ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

NEROGRAV Spring School 2025

# Mass Change of the Cryosphere

**Dr. Ingo Sasgen**

Glaciology, Alfred-Wegener-Institute, Helmholtz-Centre for Polar- und Marine Research

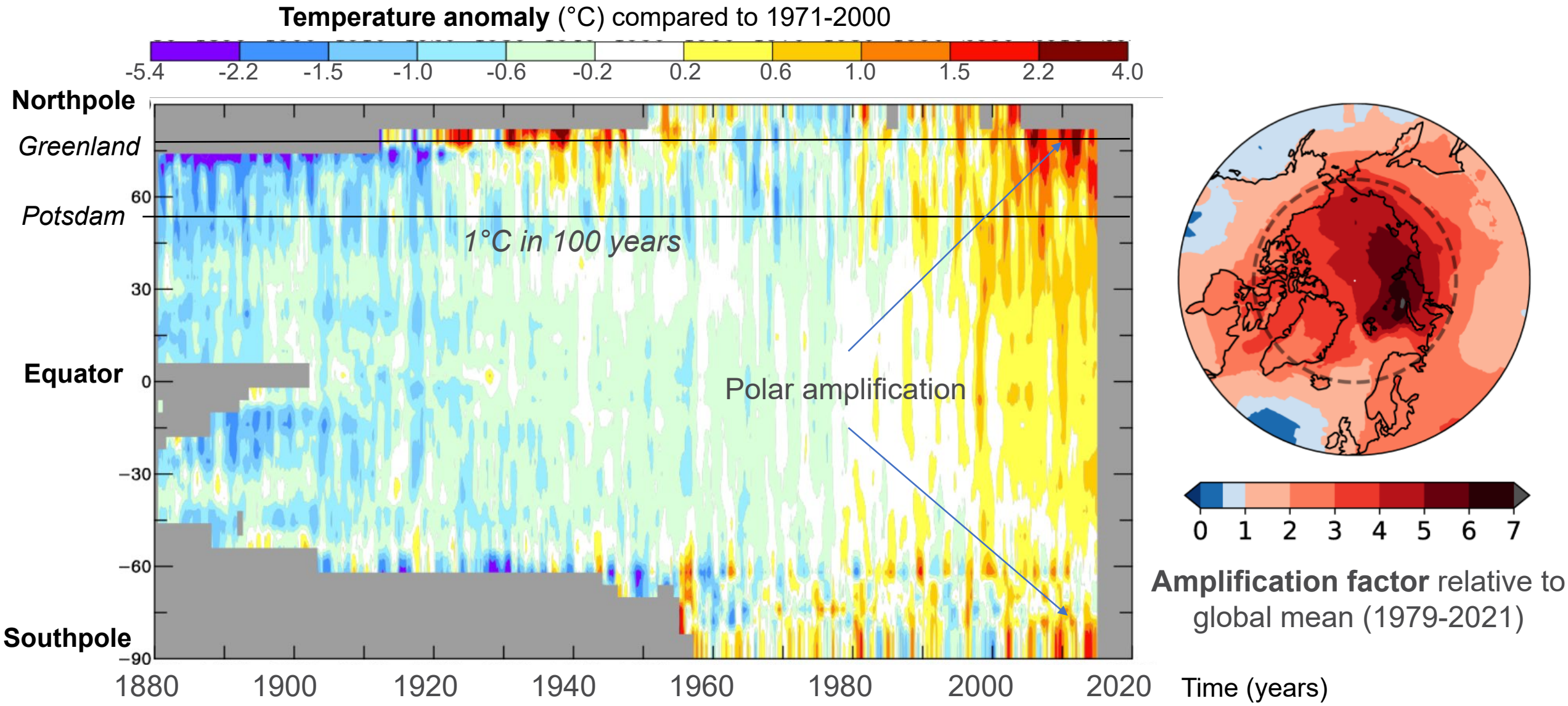
Neustadt/Weinstrasse, 12  March 2025

# Introduction

## AWI & polar change

Source: AI

# Global warming and polar amplification

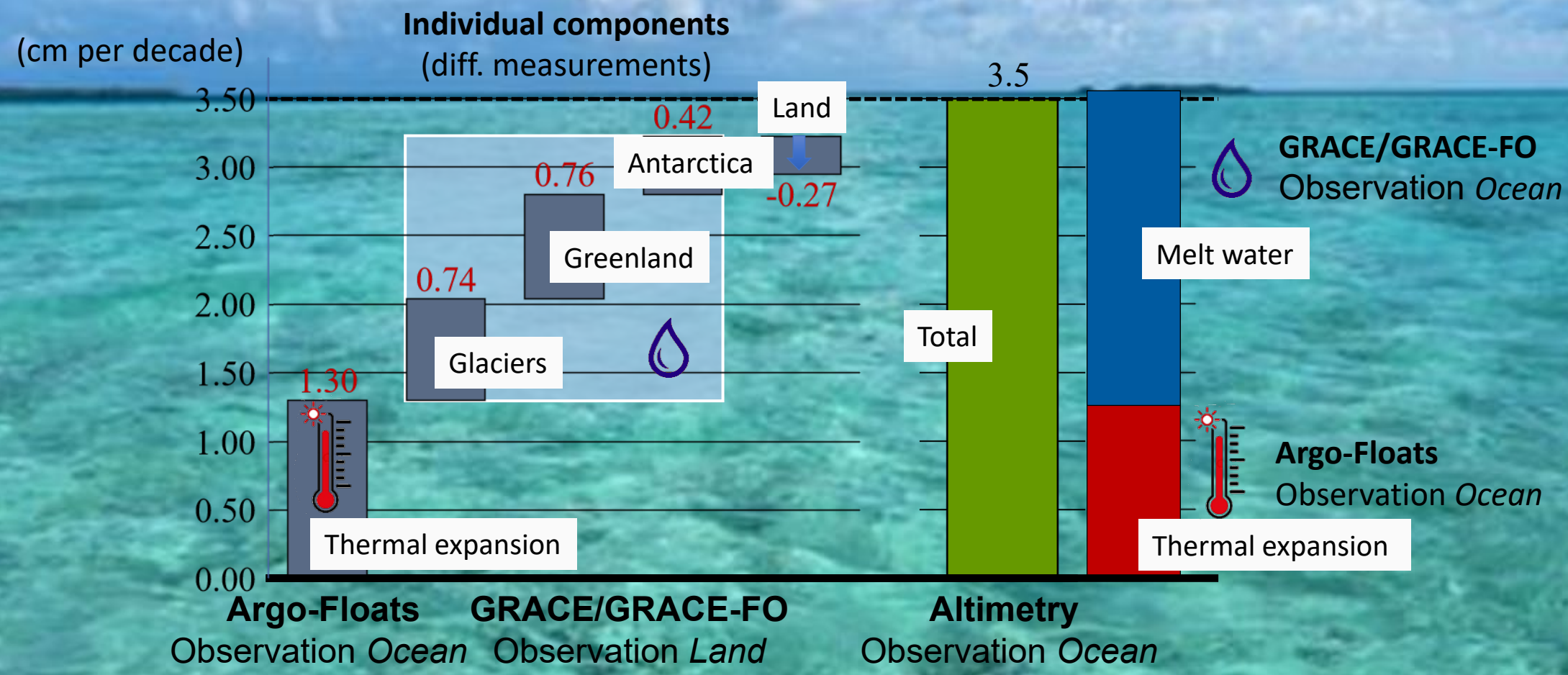



Source: https://data.giss.nasa.gov/gistemp/

Source: Rantanen et al. 2022, Nat. Comm. EE

# Global mean sea-level rise

Trends 2005-2017




After: WCRP Global Sea Level Budget Group, https://doi.org/10.5194/essd-10-1551-2018

