Foto: Ole Zeisung

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UND MEERESFORSCHUNG

Arctic glacier mass changes: insights gained through satellite gravimetry observations

Ingo Sasgen[*], Grit Steinhoefel[*], Caroline Kasprzyk[(*)], Heidrun Matthes[*], Sebastian Westermann[**], Julia Boike[*], Guido Grosse[*]

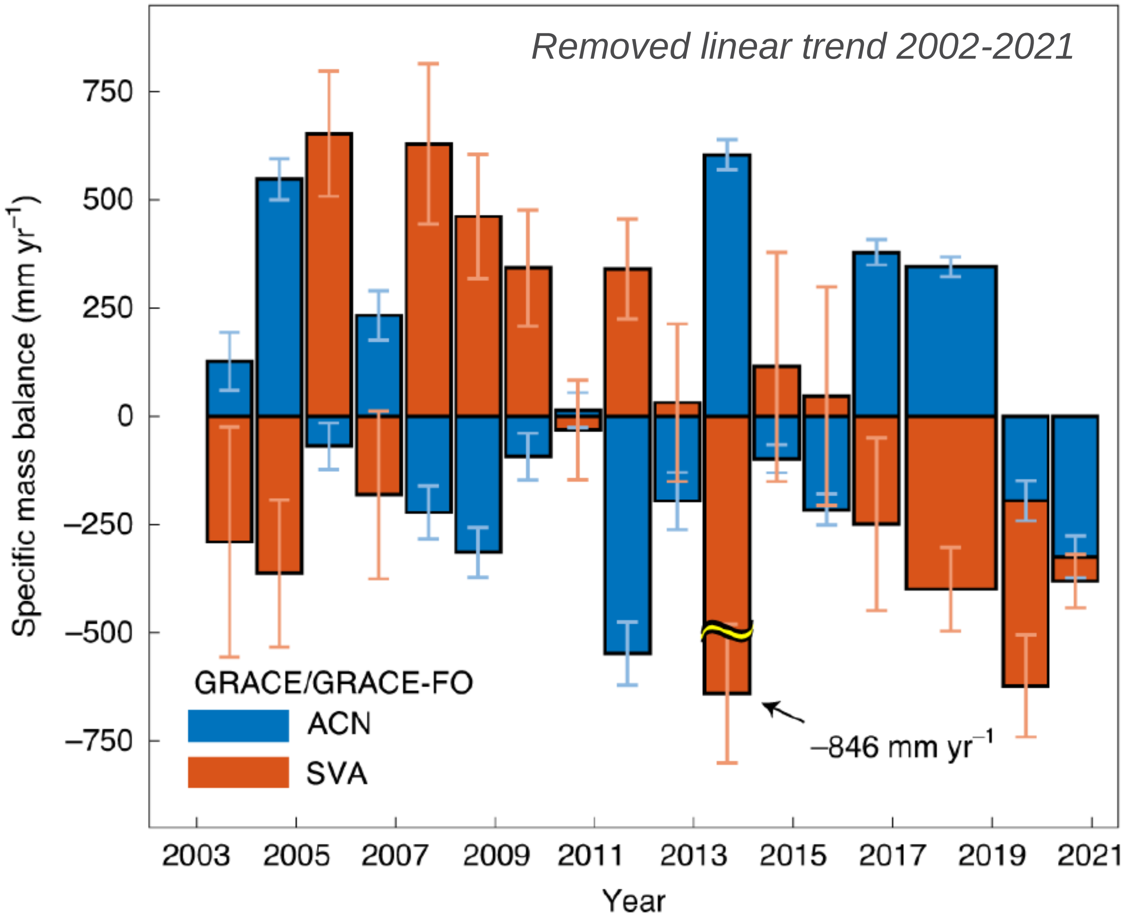
[*]AWI, [**]University of Oslo

SESSION 4 - Glacier change observations for hydrological and sea-level rise assessments

