
Fast Moving portions of Ice Sheets and Ice Caps (outlet glaciers)	100% 80%	1-5 m 10 m 50m	0.1 m 0.05 m 0.1 m	90 days 5 days 10 days	10 days 30 days
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(1) from the Decadal Survey when provided, (2) aspirational and (3) threshold

Wrap-up

- Thank you, thank you, thank you
- Next steps
  - Community survey
  - Further refinement of SATM and mapping to technologies
  - White paper summarizing input

- Feel free to send Cryo related input and recommendations directly to me: alex.s.gardner@jpl.nasa.gov