# AWI institutes in Germany


Source: Alfred Wegener Institute

# AWI research infrastructure


Neumayer-Station III

Dallmann-Labor

Kohnen-Station

Antarktis

Arktis

Polar 5 | Polar 6

Samoylov-Station

AWIPEV

Alfred-Wegener-Institut

FS Polarstern

FS Mya II

MB Diker & Aade

FK Uthörn

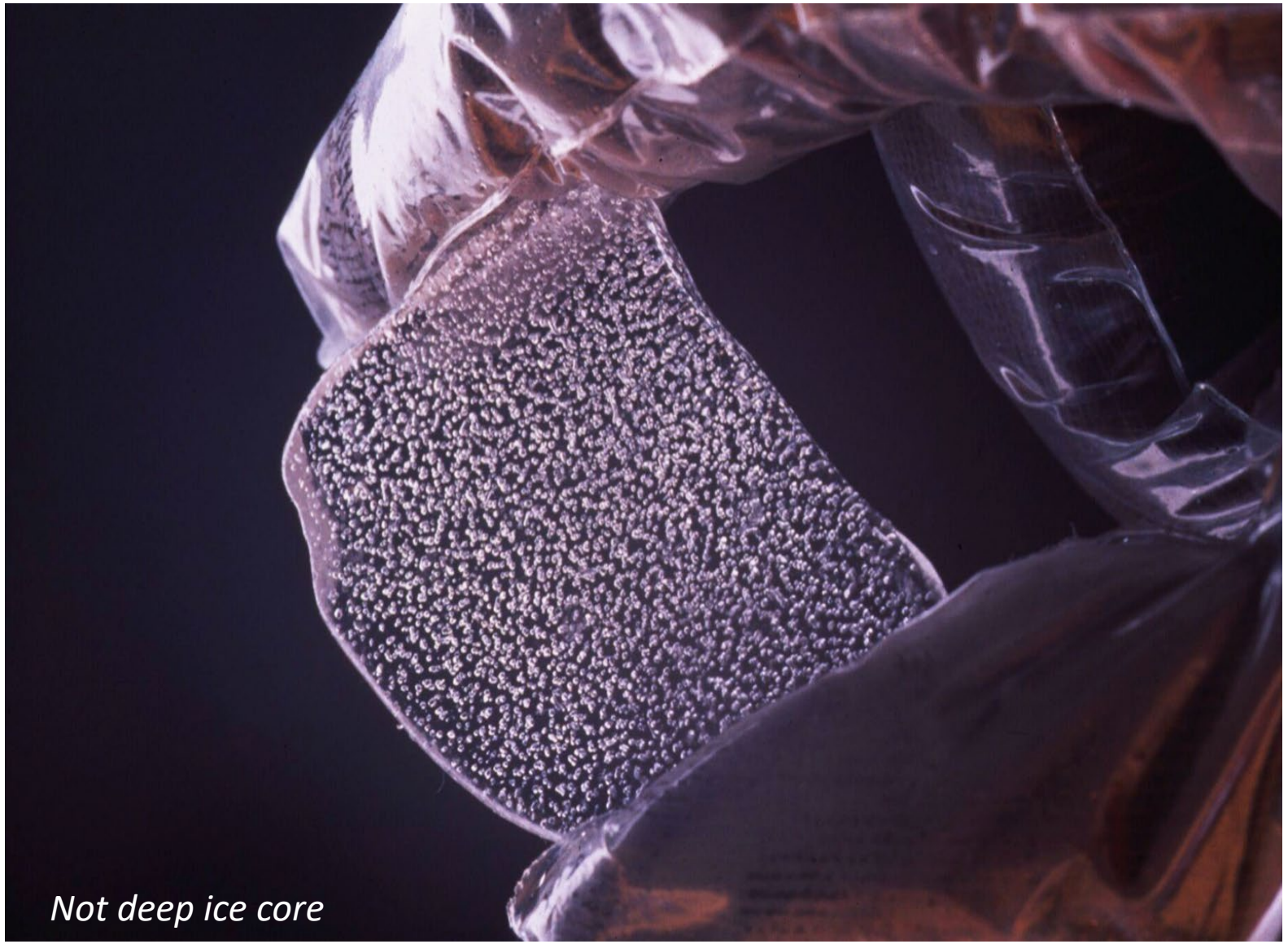
FS Heincke

Source: Alfred Wegener Institute

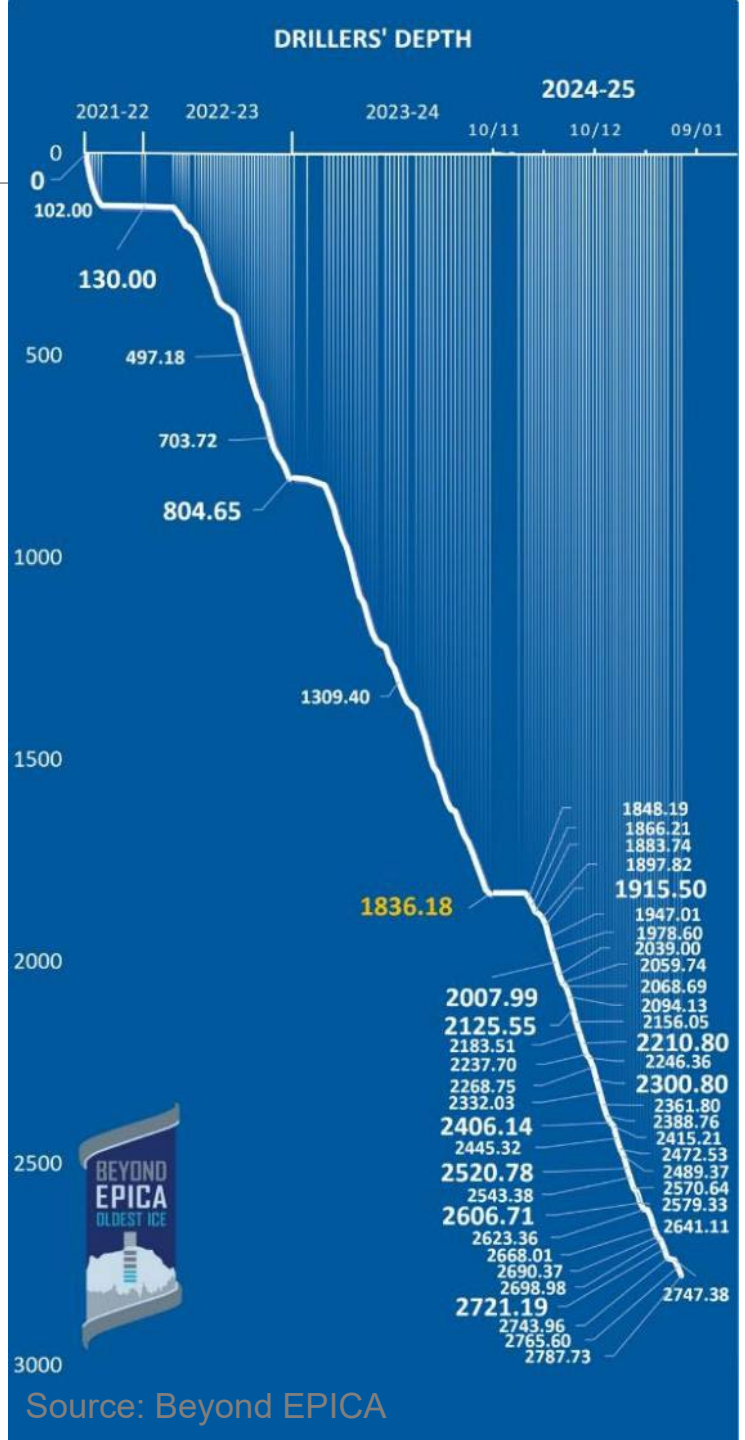
Source: Alfred Wegener Institute


Source: Beyond EPICA, Alfred Wegener Institute

# Ice cores as climate archive

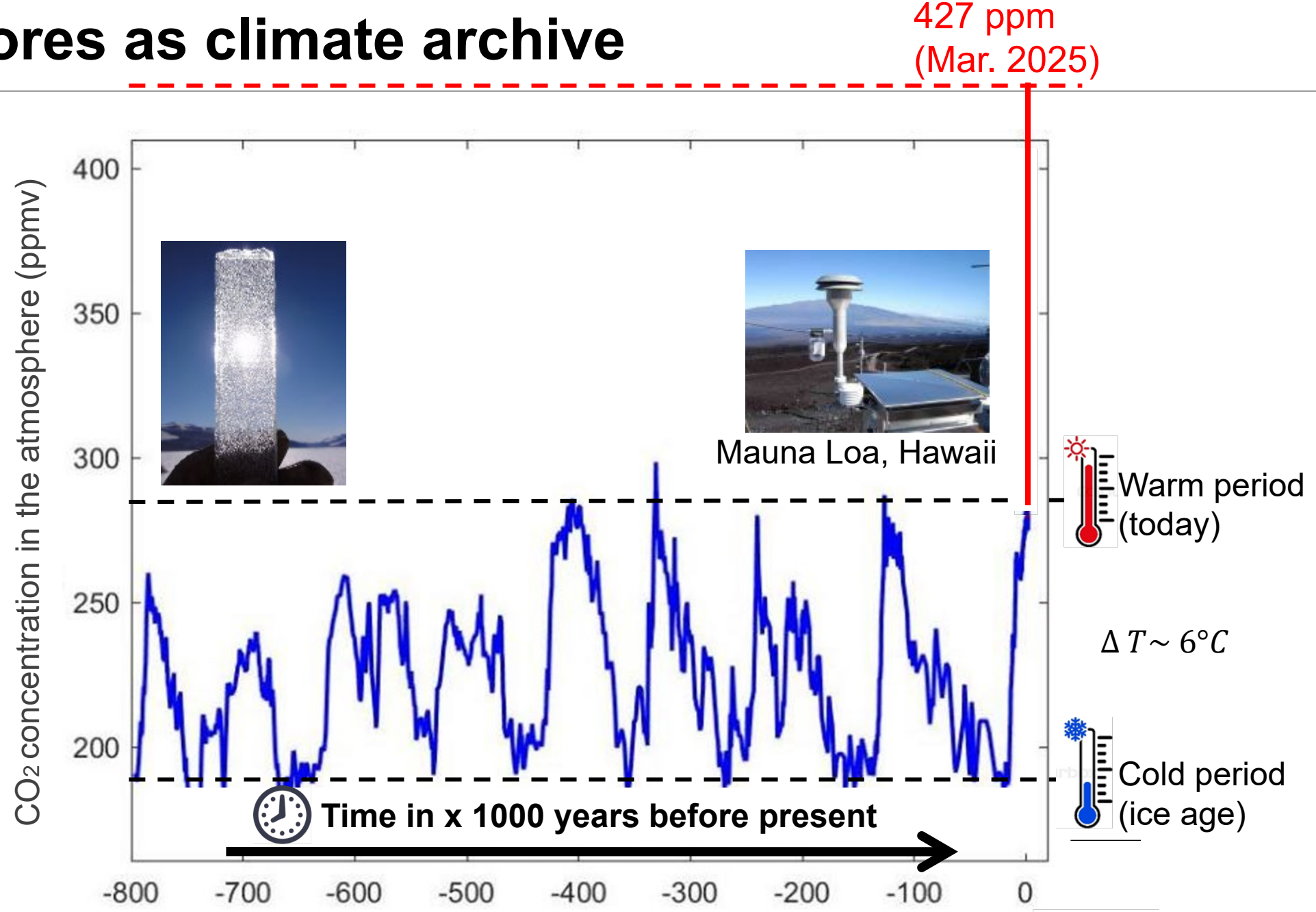



Source: Alfred Wegener Institute

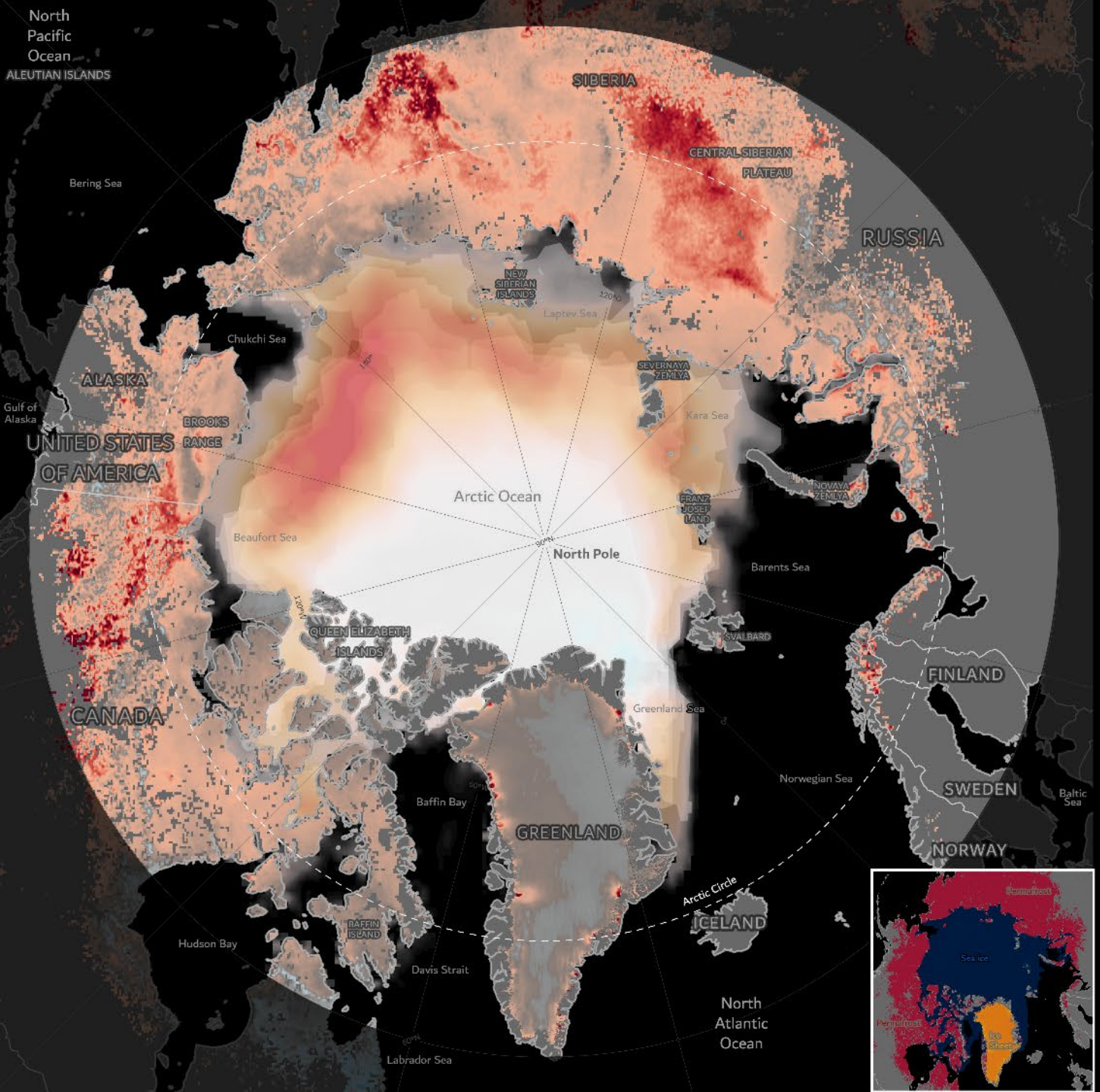



Source: Beyond EPICA

# Ice cores as climate archive



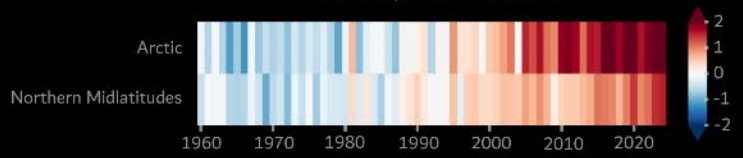

Source: Alfred Wegener Institute




# ARCTIC CHANGE

## WARMING IMPACTS ON THE CRYOPSHERE

**Temperature,**
anomalies compared to 1960-2010 in °C[5]

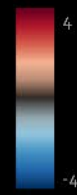



The Arctic is warming much faster than the global average due to polar amplification[1], driving substantial changes in land ice, permafrost, and sea ice. The Greenland Ice Sheet is losing an average of 235 billion tons of ice per year since 2002[2]. Permafrost thaw is deepening due to rising ground temperatures[3]. Sea ice thickness, extent, and concentration are declining, frequently reaching record lows in summer[4]. These changes accelerate sea-level rise, greenhouse gas emissions, and cause shifts in atmospheric and oceanic circulation, triggering widespread environmental transformations extending beyond the Arctic.

**Sea ice,**
decrease in end-of-summer ice concentration in % per decade (1979-2023)[4]


**Permafrost,**
relative increase in thaw depth in % per year (2003-2019)[3]


**Greenland Ice Sheet,**
reduction in ice thickness in m per year (2011-2022)[2]




**Sea ice extent,**
relative end-of summer occurrence (1979-2024)[5]


Maps & Layout: Theresa Schreglmann
Scientific Advisory & Text: Dr. Ingo Sasgen (AWI) & Dr. Nils Hutter (GEOMAR)

Main Map Scale: 1:22.000.000
Side Map Scale: 1:101.000.000
Projection: NSIDC Sea Ice Polar Stereographic North
Data Sources: Staates, Ocean, Geographic Boundaries; Natural Earth

AWI

[1]Data Temperature: Annual near-surface air temperature anomalies compared to global long-term average for 1960-2010 for zonal bands of the Arctic (64°N-90°N) and Northern Midlatitudes (44°N-64°N), https://data.giss.nasa.gov/gistemp/

[2]Data Greenland Ice Sheet: CryoSat-2 rates of surface-elevation change, update to doi: 10.5194/tc-8-1539-2014; mass balance Greenland, doi: 10.1038/s43247-020-0010-1

[3]Data Permafrost: Data Permafrost: ESA CCI Permafrost Active Layer Thickness, https://climate.esa.int/en/projects/permafrost/data/ . Relative changes represent the linear trend normalized by the detrended standard deviation.

[4]Data Sea Ice: Data Sea Ice: OSI SAF Global Sea Ice Concentration v3.0. C3S/ECMWF/EUMETSAT/MET Norway, https://climate.copernicus.eu/climate-indicators/sea-ice

[5]Data Sea Ice Extent: Monthly NSIDC sea-ice extent for September, version 3.0, https://nsidc.org/data/seaice_index

# Concept and relevance of ice sheet mass balance

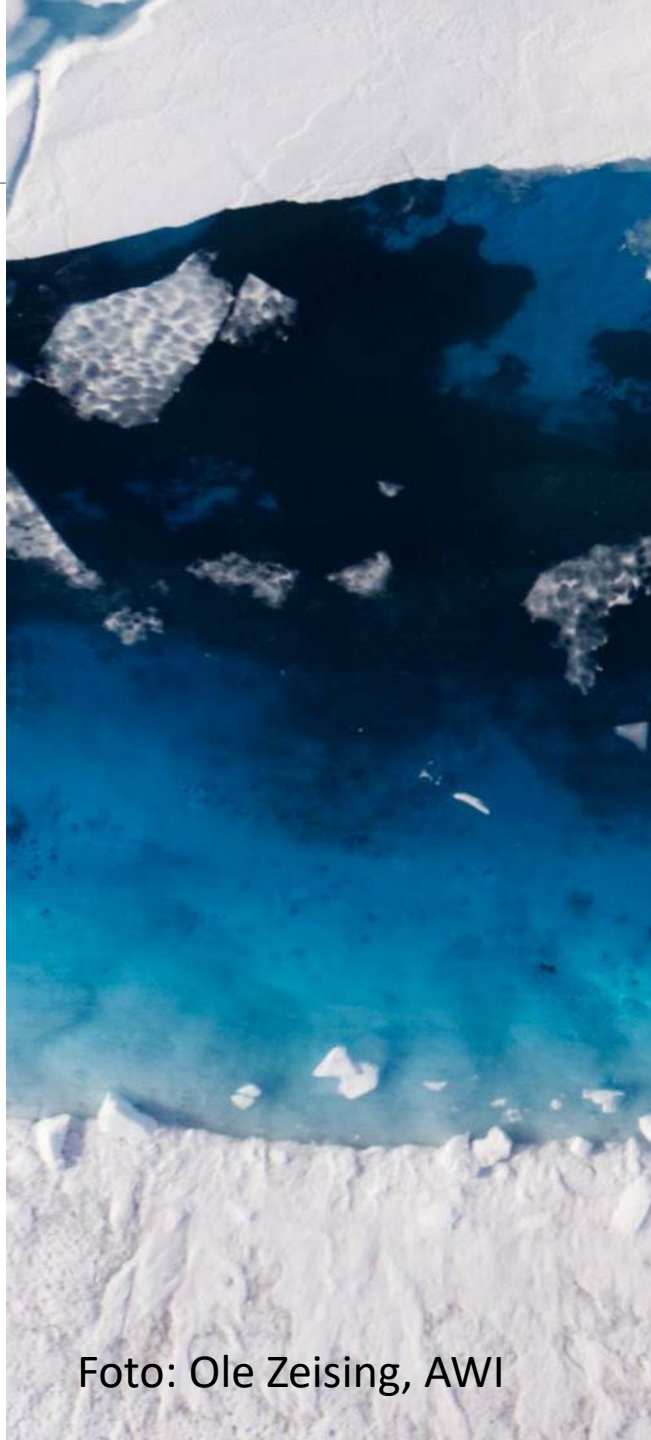
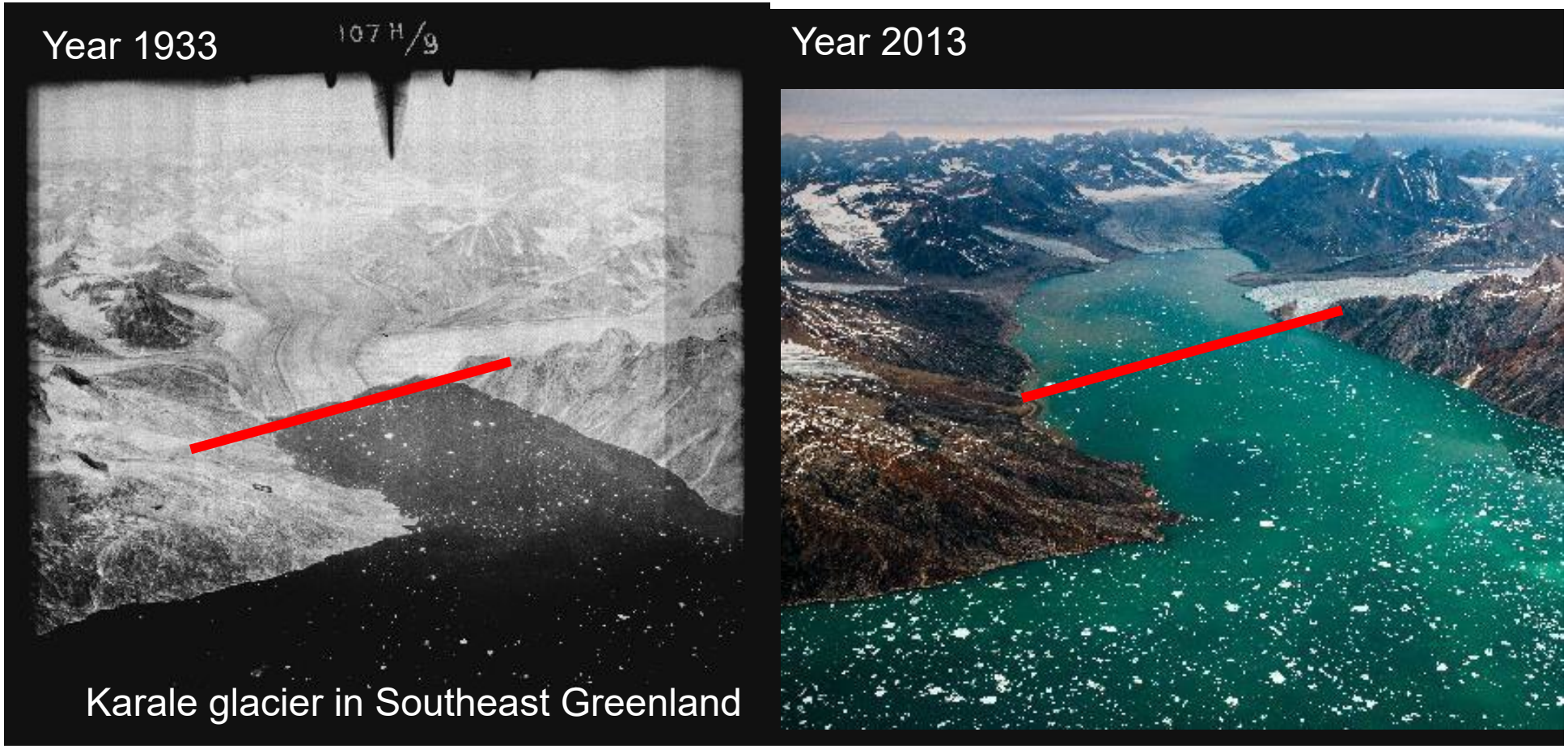


Foto: Ole Zeising, AWI

# Greenland ice retreat




→ **Retreat of the calving front position**

Credit (l): Natural History Museum of Denmark & Agency for Data Supply and Efficiency, (r): Natural History Museum of Denmark & Hans Henrik Thostrup

# Mass balance concept for ice sheets

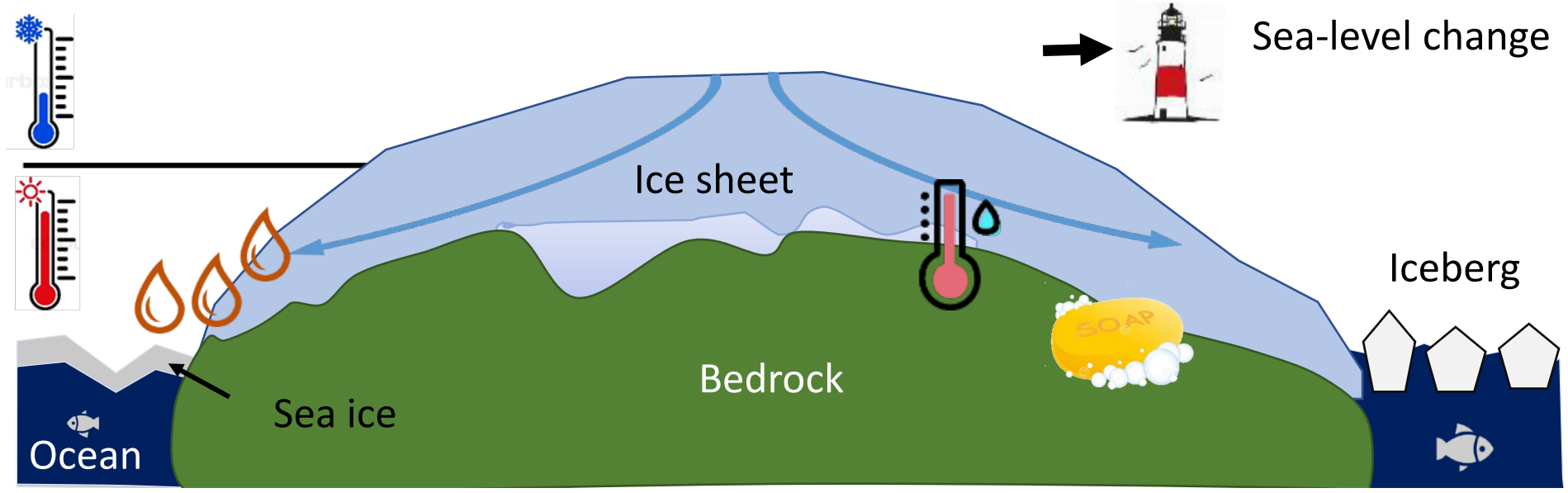
Snowfall

− Calving

− Melt

**0 > ≠** Mass balance

→ Sea-level change



# Calving event at the Helheim Gletscher, East Greenland

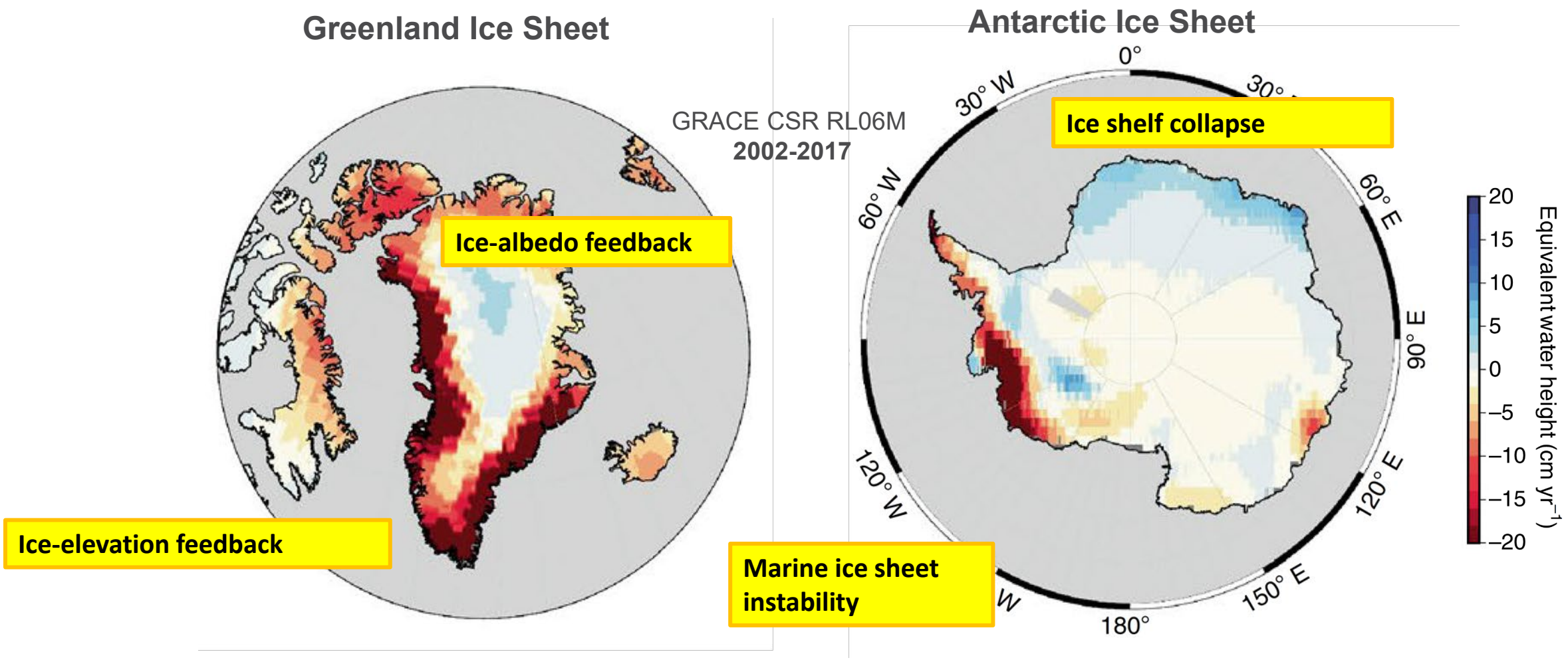
Source: Nicolaj Krog Larsen (Time-lapse of ca. 6 min)