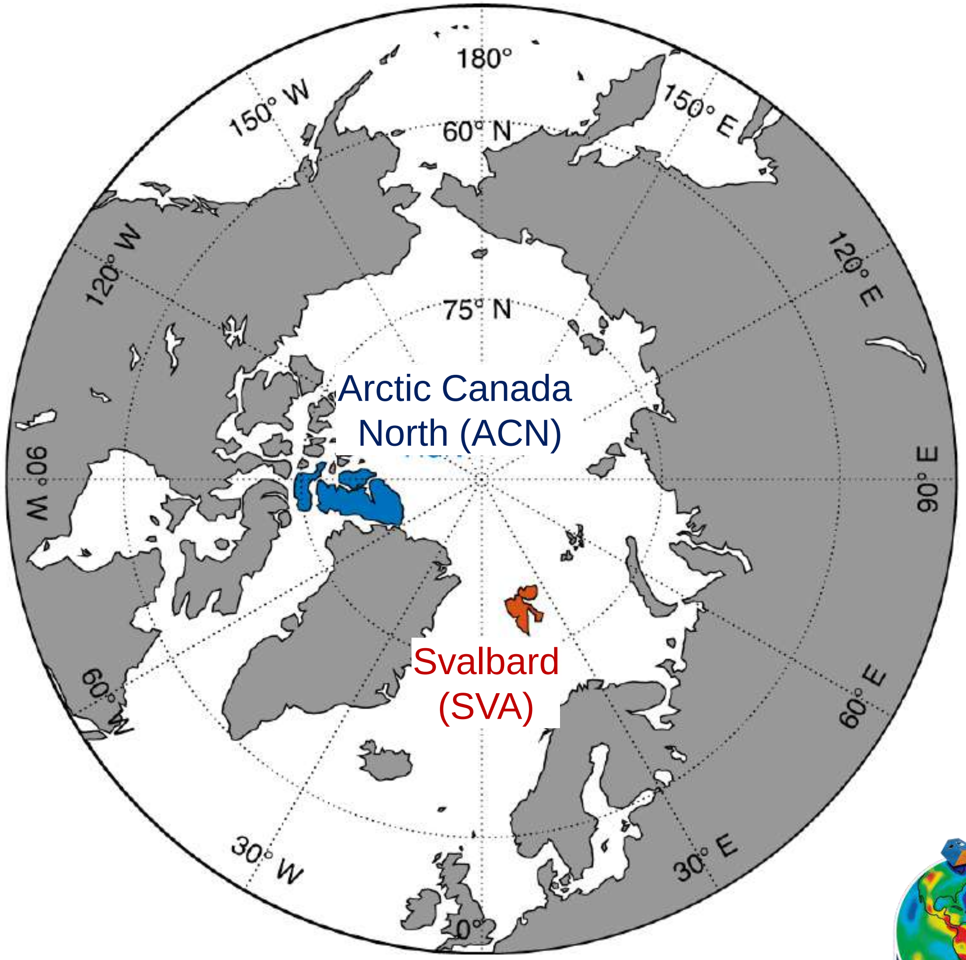
HELMHOLTZ

GRACE/GRACE-FO annual balances

Annual mass balance anomalies



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

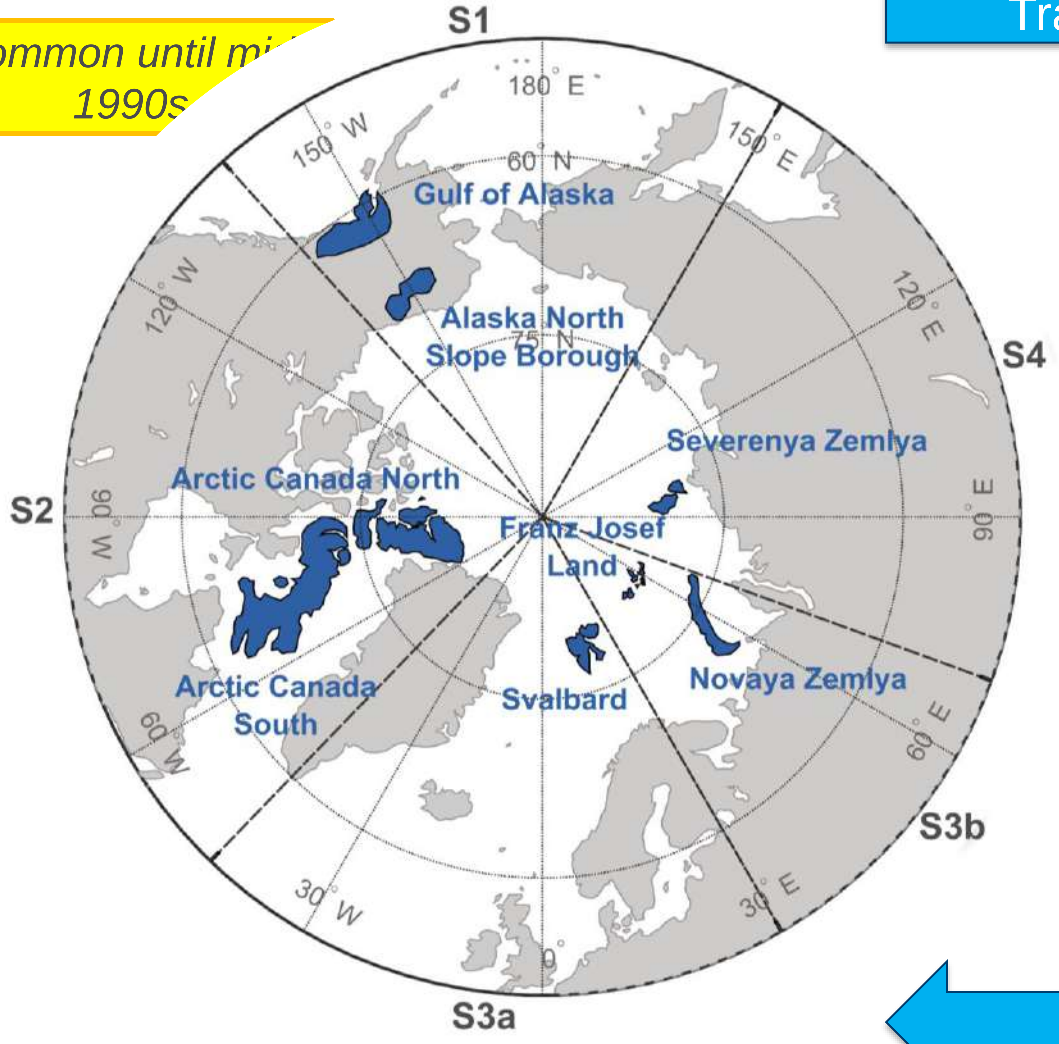


Sasgen *et al.* 2022, *Nat. Clim. Change*

Introduction

"Zonal"