# Melt event, Watson River, Southwest Greenland 2012

Source: https://youtu.be/RauzduvlYog

# Possible ice sheet tipping points

*Mass balance 2003-2017 from GRACE/GRACE-FO satellite gravimetry data*




Tapley et al. 2018, Contributions of GRACE to understanding climate change, Nat. Clim. Change

Source: Alfred Wegener Institute

# Arctic glaciers from GRACE/GRACE-FO

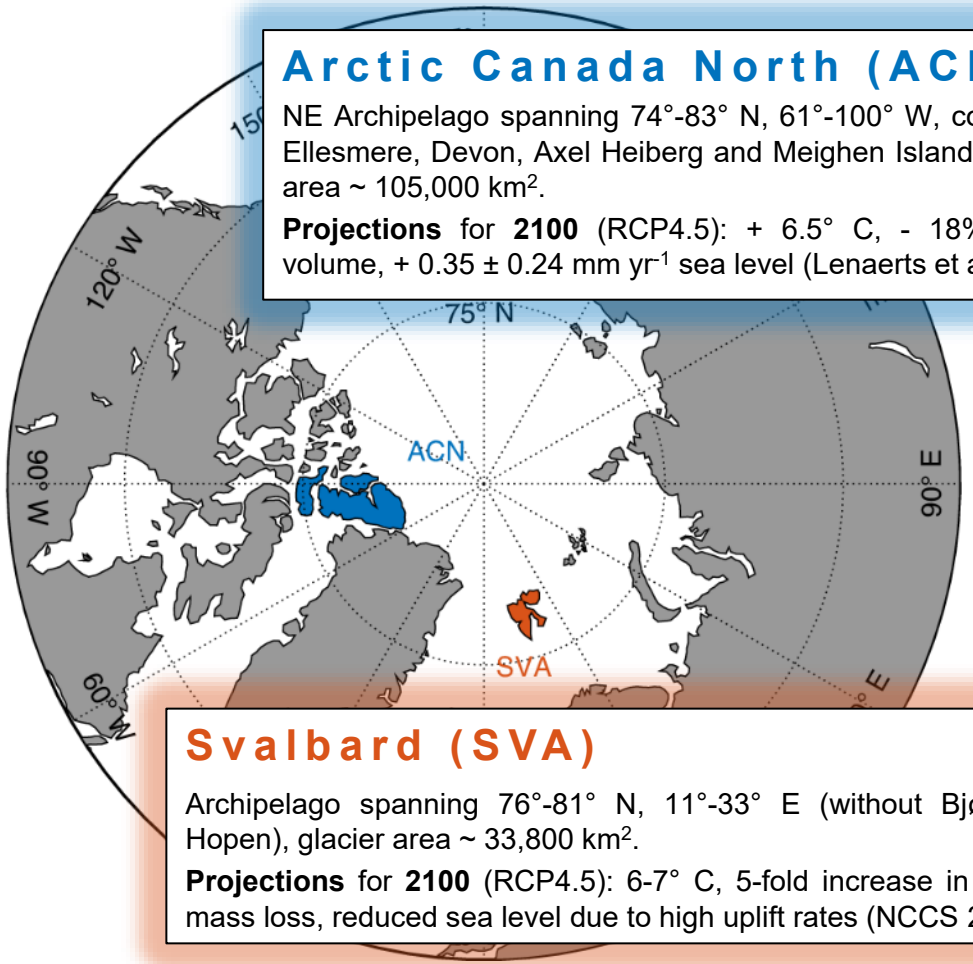
Source: Beyond EPICA

# Introduction

## Arctic Canada North (ACN)

NE Archipelago spanning 74°-83° N, 61°-100° W, consists of Ellesmere, Devon, Axel Heiberg and Meighen Islands, glacier area ~ 105,000 km$^2$.

**Projections** for **2100** (RCP4.5): + 6.5° C, - 18% glacier volume, + 0.35 ± 0.24 mm yr$^{-1}$ sea level (Lenaerts et al. 2013).




## Svalbard (SVA)

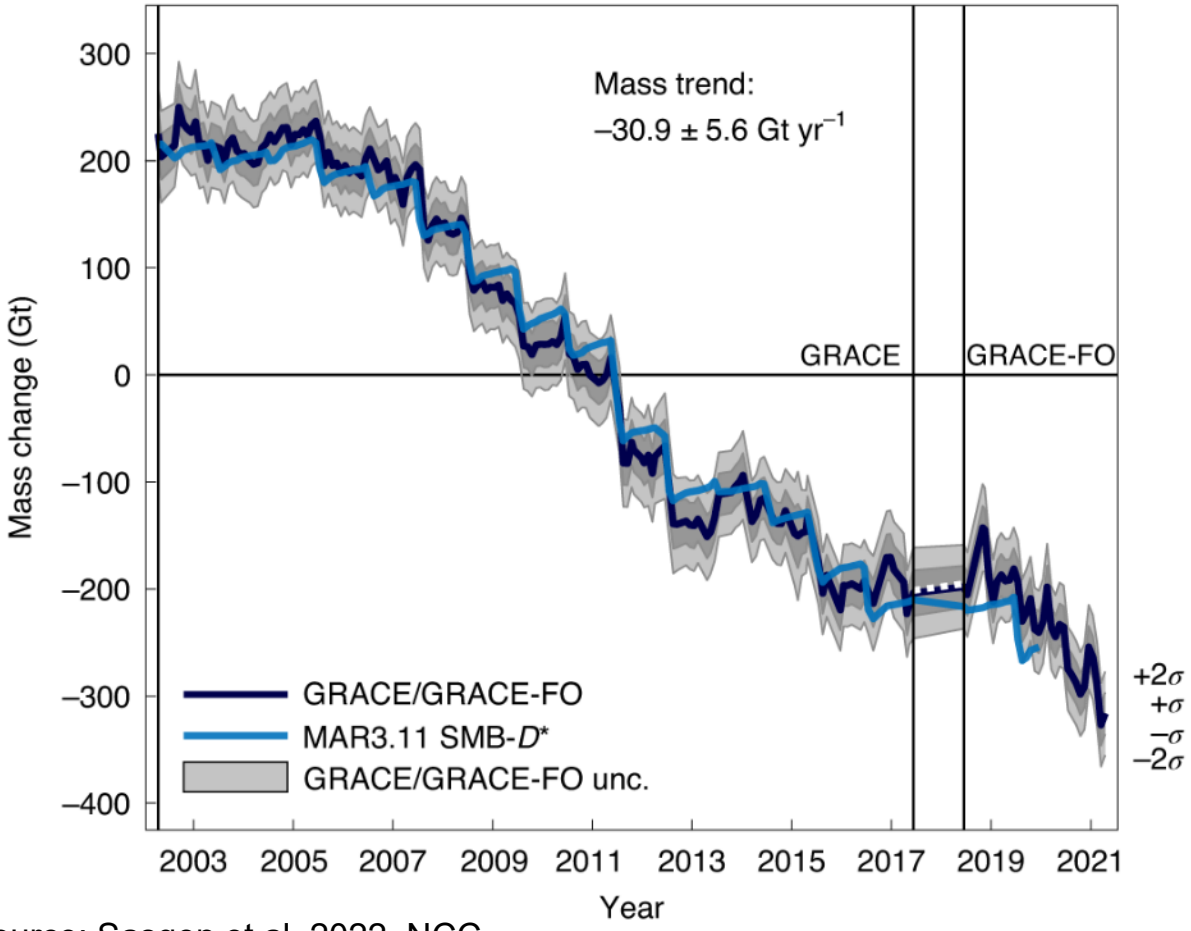
Archipelago spanning 76°-81° N, 11°-33° E (without Bjørnøya, Hopen), glacier area ~ 33,800 km$^2$.

**Projections** for **2100** (RCP4.5): 6-7° C, 5-fold increase in glacier mass loss, reduced sea level due to high uplift rates (NCCS 2019).

Source: Sasgen et al. 2022, NCC

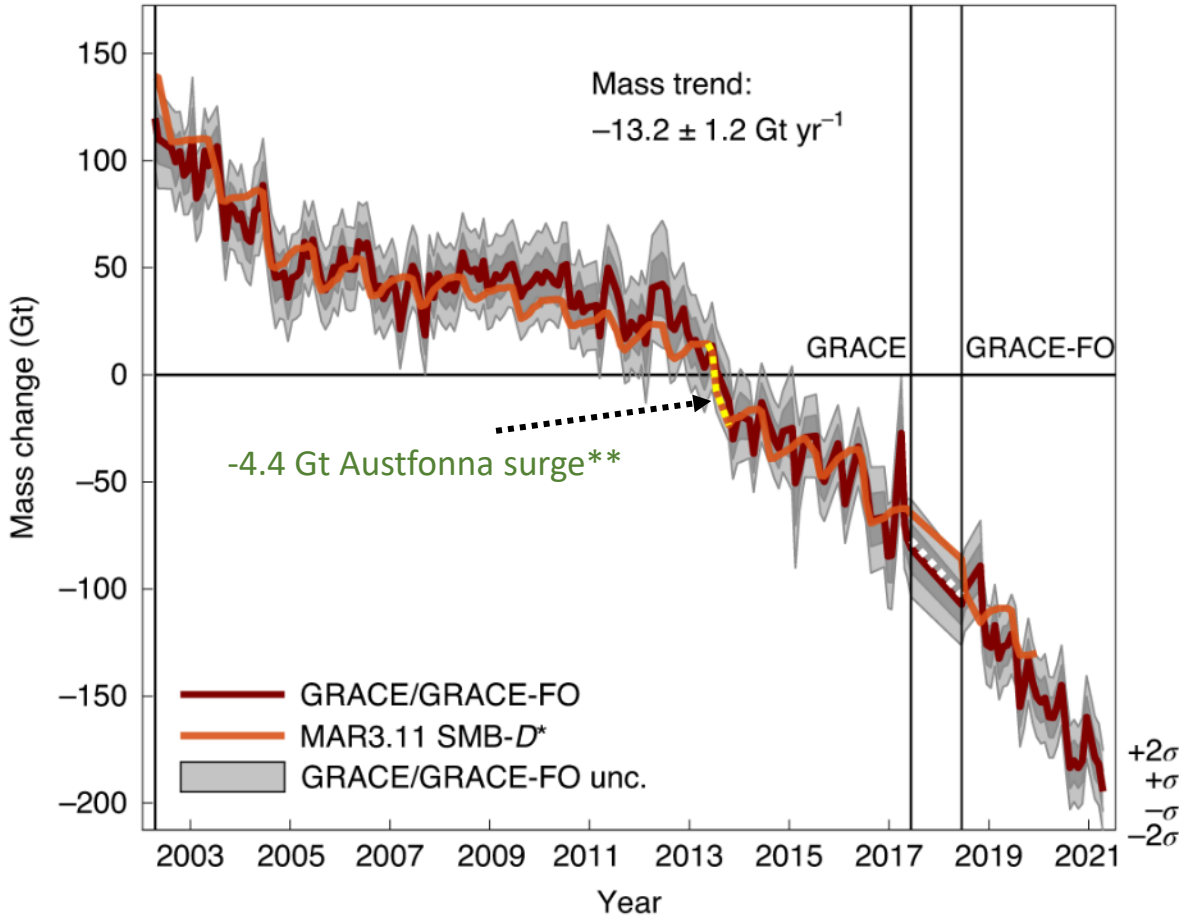
# Mass change from GRACE/GRACE-FO and SMB

## Arctic Canada North (ACN)




Source: Sasgen et al. 2022, NCC

## Svalbard (SVA)

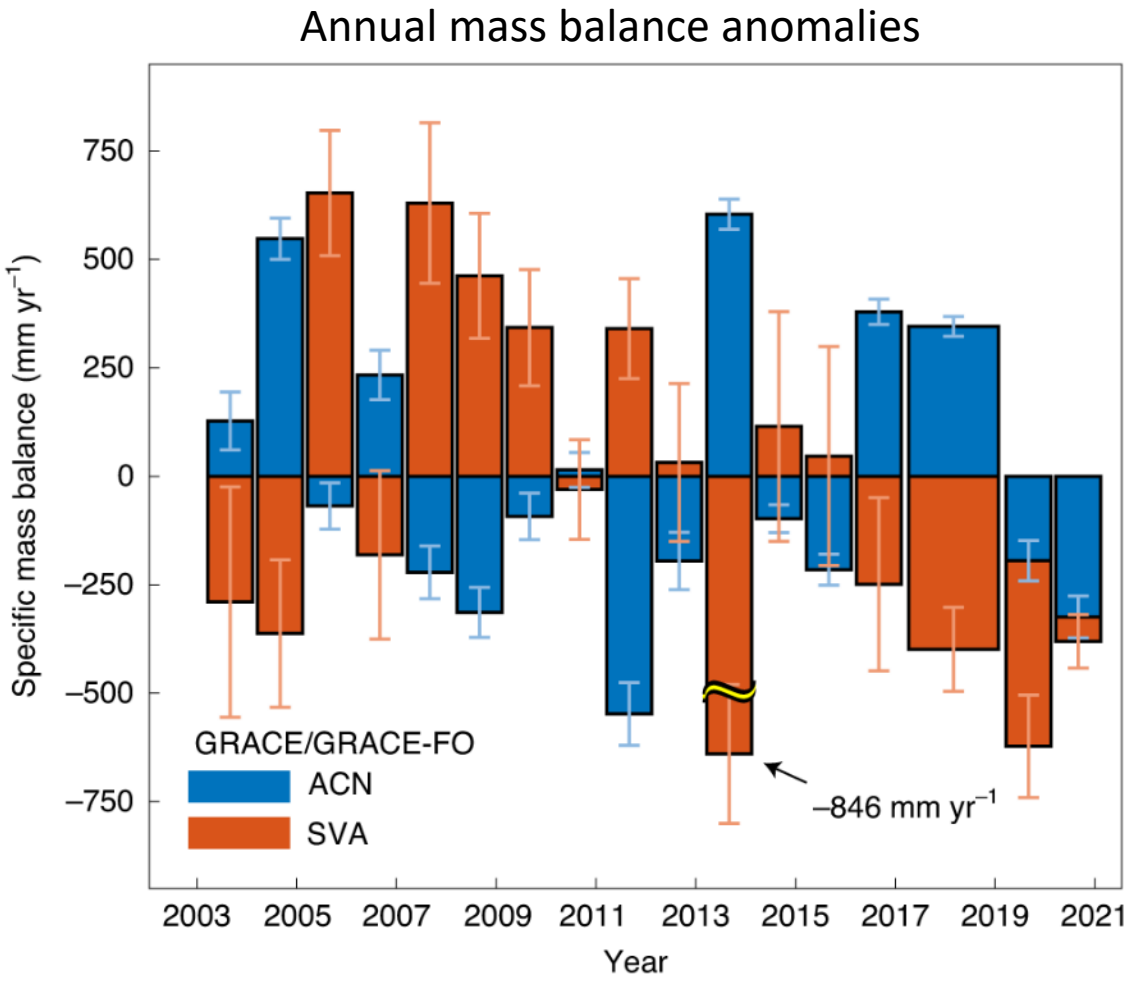


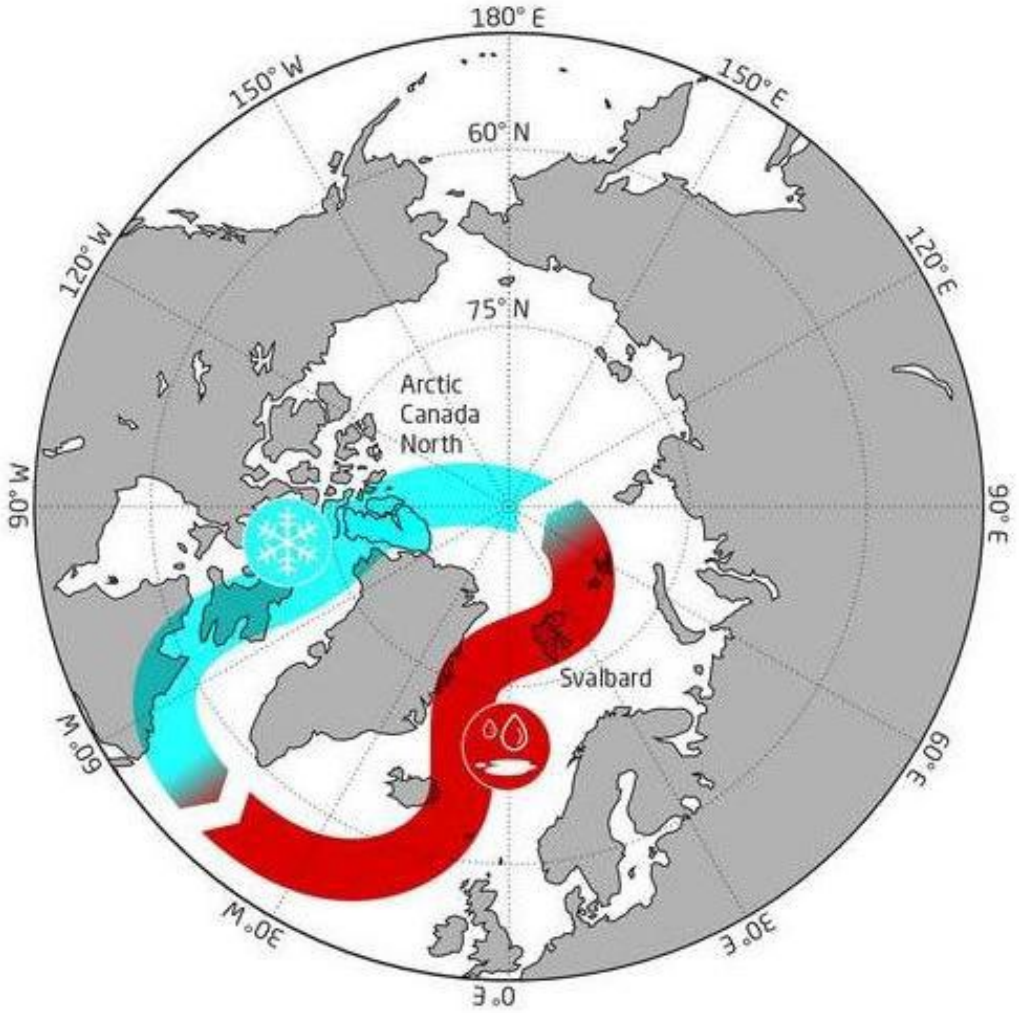

Discharge (D) estimates from literature:
ACN: -4.6±1.9 Gtyr$^{-1}$ (Gardner et al. 2011)
SVA: -5.2±1.5 Gtyr$^{-1}$ (Blaszczyk et al. 2009)