Common until mid-1990s

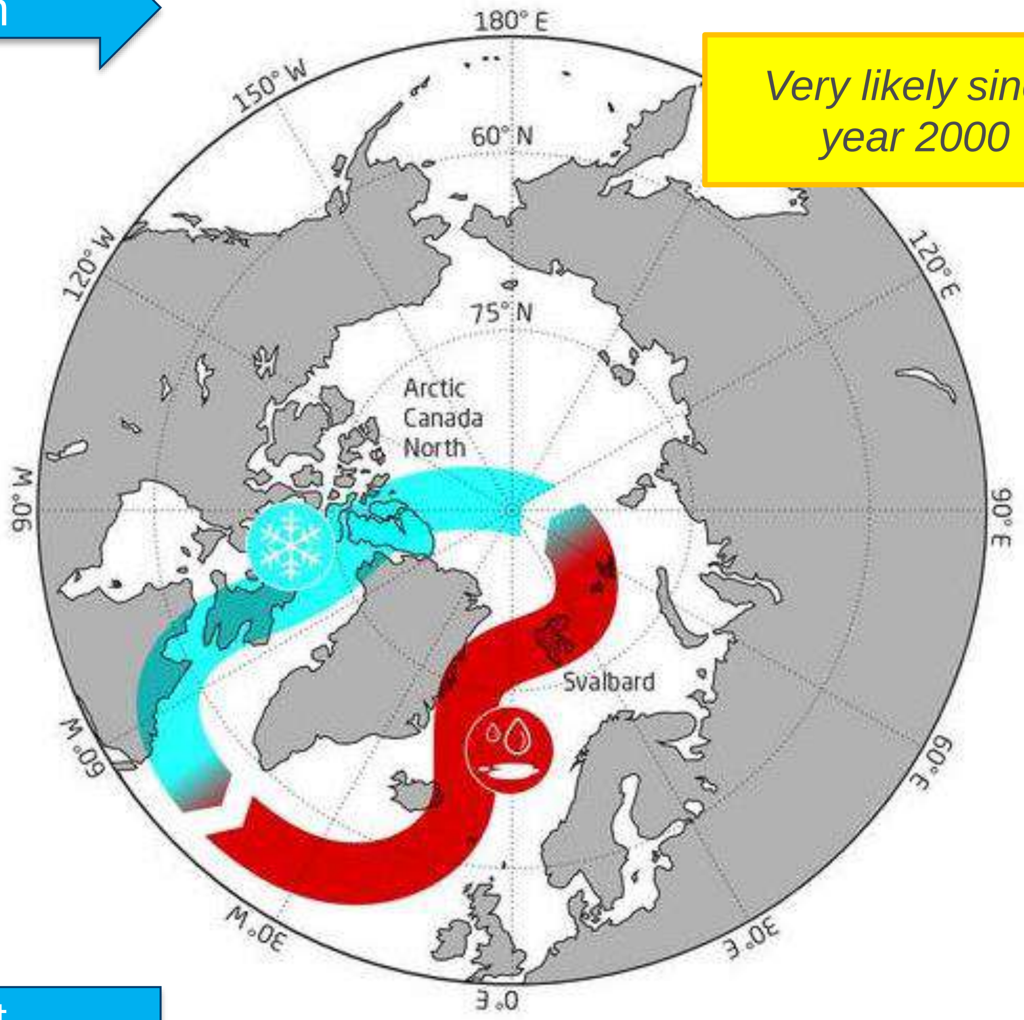


Transition

Impact

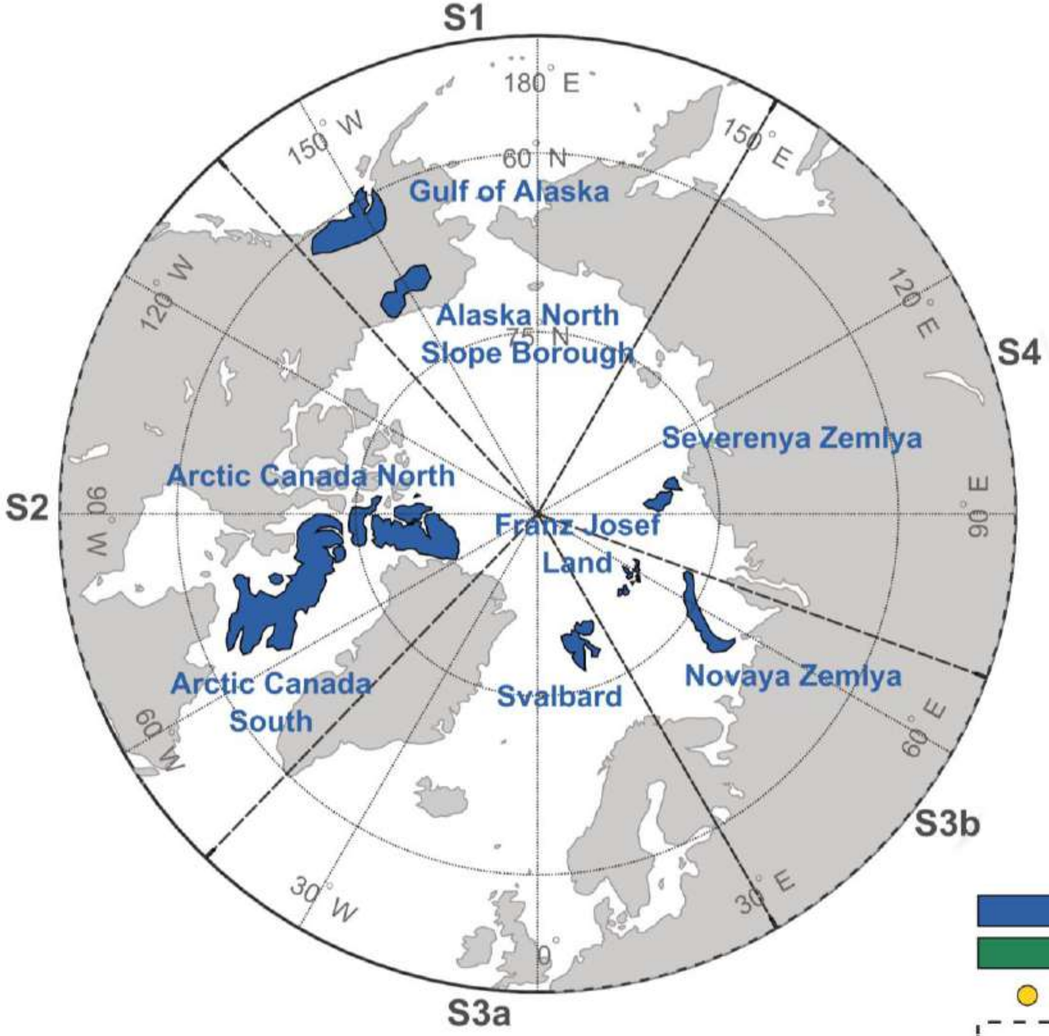
"Meridional"

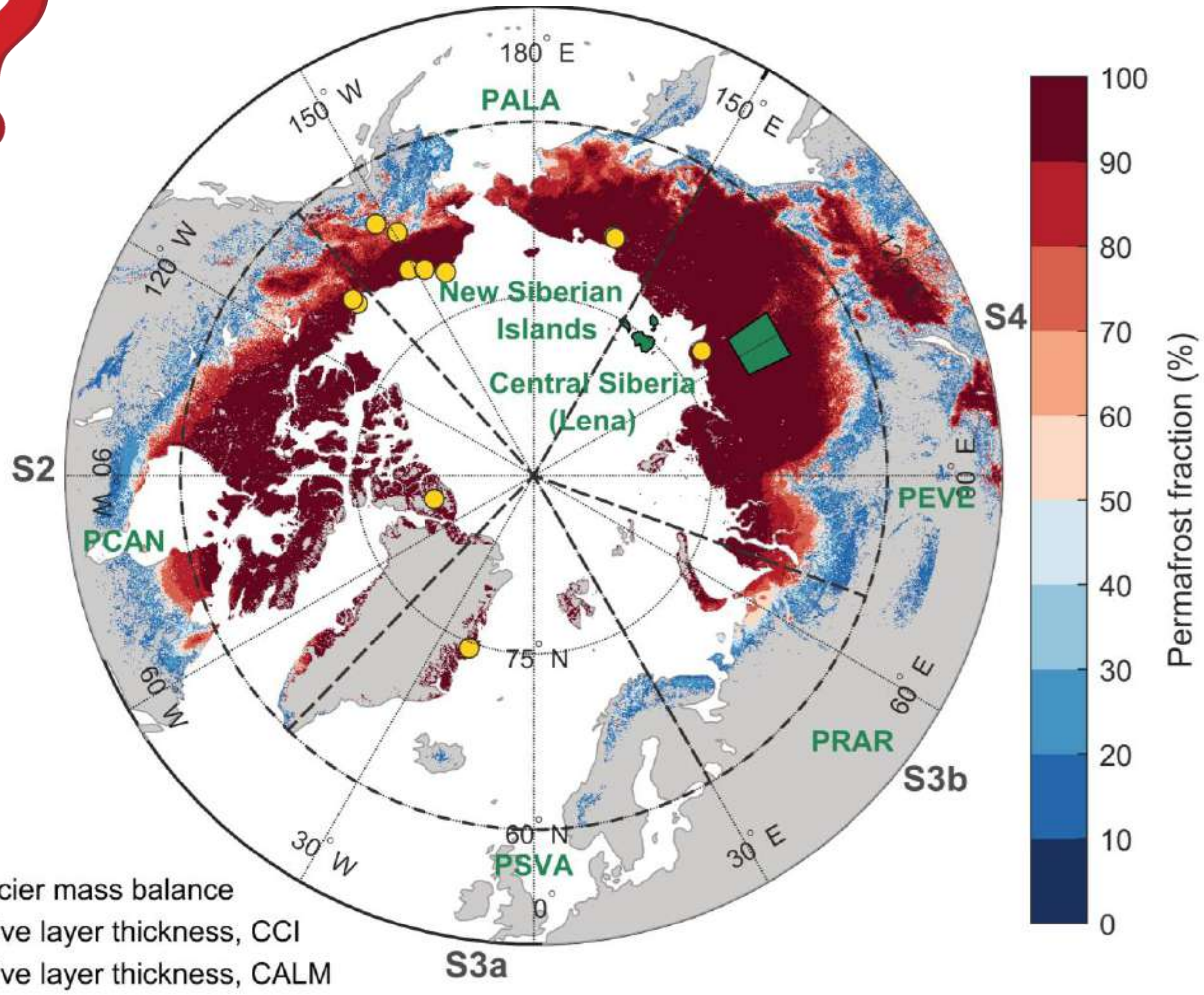
Very likely since year 2000



Sasgen et al. 2022, *Nat. Clim. Change*

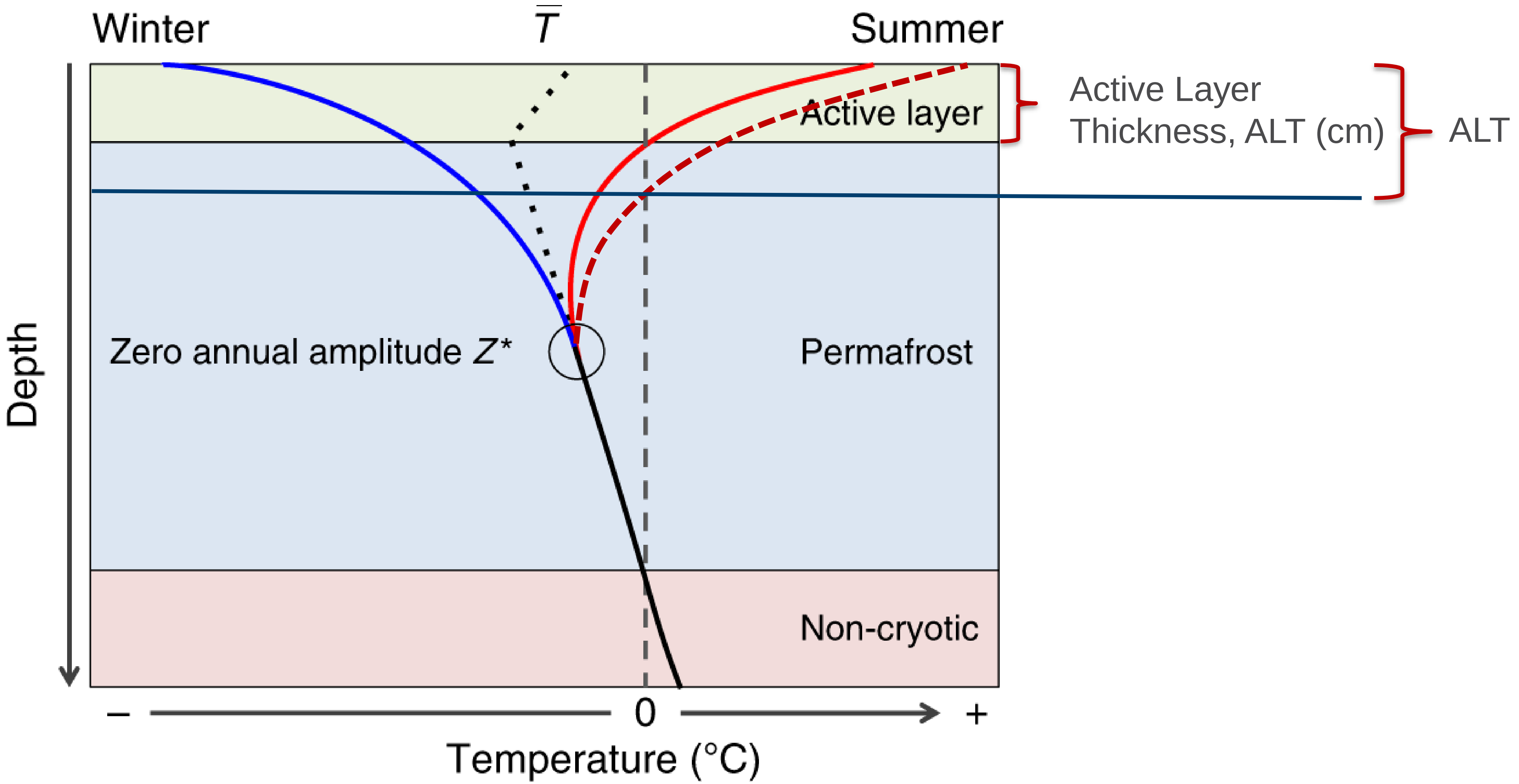
Arctic glaciers and permafrost





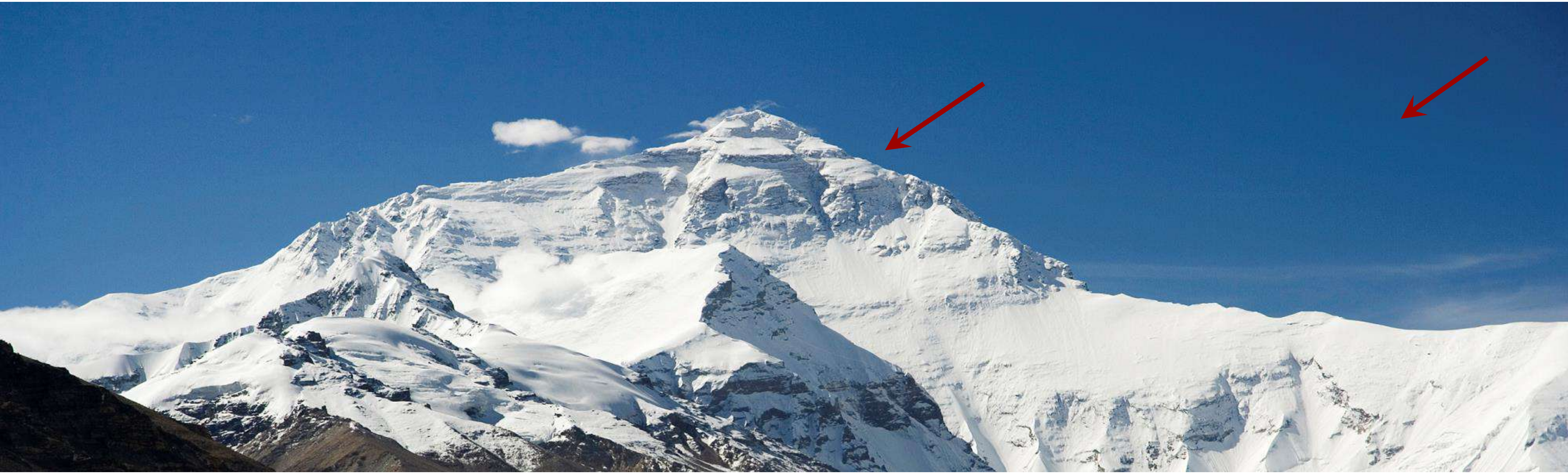
Glacier mass balance
Active layer thickness, CCI
Active layer thickness, CALM
Sector boundaries