* Wouters et al. 2019, https://doi.org/10.3389/feart.2019.00096

**McMillan et al. 2014, Helm, *pers. comm.*

# GRACE/GRACE-FO annual balances



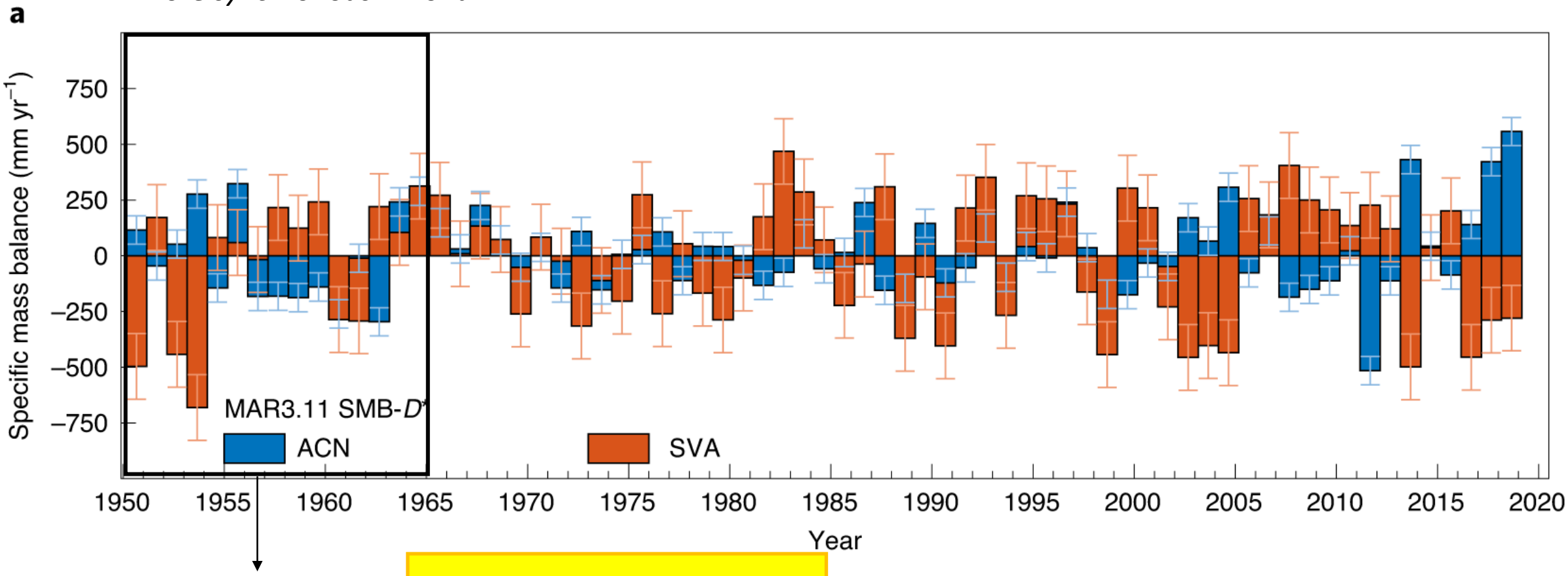

→ Striking ***contrary behavior*** between ACN and SVA
(15 out of 17 with opposite-sign anomalies)

*Removed linear trend 2002-2021*

Source: Sasgen et al. 2022, NCC

# Annual balance anomalies from 1950 to 2015

*More synchronous - "Zonal"*




Binning
(e.g. 15 years)

*Calculate running correlation of mass balance anomalies…*

*After removal of polynomial fit (n=3) over 1950-2019*

Source: Sasgen et al. 2022, NCC

# Drivers of mass balance

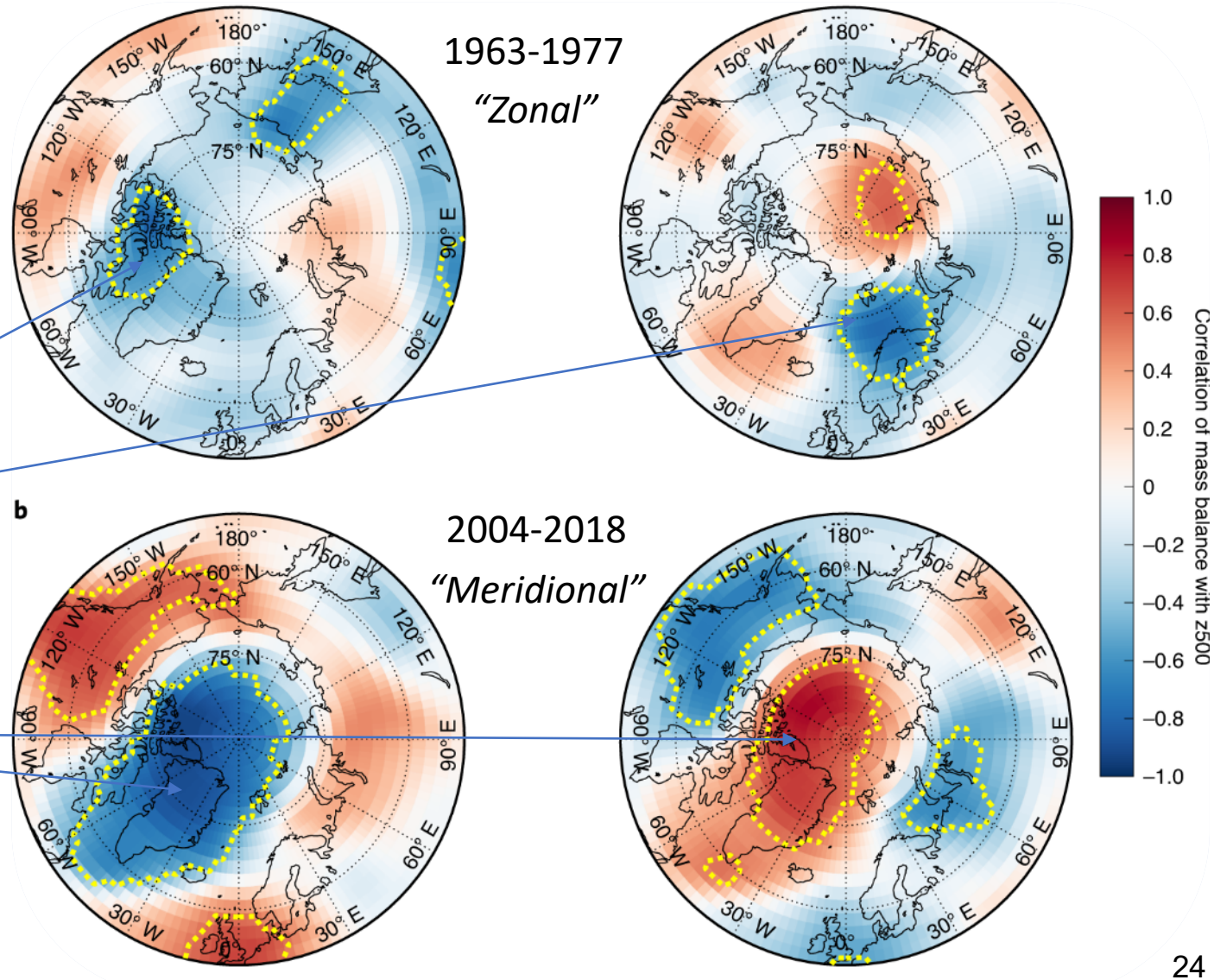
Correlation of each region's **mass balance anomaly** with **500 hPa geopotential height** (GPH) during June-July-August (JJA)

- mid- to upper troposphere
- indicative of ridges and troughs

*Local geopotential height most relevant*

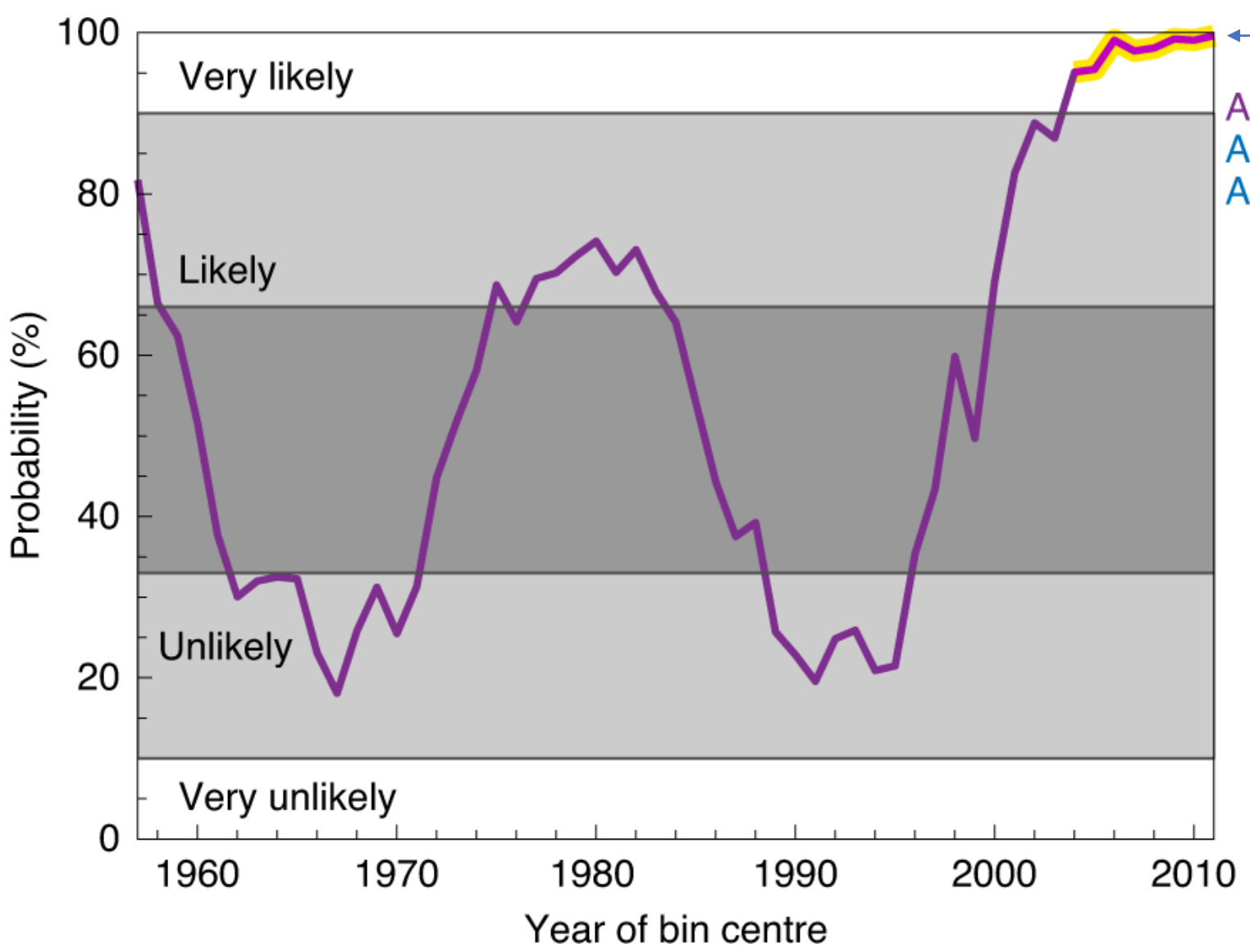
*Geopotential height over Greenland and lower Arctic most relevant*

*Focus on JJA, as summer months primarily control annual balance*




Source: Sasgen et al. 2022, NCC

# Probability of category of annual mass balance




Exceeding 95 % confidence limit

Asynchronous
ACN + | SVA –
ACN – | SVA +

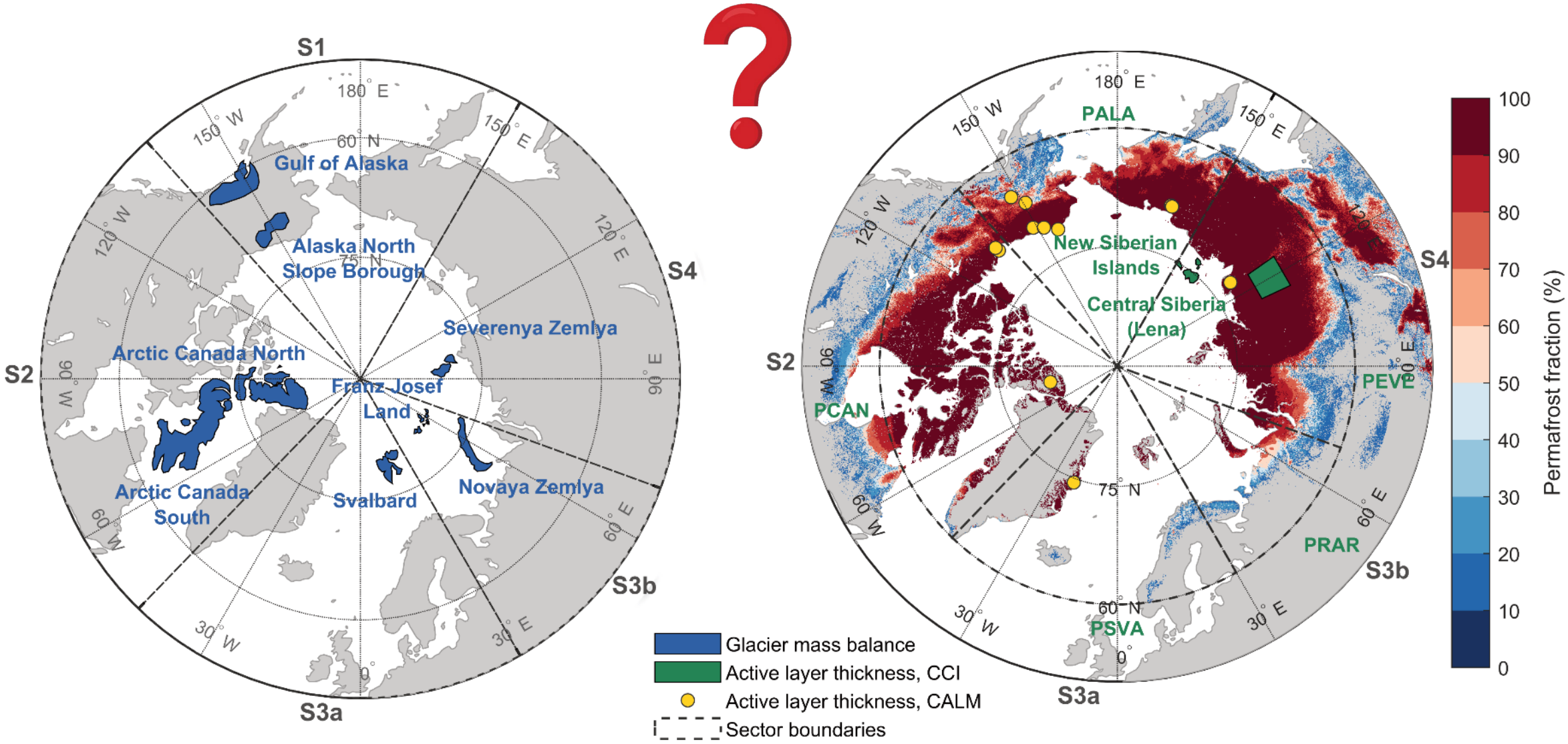
*After 2000, asynchronous years very likely*

*Up to 2000, fluctuations between synchronicity and asynchronicity*

*SMB uncertainties propagated to categorization.*

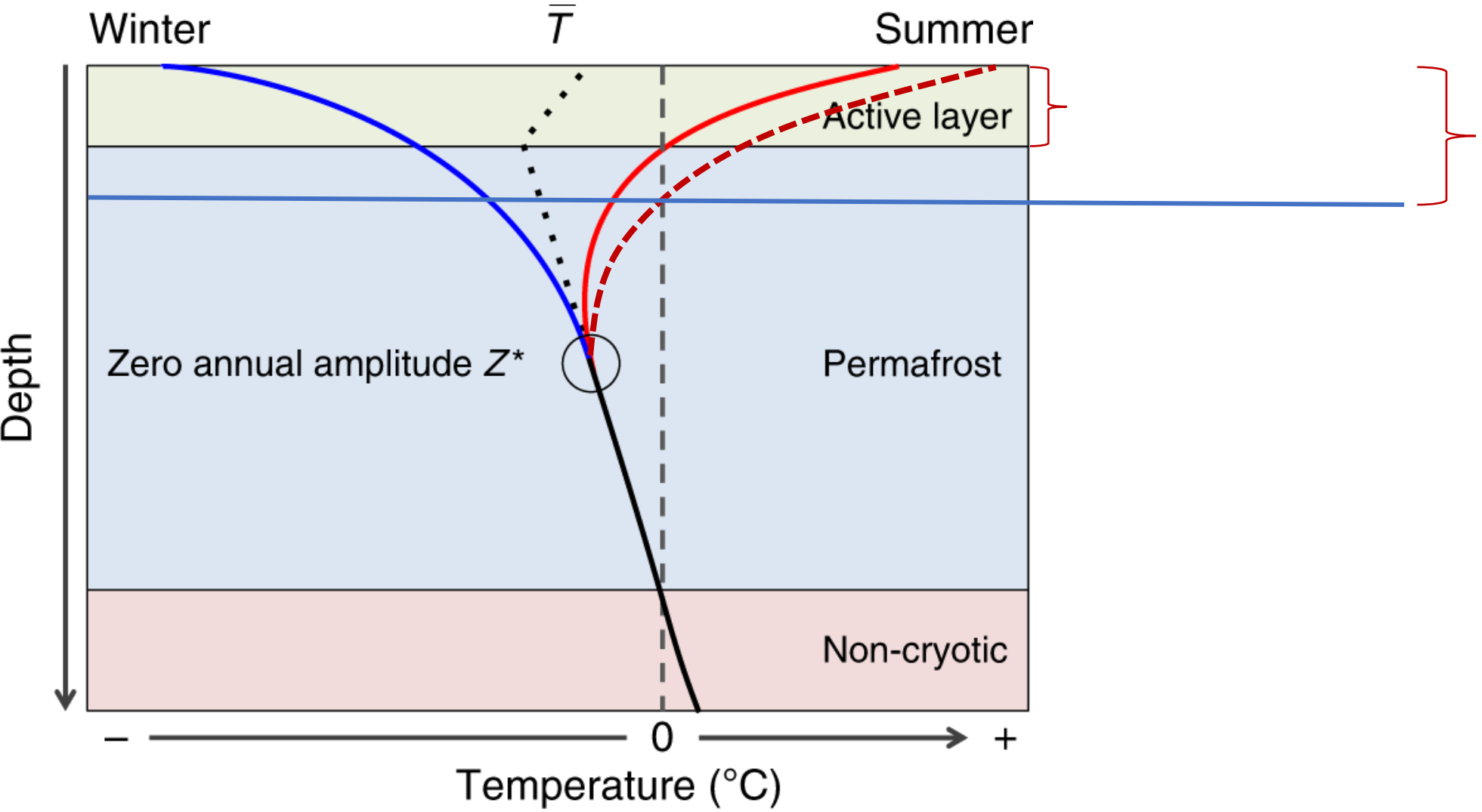
Source: Sasgen et al. 2022, NCC

# Arctic glaciers and permafrost




Source: Sasgen et al. 2022, NCC

# Thermal regime of permafrost



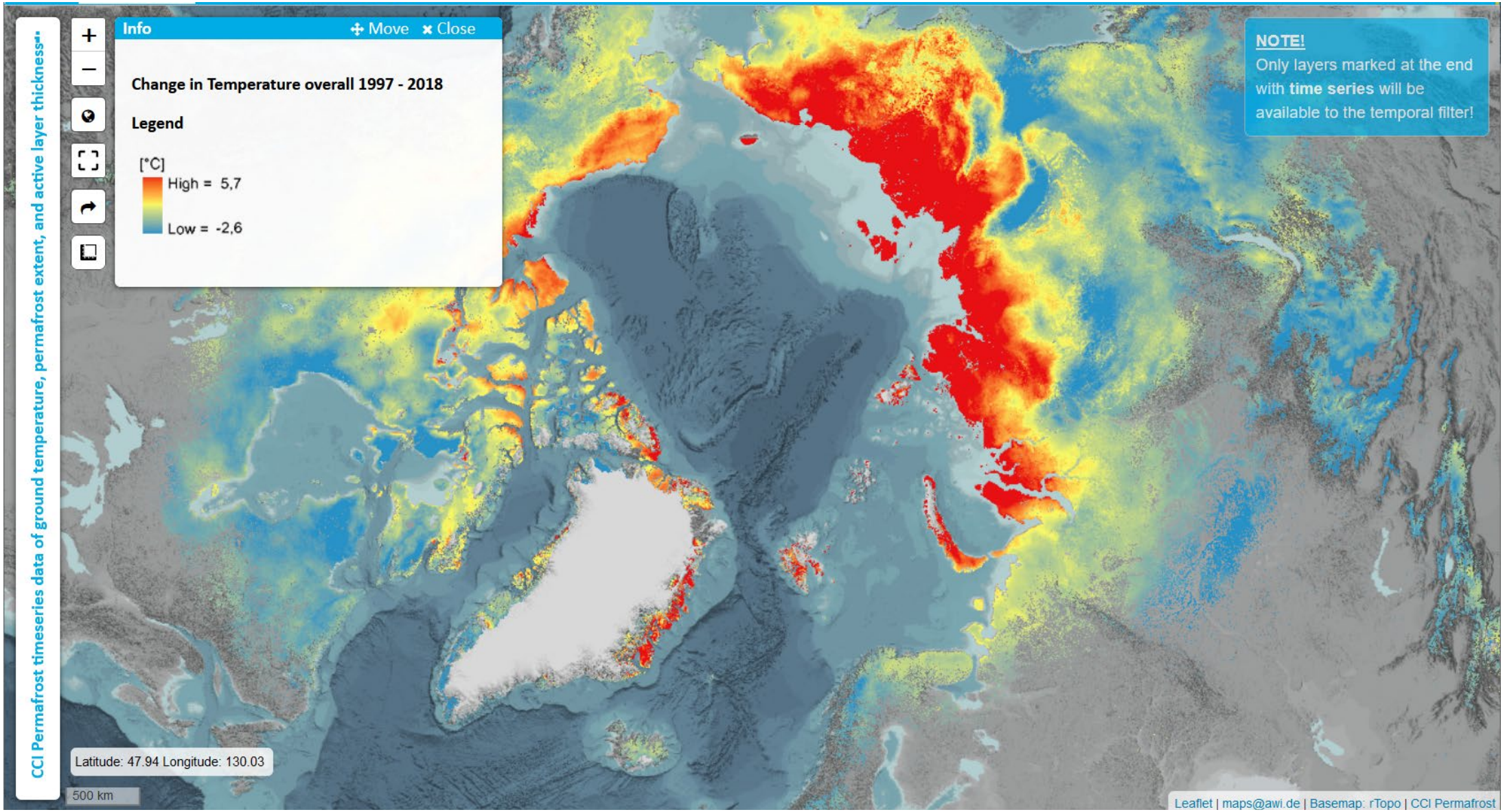

Biskaborn et al. 2019, *Nat.Comm.*

# *In situ:* Samoylov AWI long-term observatory, Russia


*Establishment & data collection: Julia Boike (AWI)*

https://www.awi.de/forschung/geowissenschaften/permafrostforschung/schwerpunkte/energie-und-wasserbilanz/galerien/samoylov.html