Thermal regime of permafrost



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

Mass change from GRACE/GRACE-FO satellites



GRACE (2002-2017) GRACE-FO (2018 to present) GRACE-C (sched. 2028) MAGIC constellation (sched. 2032)

Courtesy: D. Schütze (AEI Hannover)

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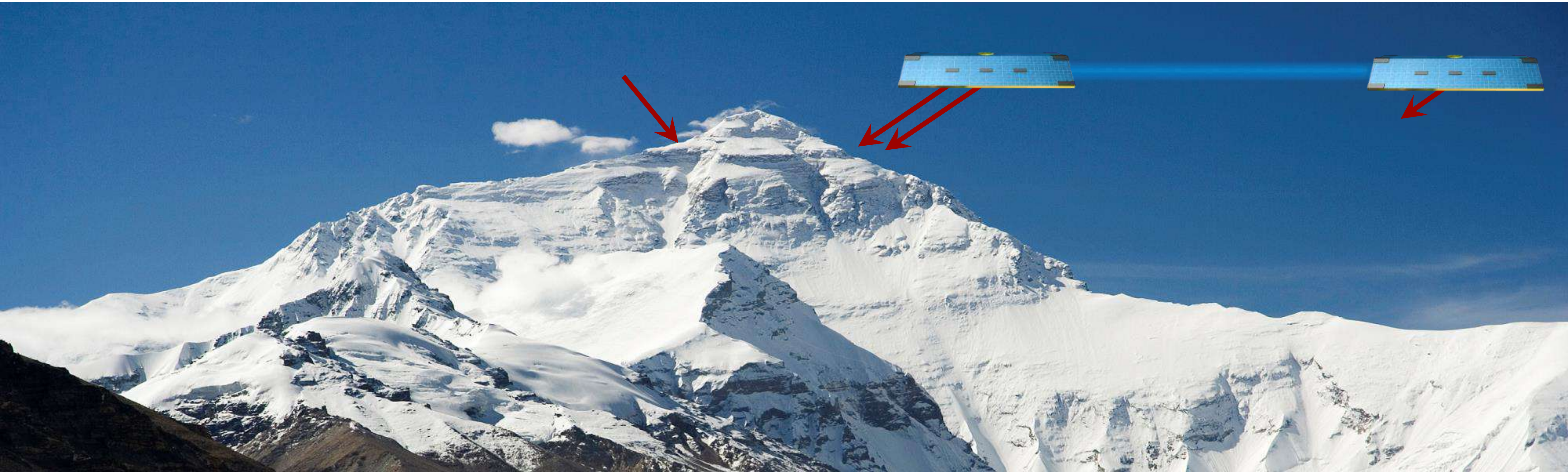

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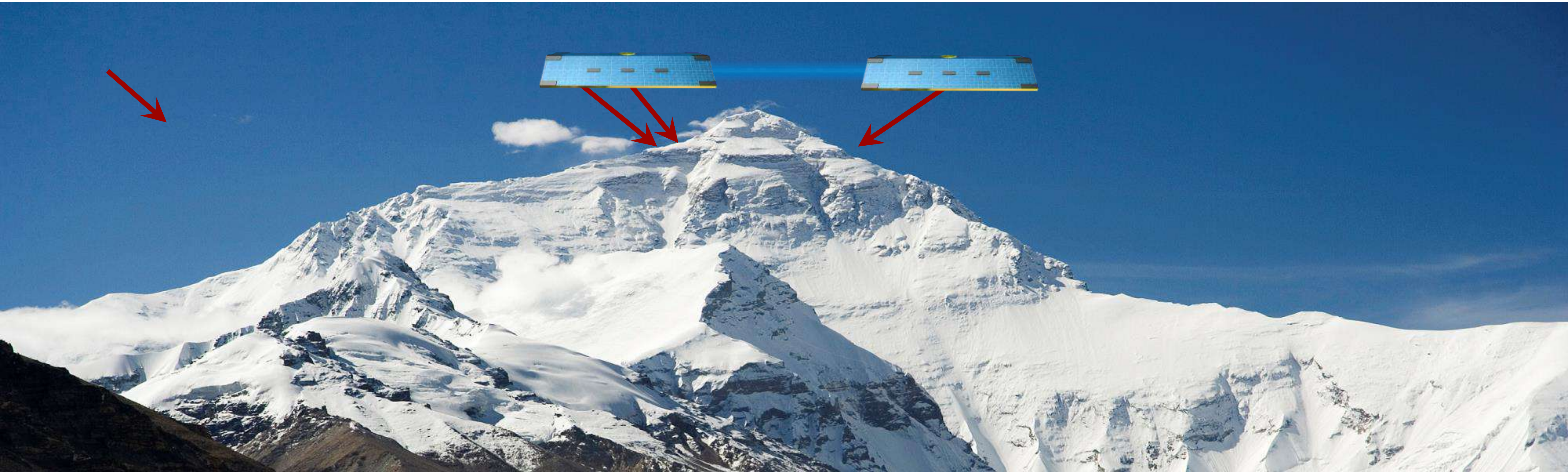
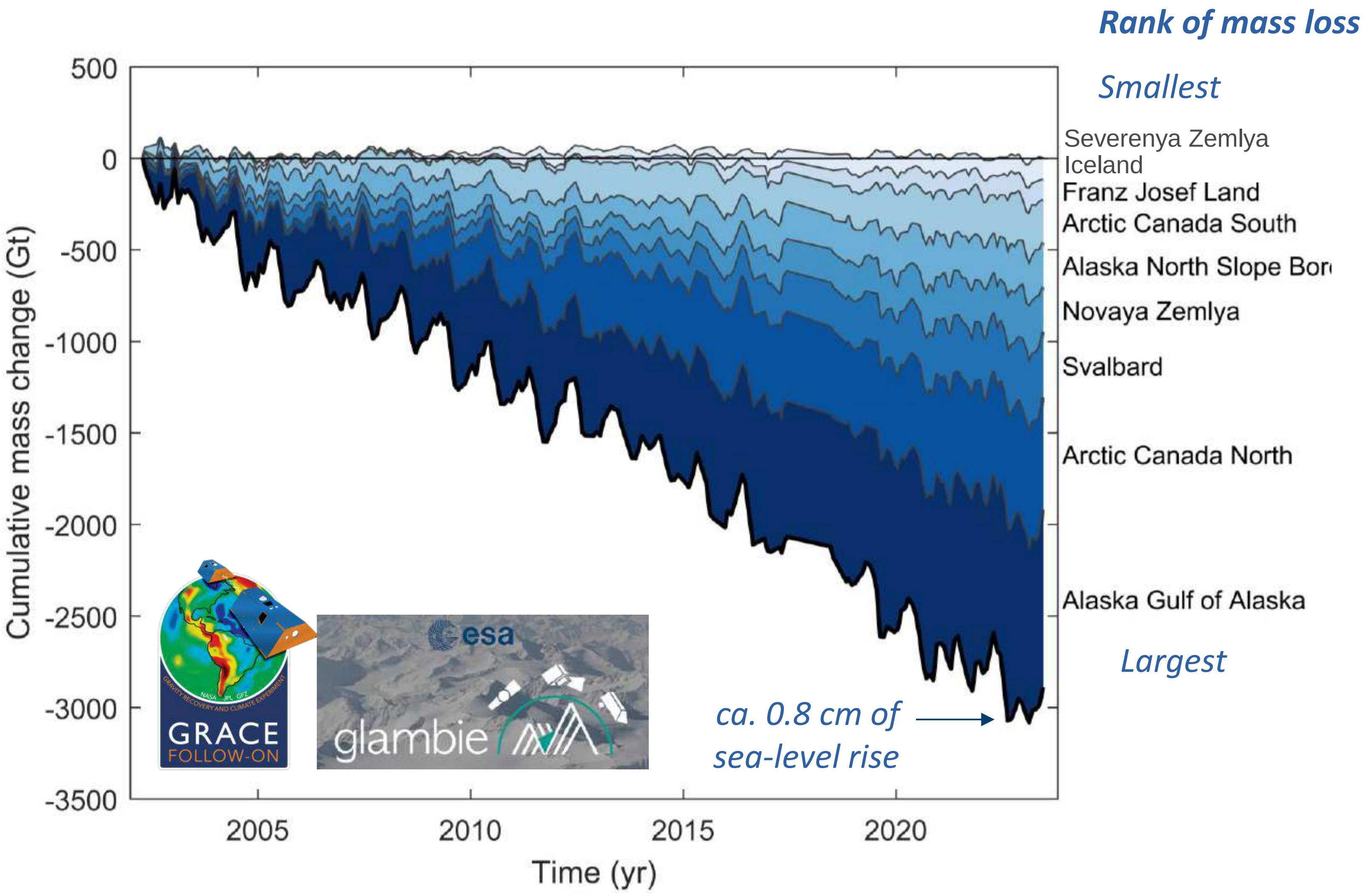