# *Remote sensing & model:* ESA CCI permafrost




https://maps.awi.de/

# Regression of impacts observations onto index

*In situ*

○ Active layer thickness, CALM

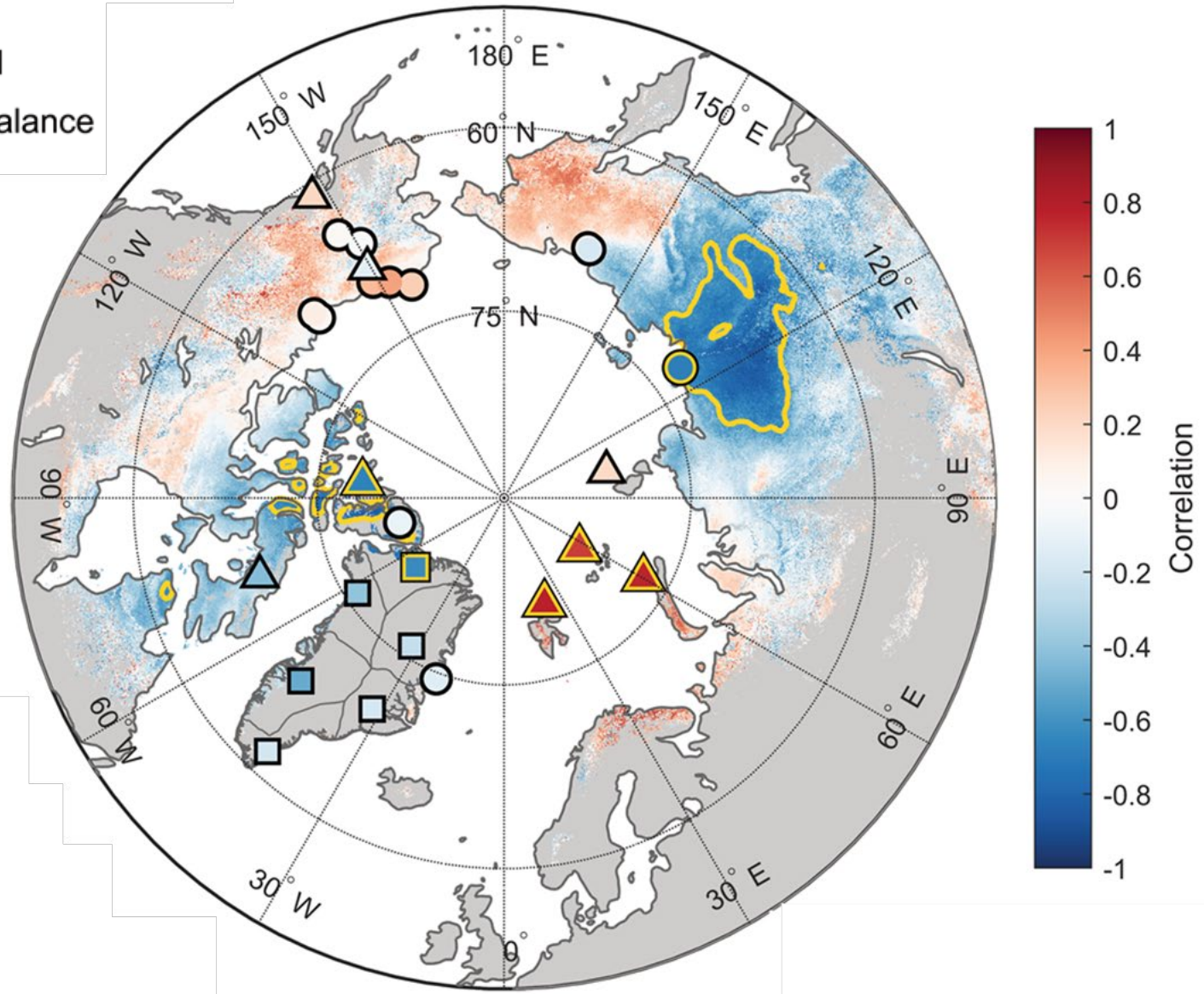
*GRACE/GRACE-FO*

□ Greenland Ice Sheet mass balance

△ Glacier mass balance

*Remote sensing*

▨ Active layer thickness



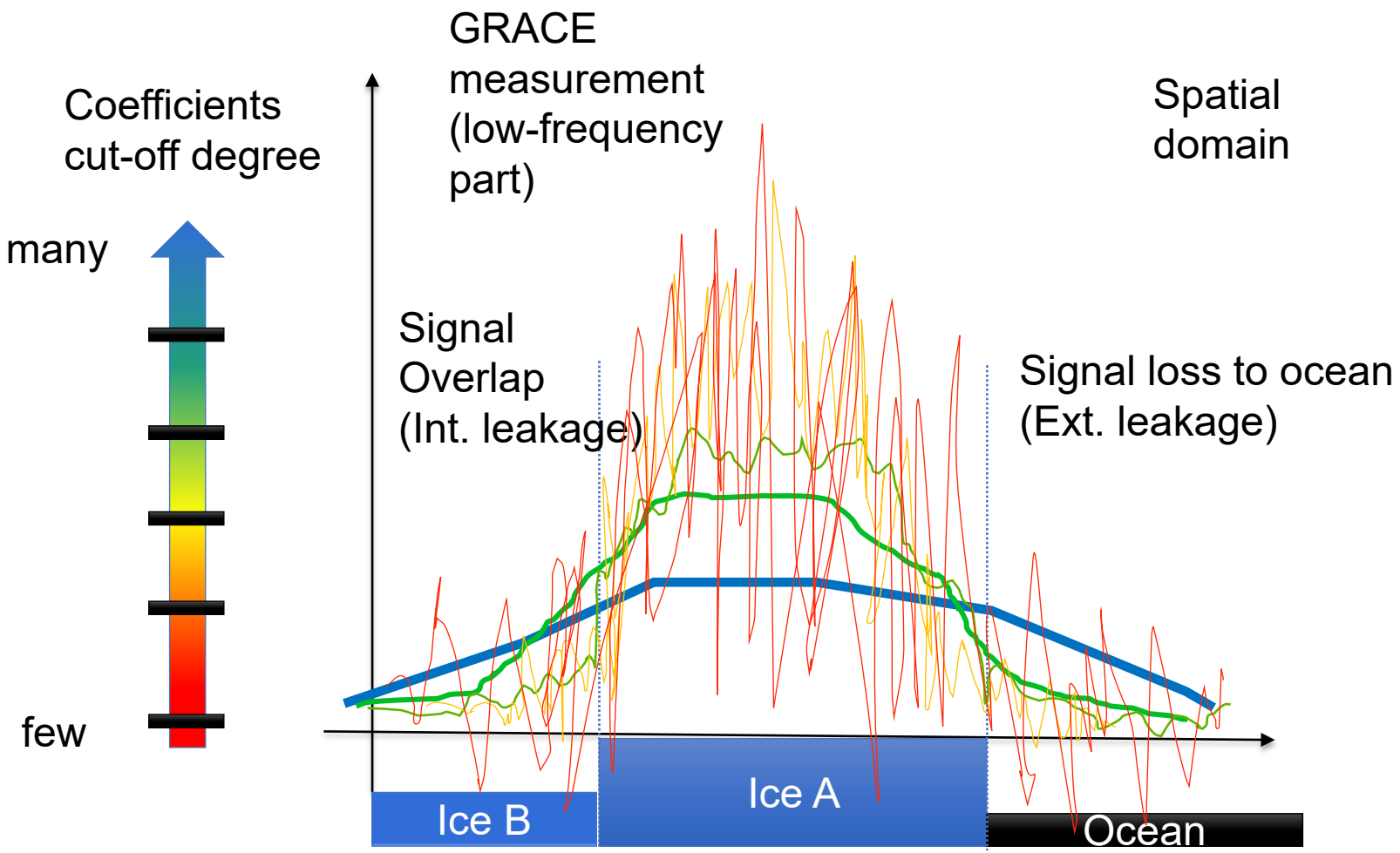

Source: Sasgen et al. 2024, Nat. Comm. EE

Source: Alfred Wegener Institute

# Satellite data combination

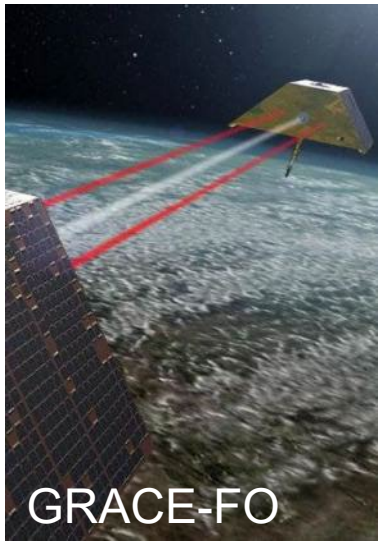
## Example of gravimetry and altimetry

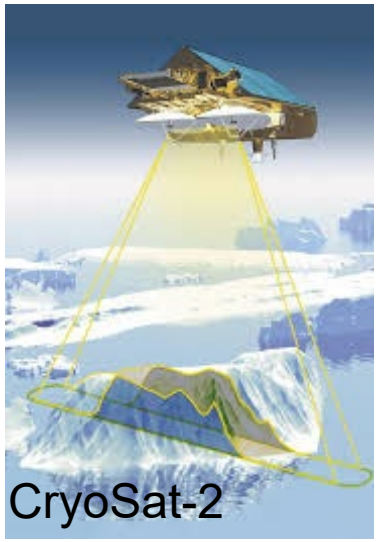
# Motivation

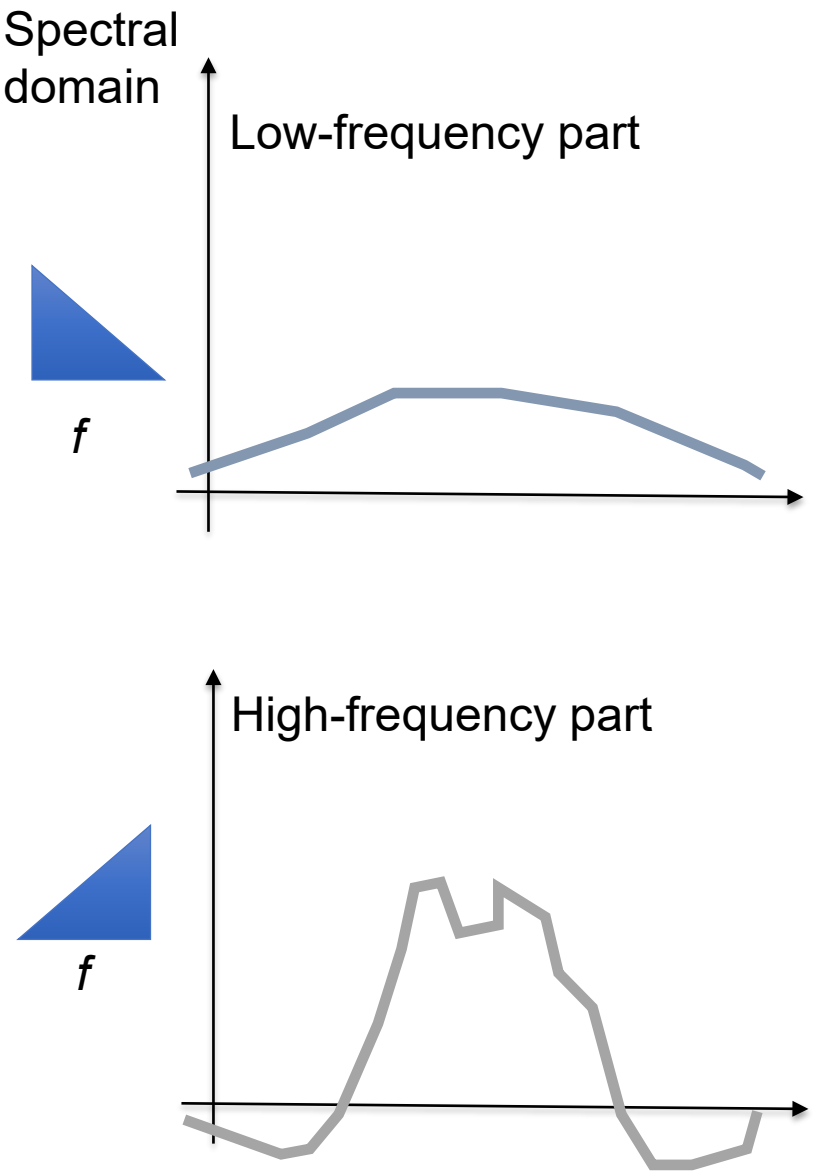


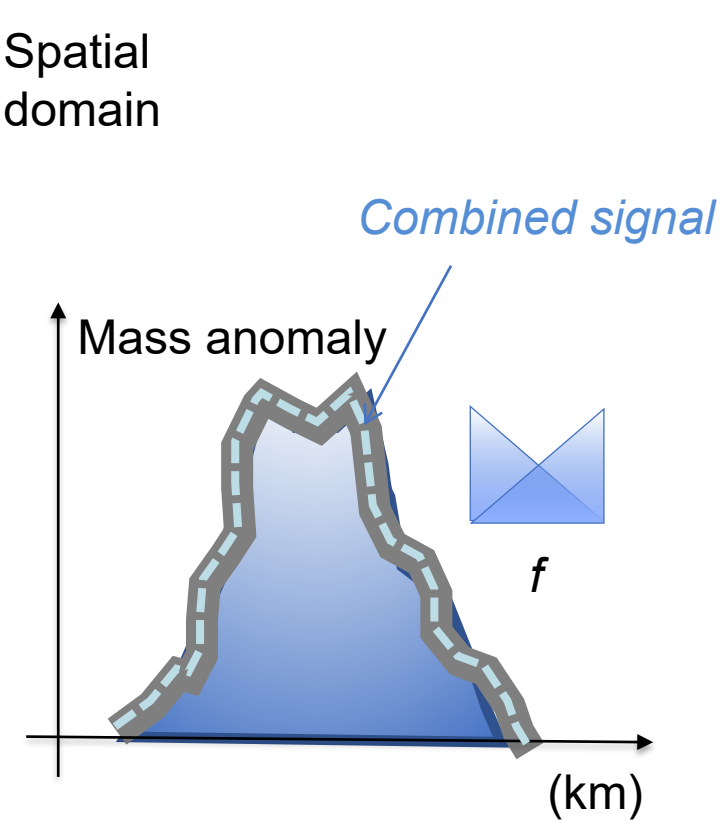

Source: Sasgen et al. 2019, Remote Sensing

# Motivation



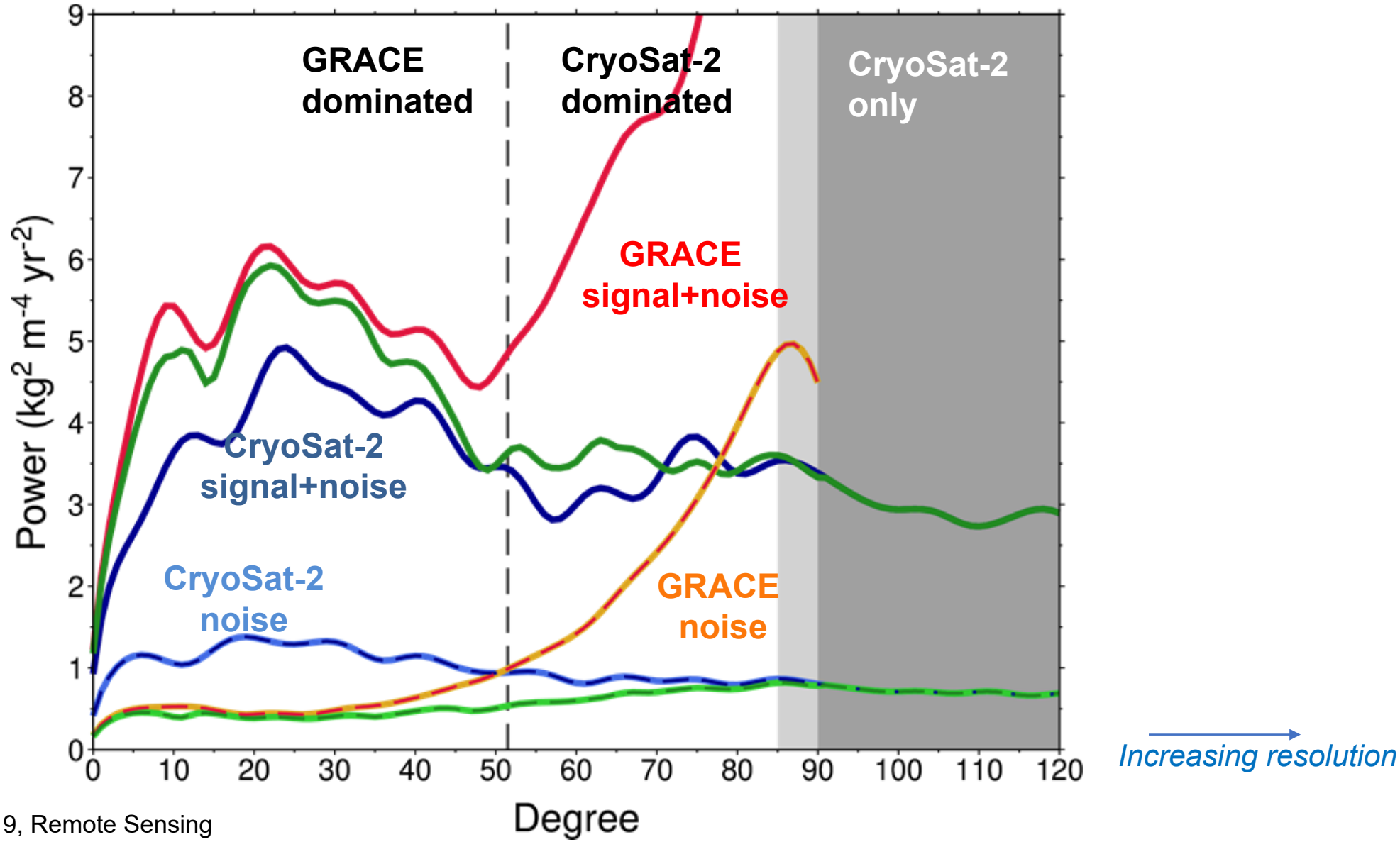



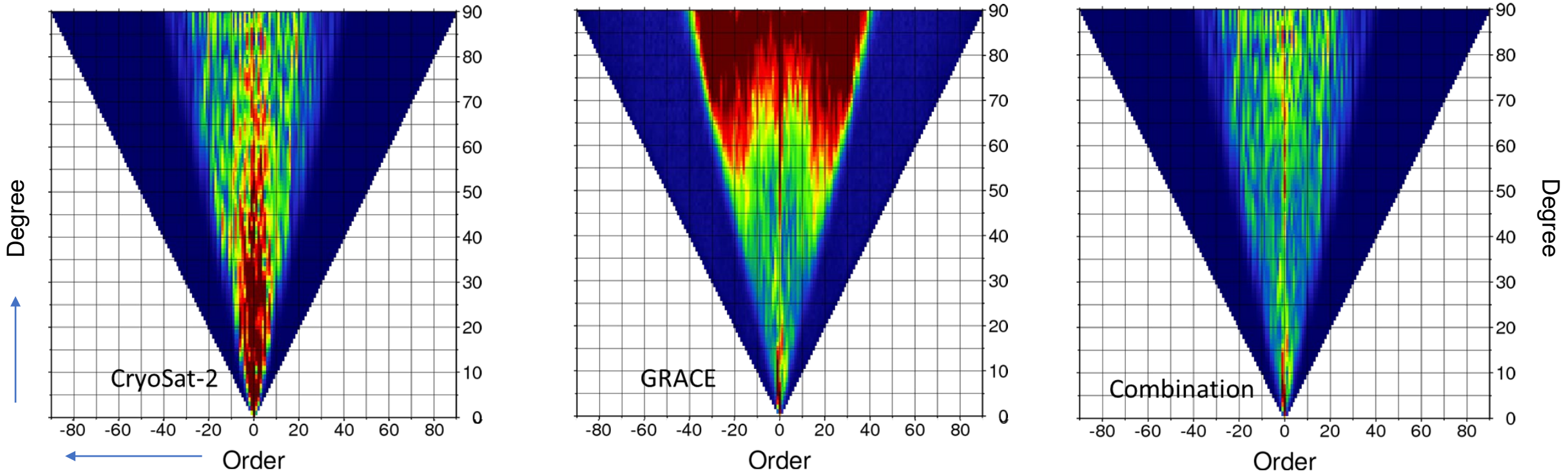

Source: Sasgen et al. 2019, Remote Sensing

# Ensemble mean and std. dev.



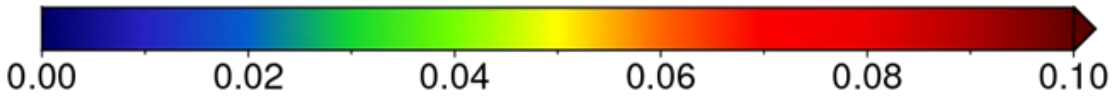

Source: Sasgen et al. 2019, Remote Sensing

# Uncertainty in the spectral domain




*Increasing resolution*

**Uncertainty of mass change 2011-2017**

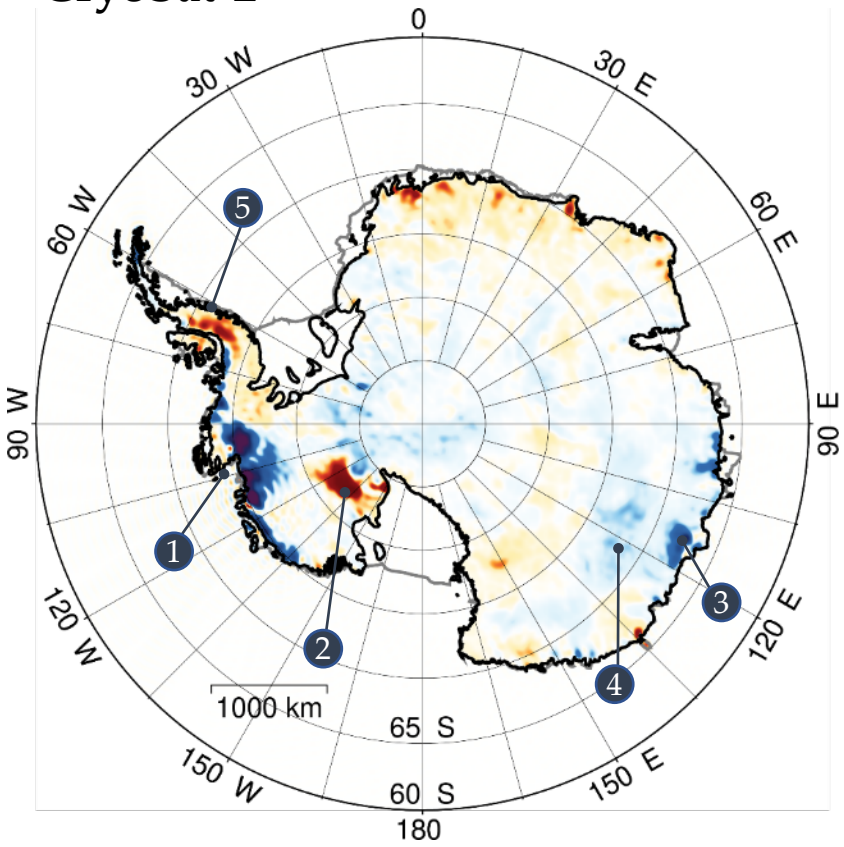



Standard deviation of coefficient (kg $m^{-2}yr^{-1}$)

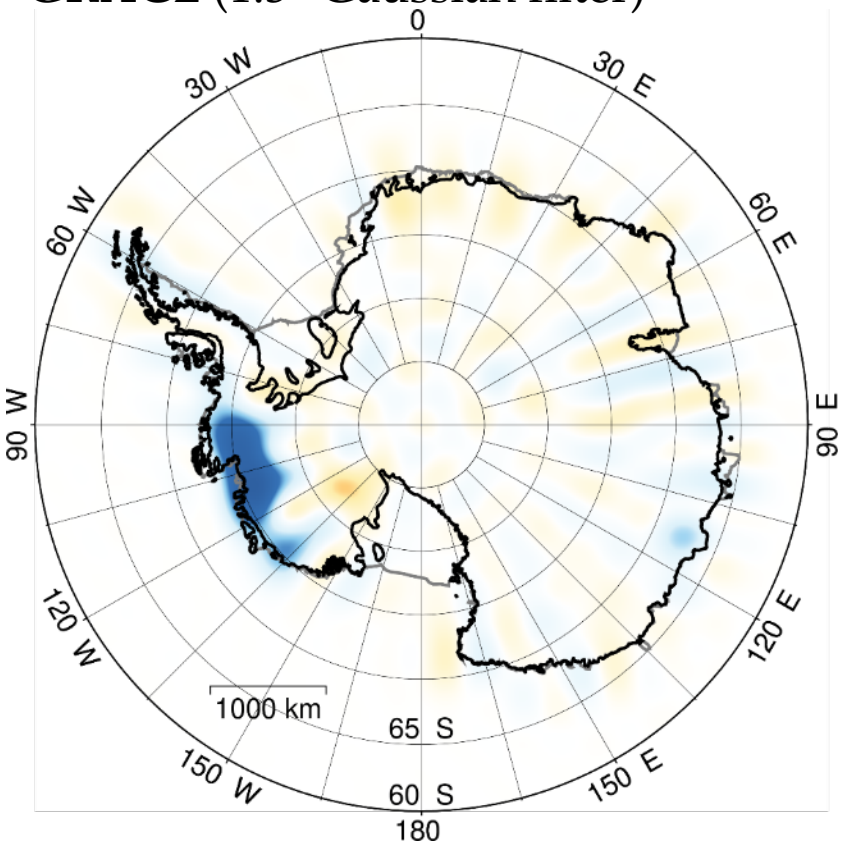
Source: Sasgen et al. 2019, Remote Sensing