GRACE (2002-2017) GRACE-FO (2018 to present) GRACE-C (sched. 2028) MAGIC constellation (sched. 2032)

Courtesy: D. Schütze (AEI Hannover)

Arctic glacier mass loss from gravimetry

GRACE/GRACE-FO mass change 2002–2023



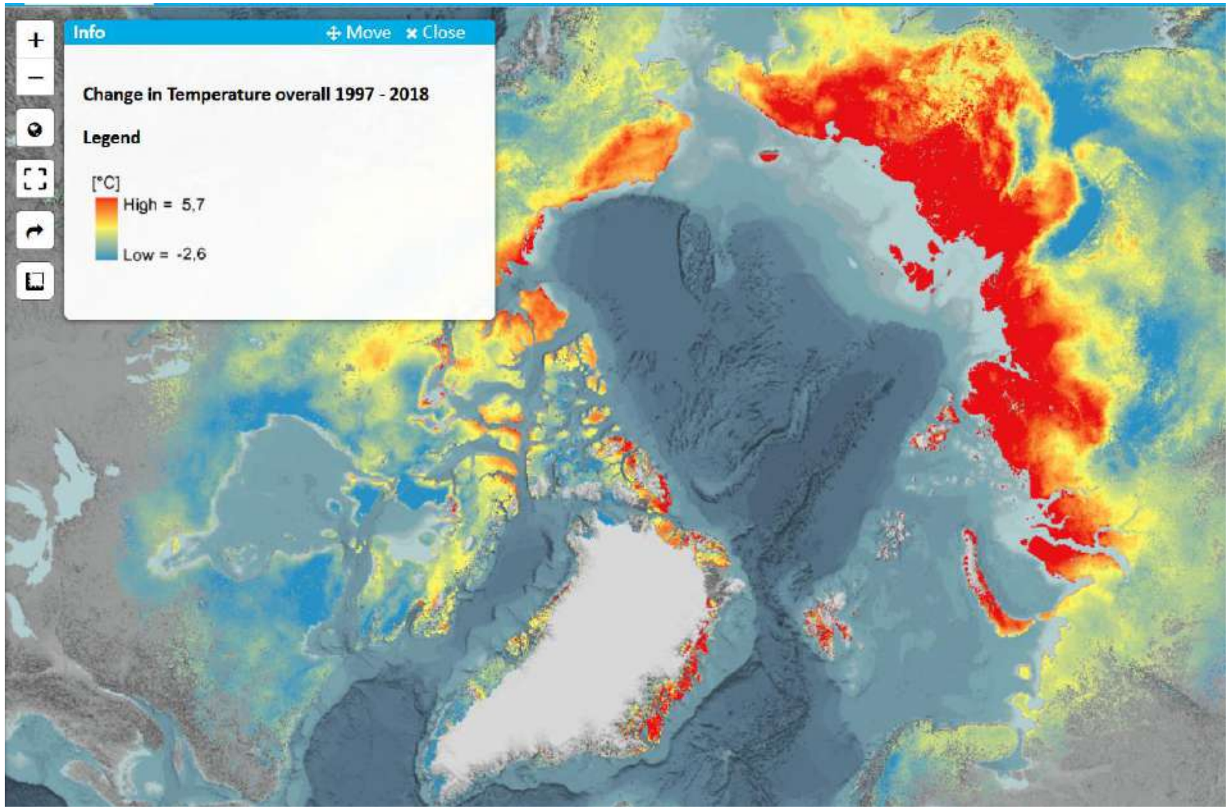
GRACE/GRACE-FO data

- CSR/GFZ/JPL combined solution
- Forward-modelling based inversion
- Nine Arctic glacier systems
- Time period 2002–2023
- 222 monthly solutions

Data submitted to Glacier mass balance intercomparison exercise (GlaMBIE), Zemp *et al.* submitted