# Signal in the spatial domain

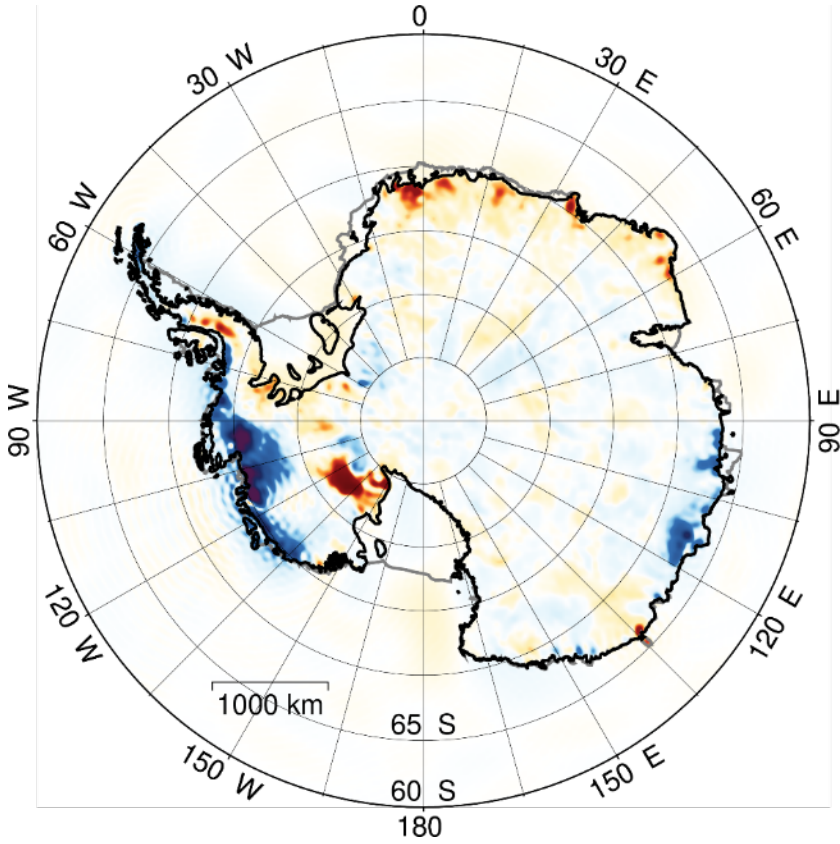
**CryoSat-2**



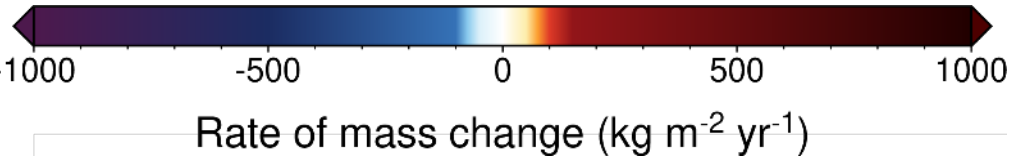

**GRACE** (1.3° Gaussian filter)




**Combination**

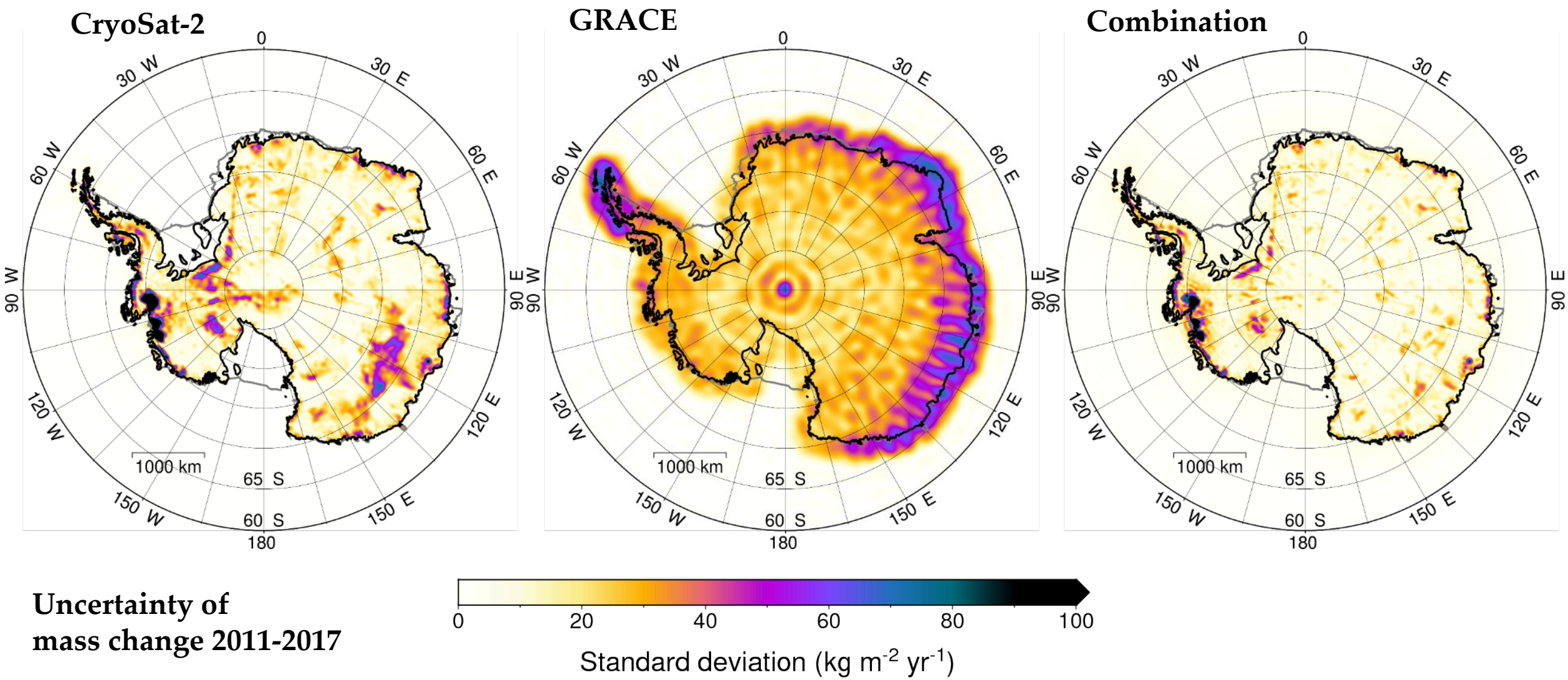



**Rate of mass change 2011-2017**




Source: Sasgen et al. 2019, Remote Sensing

# Noise in the spatial domain

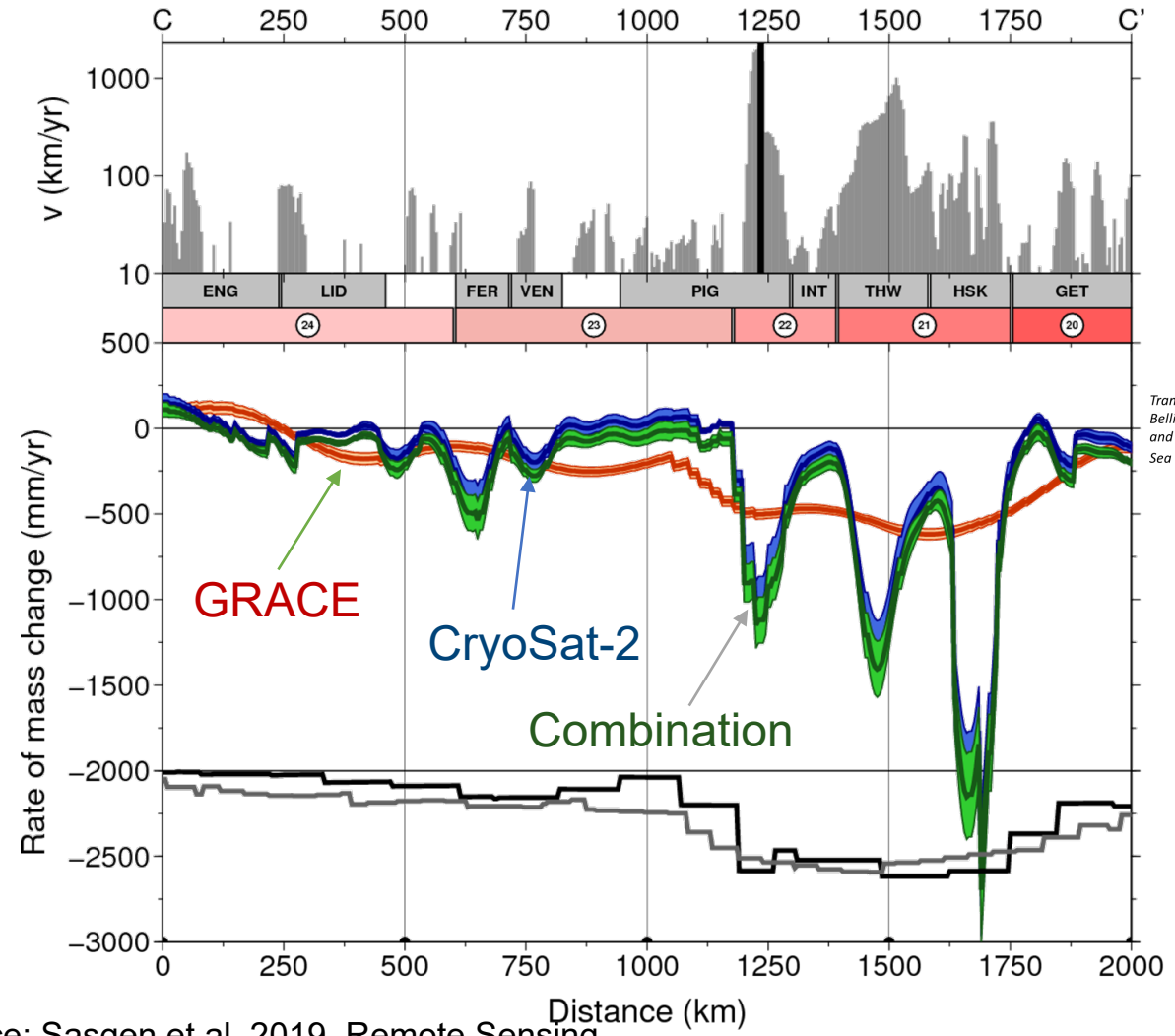


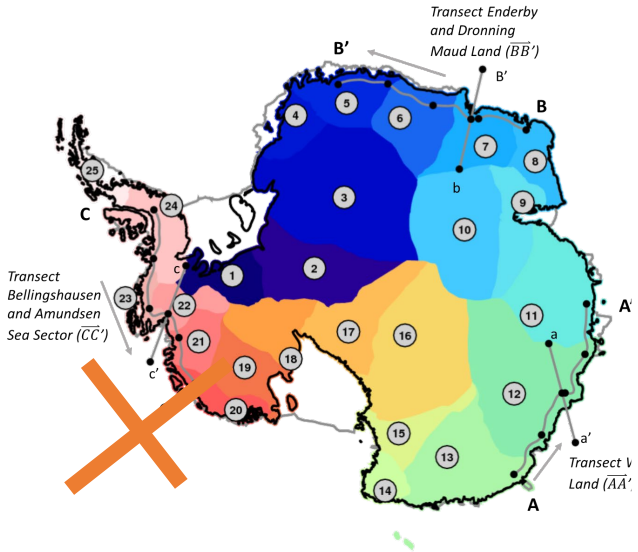

**Uncertainty of mass change 2011-2017**

Source: Sasgen et al. 2019, Remote Sensing

# Transect: Amundsen Sea

Antarctic Peninsula ← *Profile || to coastline* → Ross Ice Shelf




**GRACE Level 3 products**

CSR RL05 M

ESA CCI

Source: Sasgen et al. 2019, Remote Sensing

Source: Alfred Wegener Institute

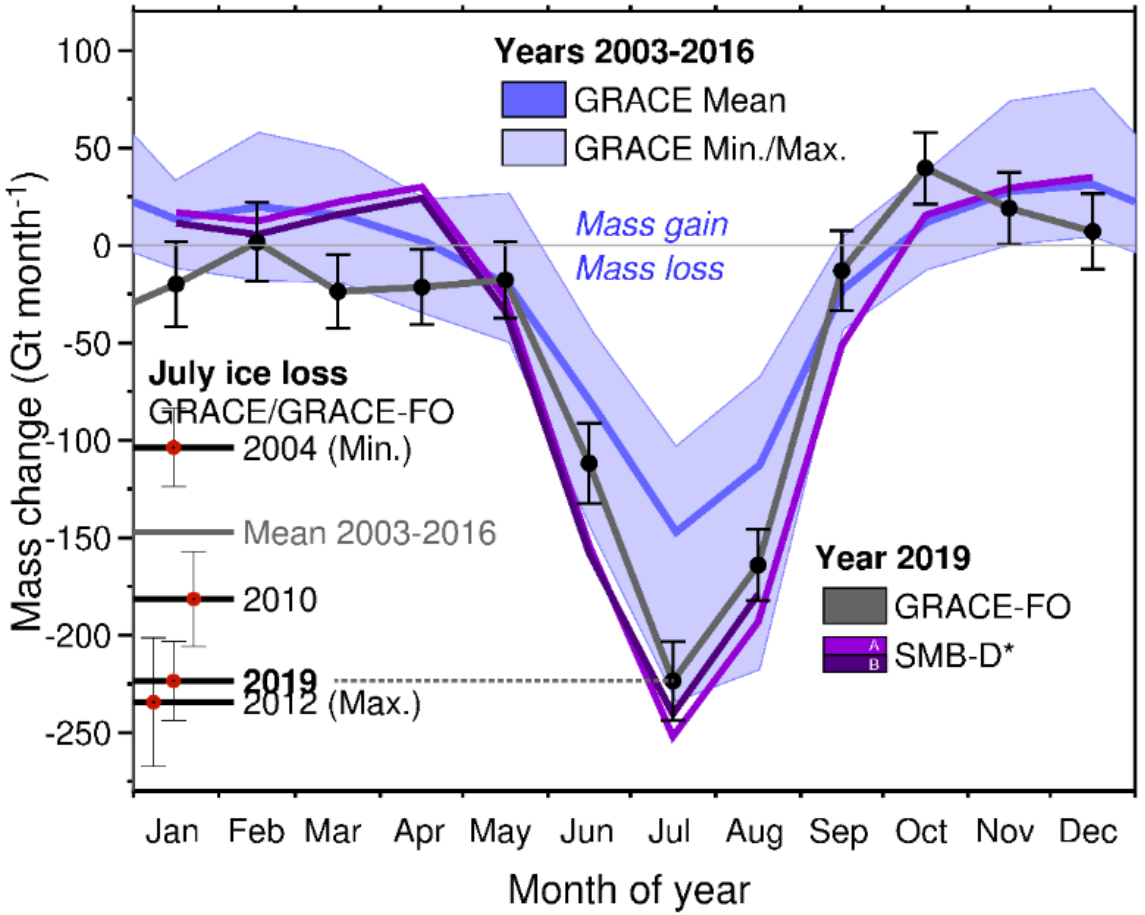
# Cryosphere changes

## Feedbacks for future evolution

Source: Alfred Wegener Institute

# Greenland record melt year 2019

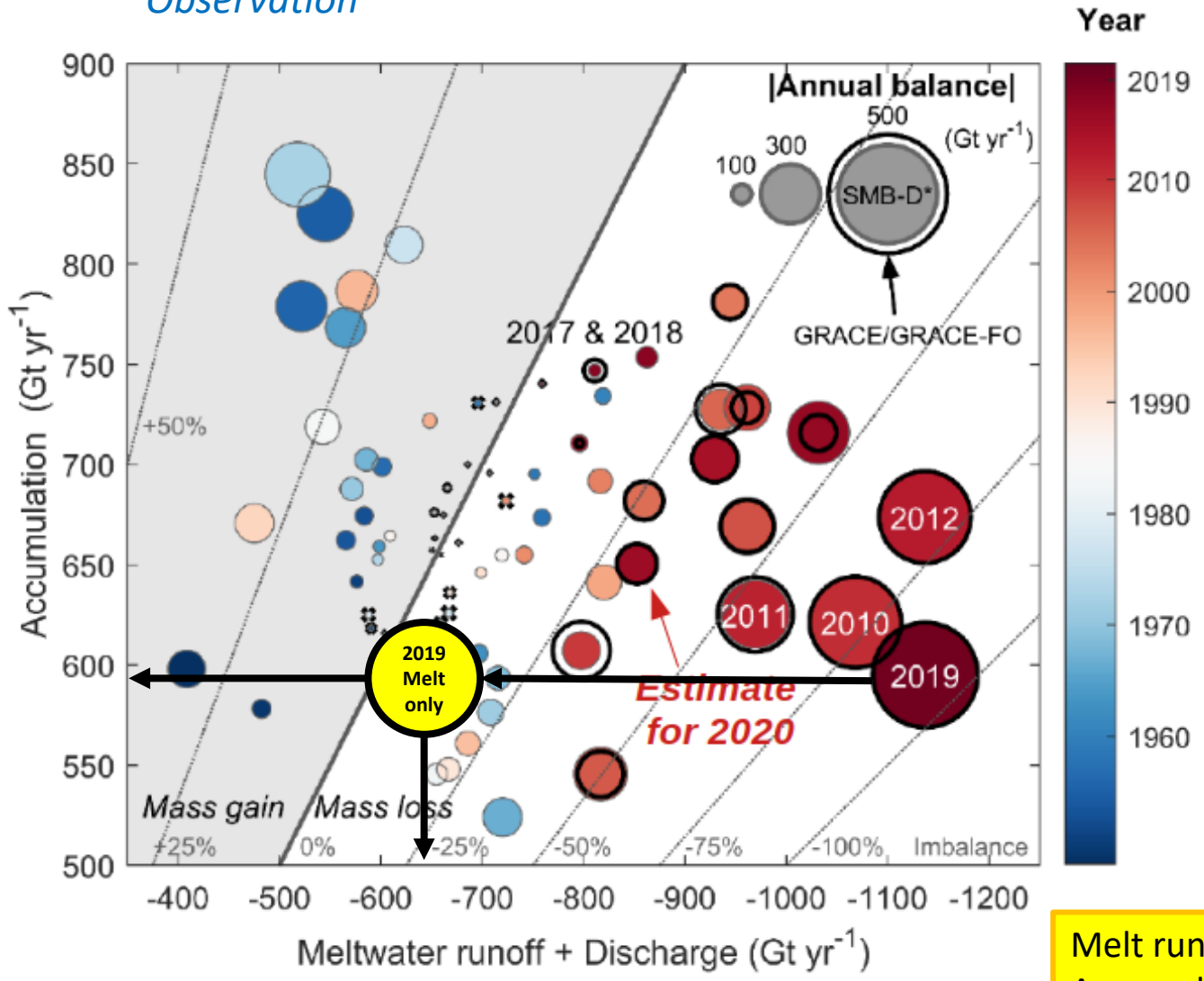
## Seasonal cycle




Sasgen et al. 2020

# Current and projected mass balance state

*Observation*

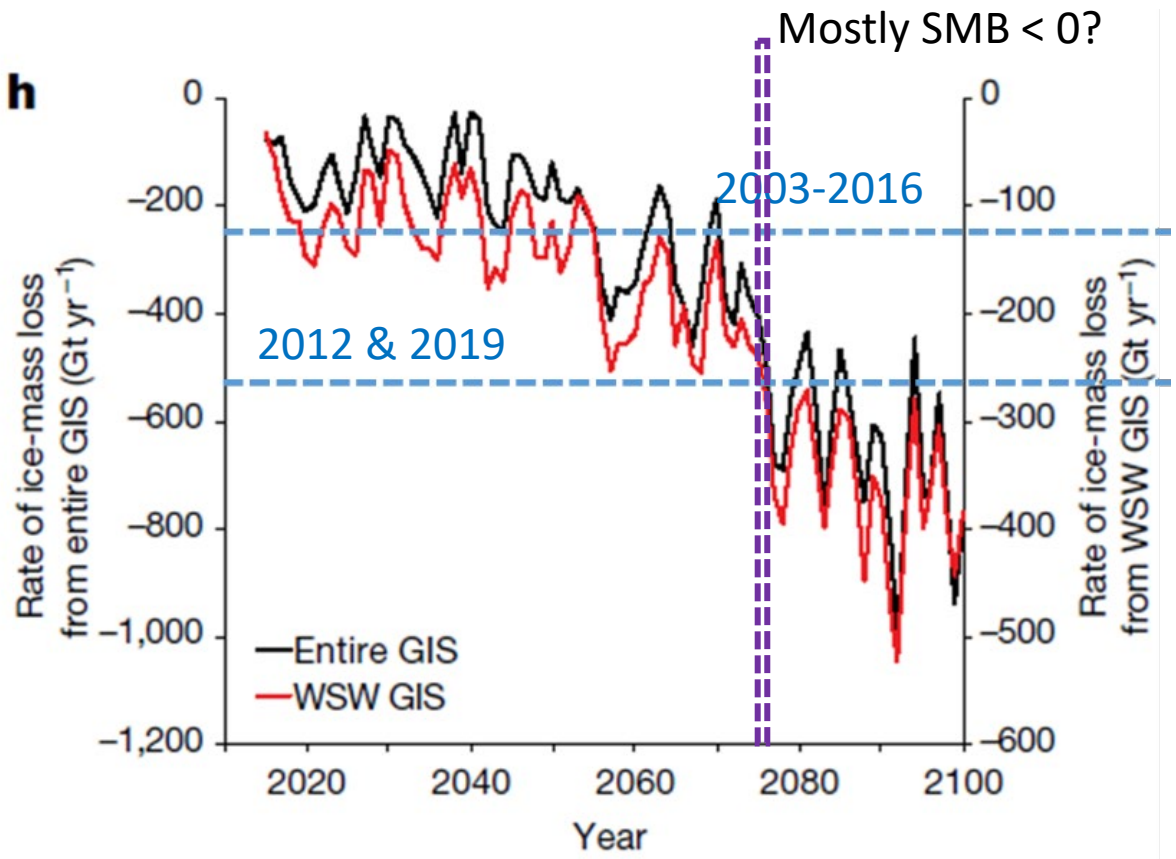






Melt runoff > Accumulation

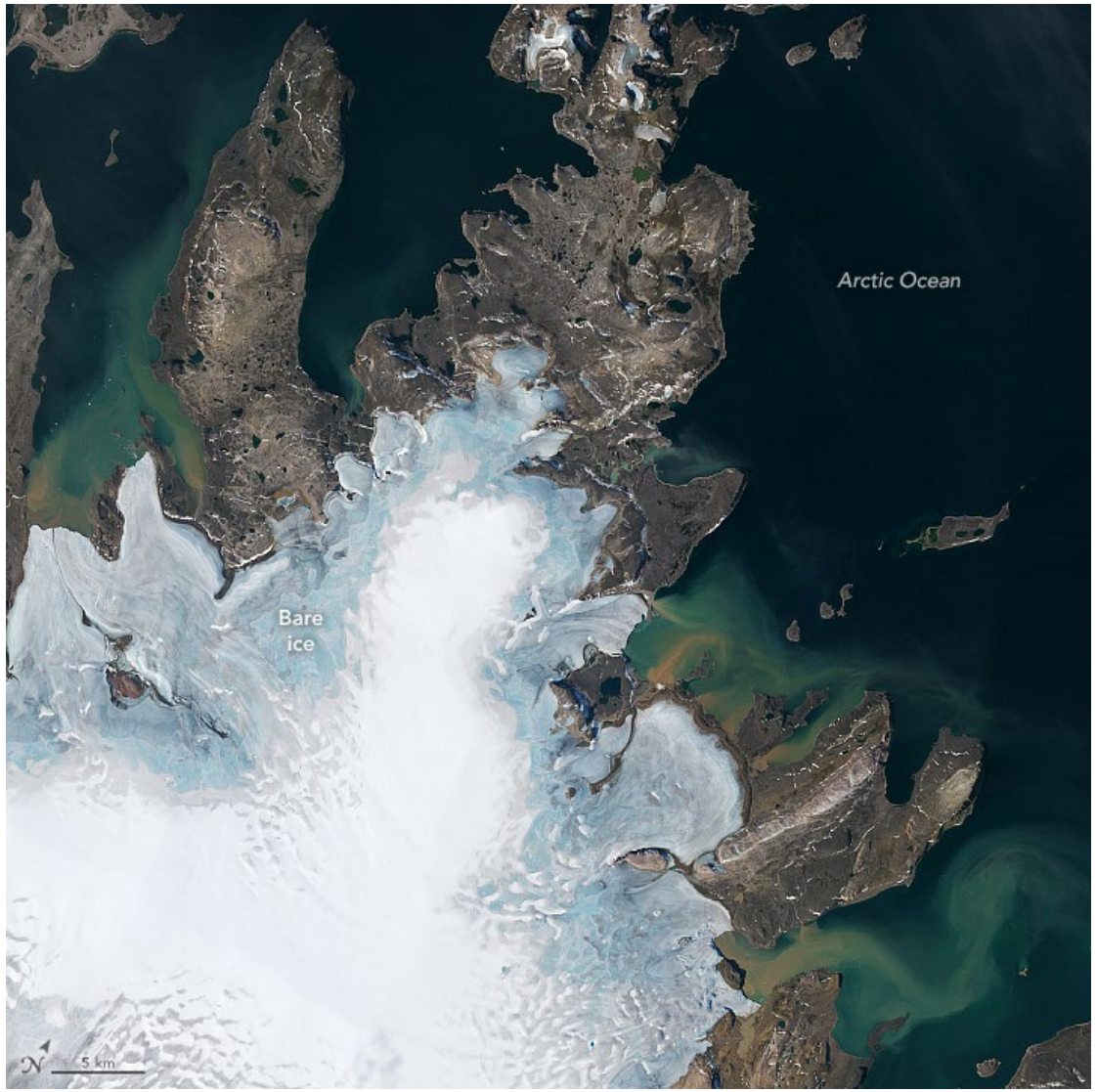
*Projection*

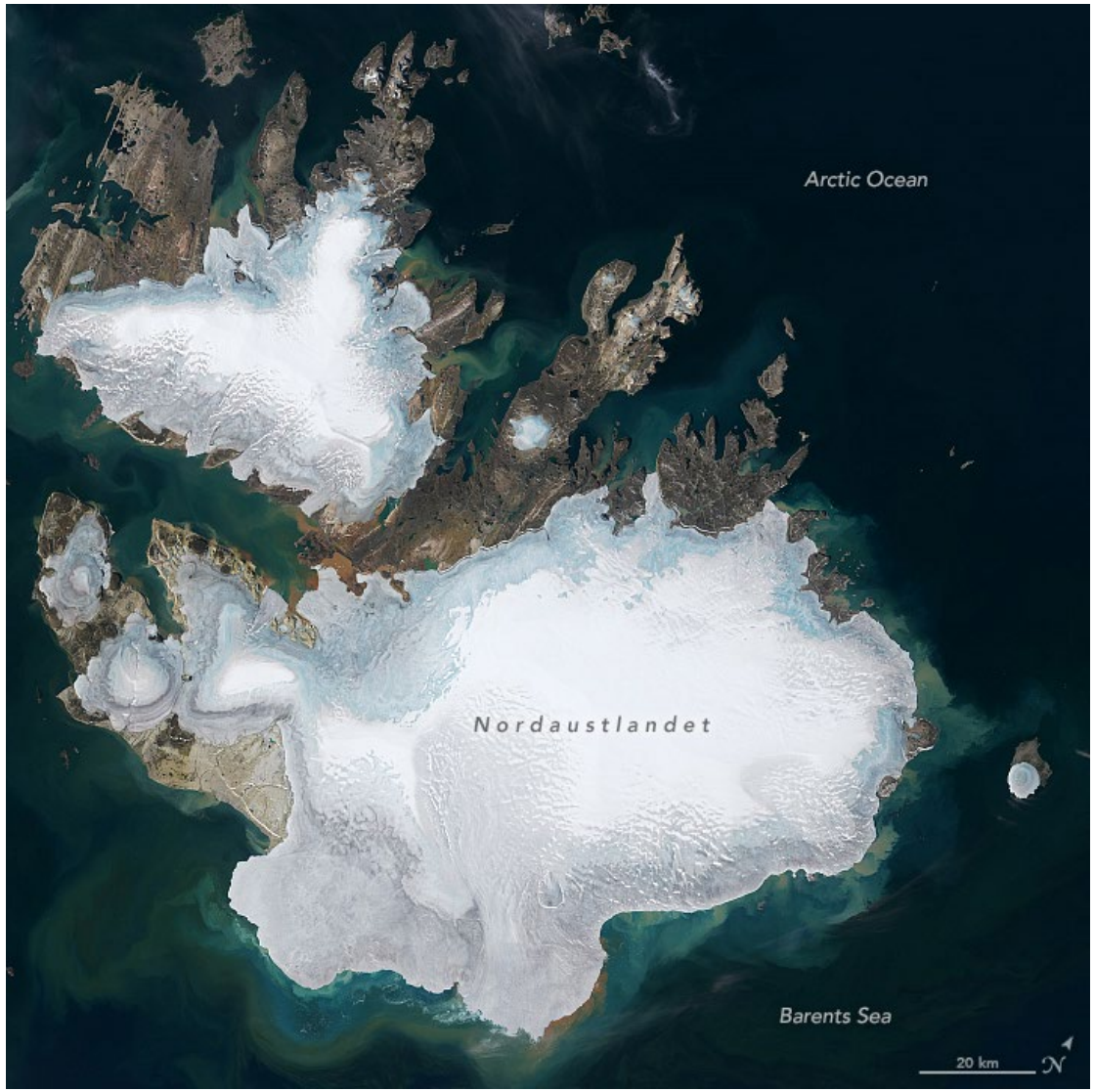



Briner et al. 2020, https://doi.org/10.1038/s41558-018-0305-8

Sasgen et al. 2020

# Surface properties change

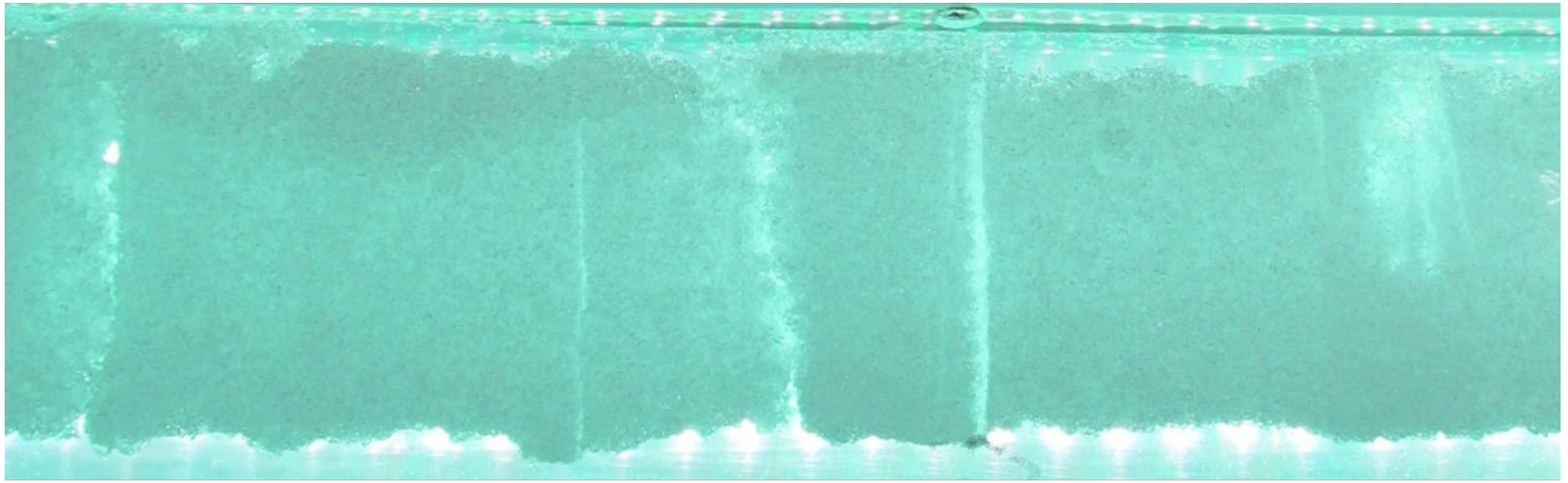


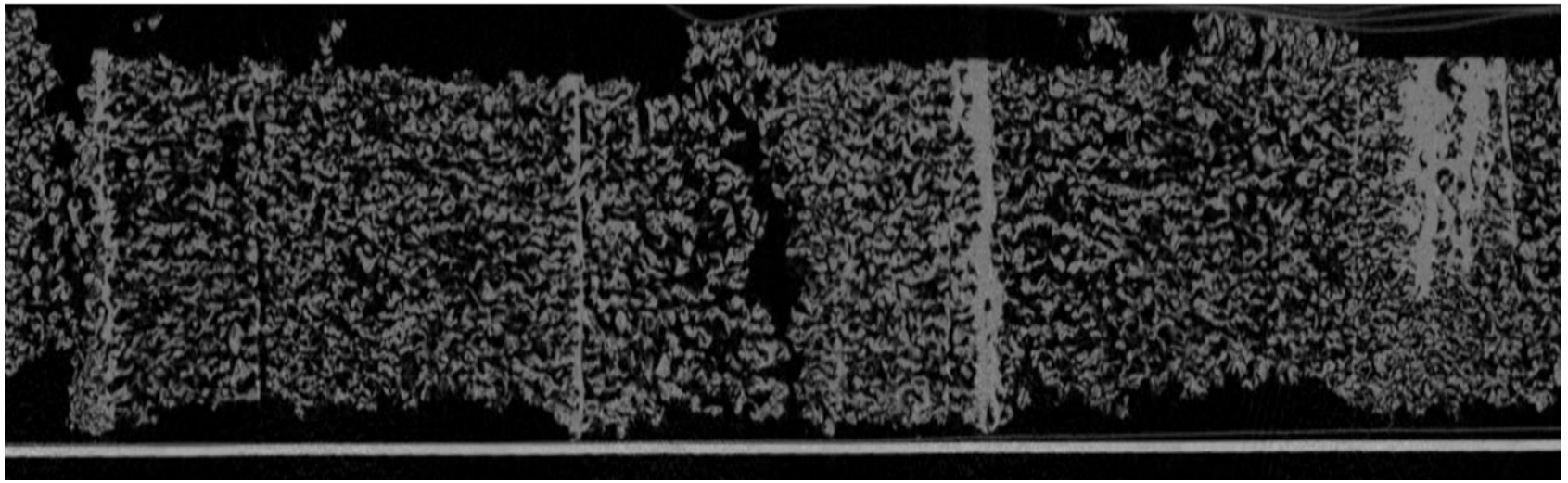



https://earthobservatory.nasa.gov/images/153189/svalbard-melts

# Melt layers in ice cores of central Greenland



Optical



CT scan

Courtesy: Samira Zander, AWI

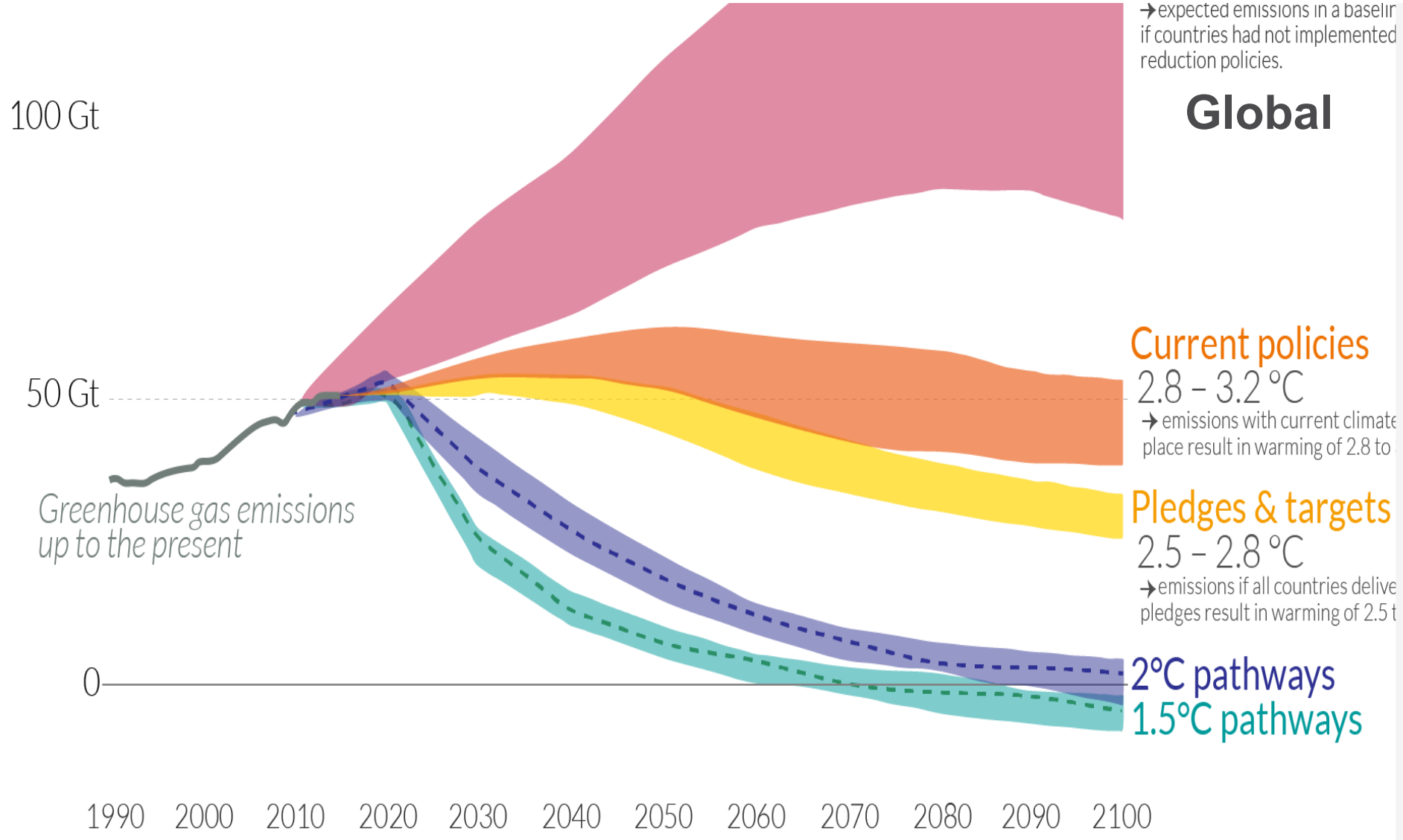
Source: Alfred Wegener Institute

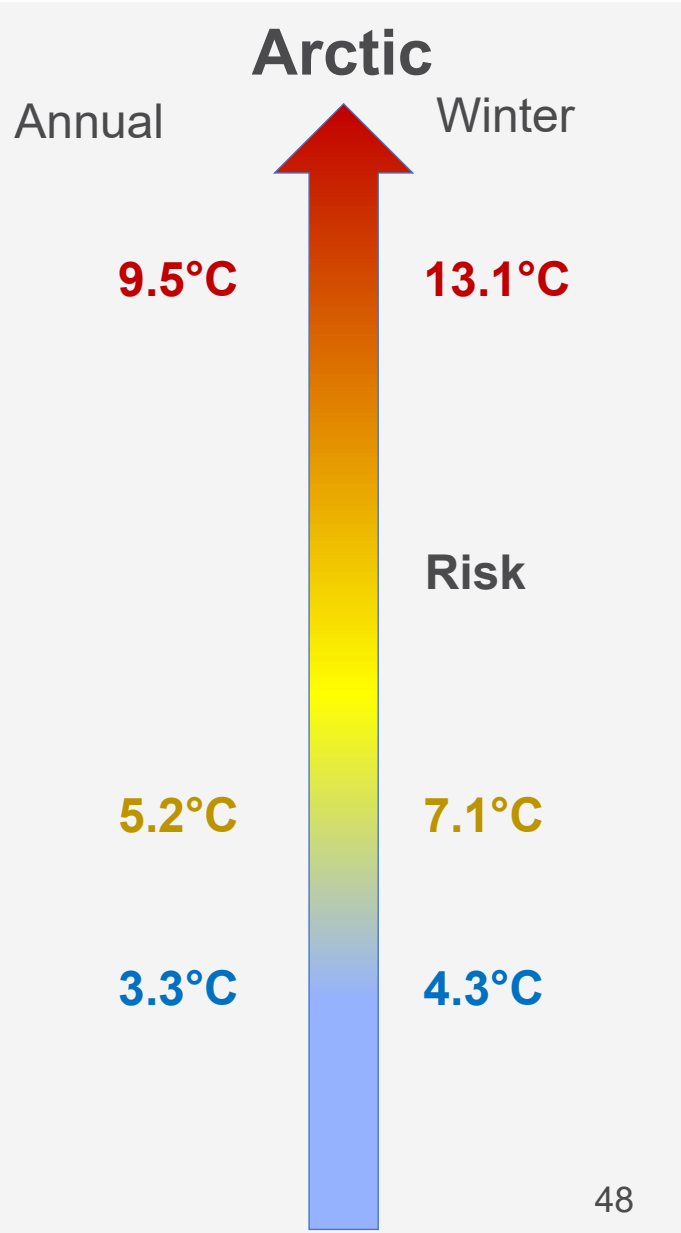
# Future gravity missions

## Resolution improvements

**Credit**
NASA/Bill Ingalls

# Global $CO_2$ emmissions and warming




Data source: Climate Action Tracker (based on national policies and pledges as of December 2019).

OurWorldinData.org – Research and data to make progress against the world's largest problems.

Overland et al. 2019


Foto: Ole Zeisung

- Contact: ingo.sasgen@awi.de