Permafrost change from remote sensing

Remote sensing & modelling active layer thickness 2003–2019



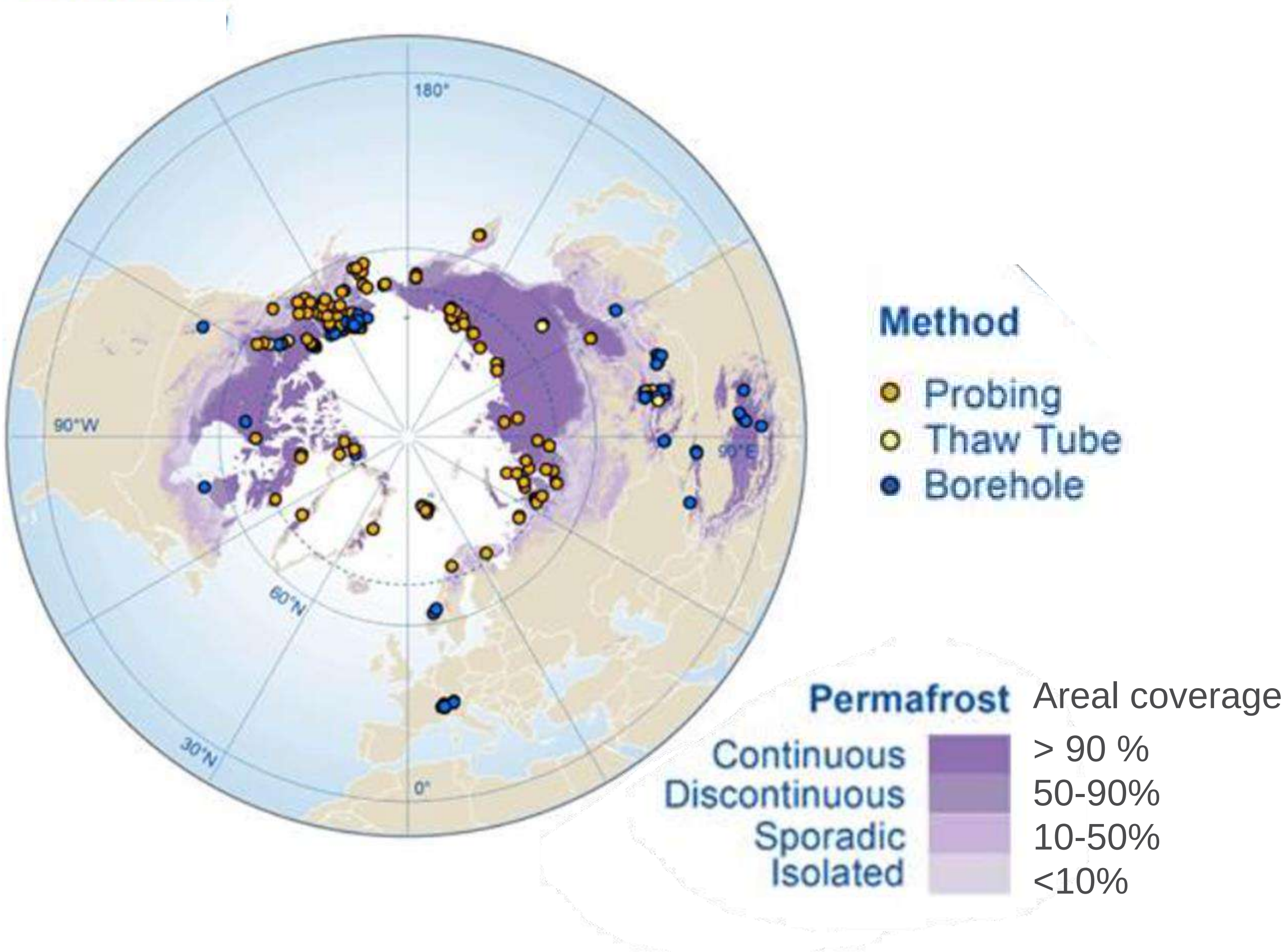
- **ESA Climate Change Initiative**
- CryoGRID ground thermal model
- Transient modelling of ground temperature
- Time period 2003-2019 (currently being updated)
- 1 km x 1 km estimates of annual maximum active layer thickness

https://climate.esa.int/en/projects/permafrost/,
Dr. Sebastian Westermann (Univ. Oslo), AWI Potsdam

Active layer measurements in the field

In situ active layer thickness

2002–2023



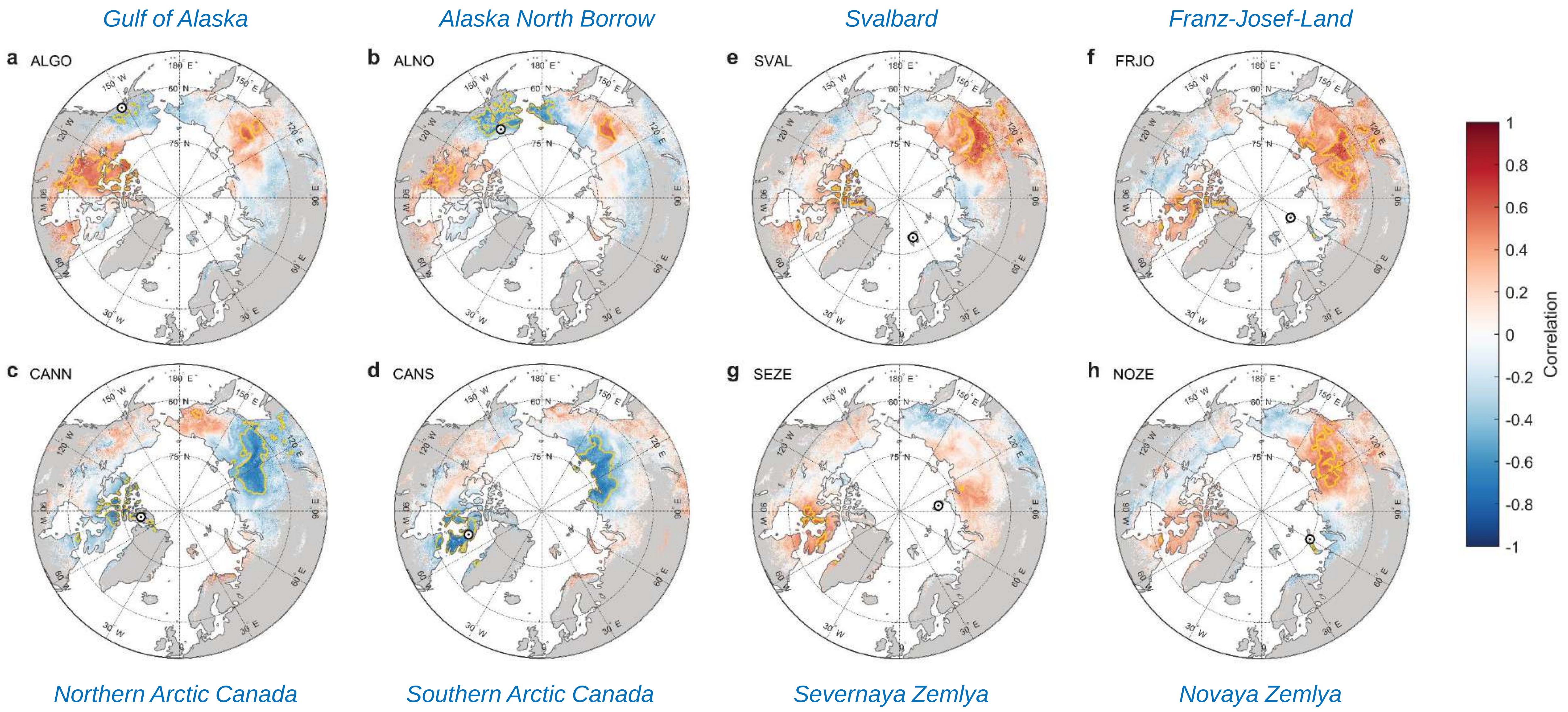
Circumarctic Active Layer Monitoring (CALM)

- 185 field measurements > 60°N
- 57 with only one missing in time period 2003-2017
- Regional representation if correlated with CCI at location

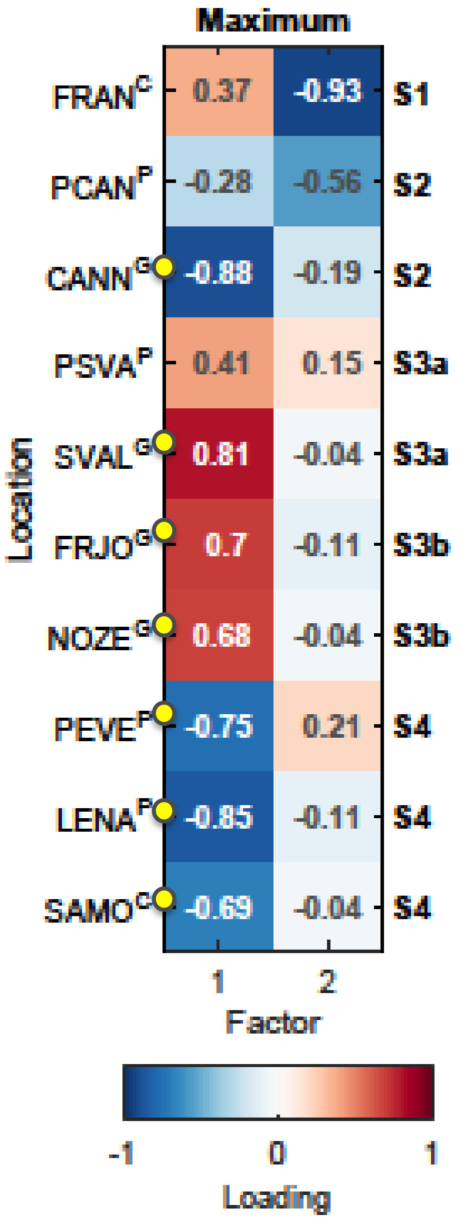
→ 13 *in situ* records of permafrost change (regional representative)

https://www2.gwu.edu/~calm/data/north.htm

Correlation mass balance & active layer thickn.



Factor analysis approach



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- Criterion of significance: $|\lambda_{1,n}| > 0.5$ & $|\lambda_{1,n}|$ - $|\lambda_{2,n}| > 0.3$

Observations (time series)

Common factor vector (common temporal variation)

$$x = \mu + \Lambda f + e$$

Unexplained variations (local origin, noise, etc.)

Mean observation

Factor loading matrix (relevance for each observation)

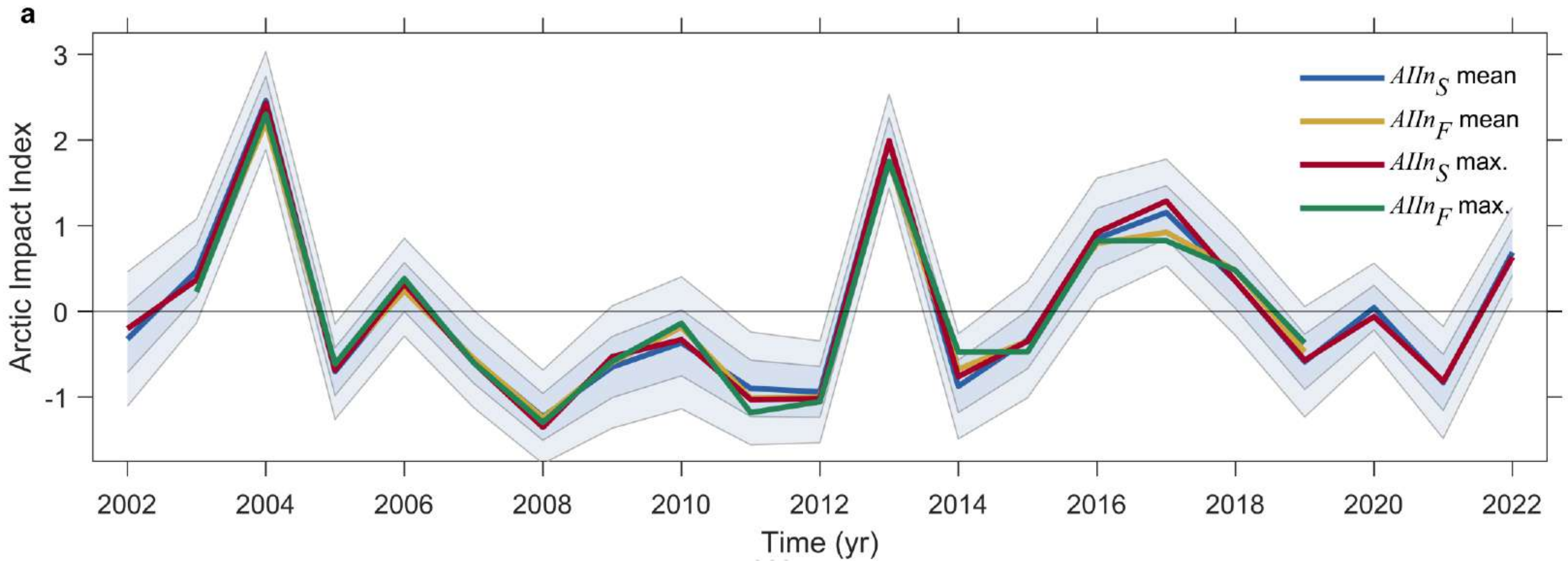
Observation pool available (28 standardized time series)

- 8 GRACE/GRACE-FO glacier mass balances
- 13 CALM stations
- 5 CCI+ sectorial averages
- 2 CC+ regional averages (New Siberian Islands, Lena Delta)

→ Random ensemble with $N \approx 14000$ members

Followi

Arctic impact index



Cold in Siberia and Northern Arctic Canada

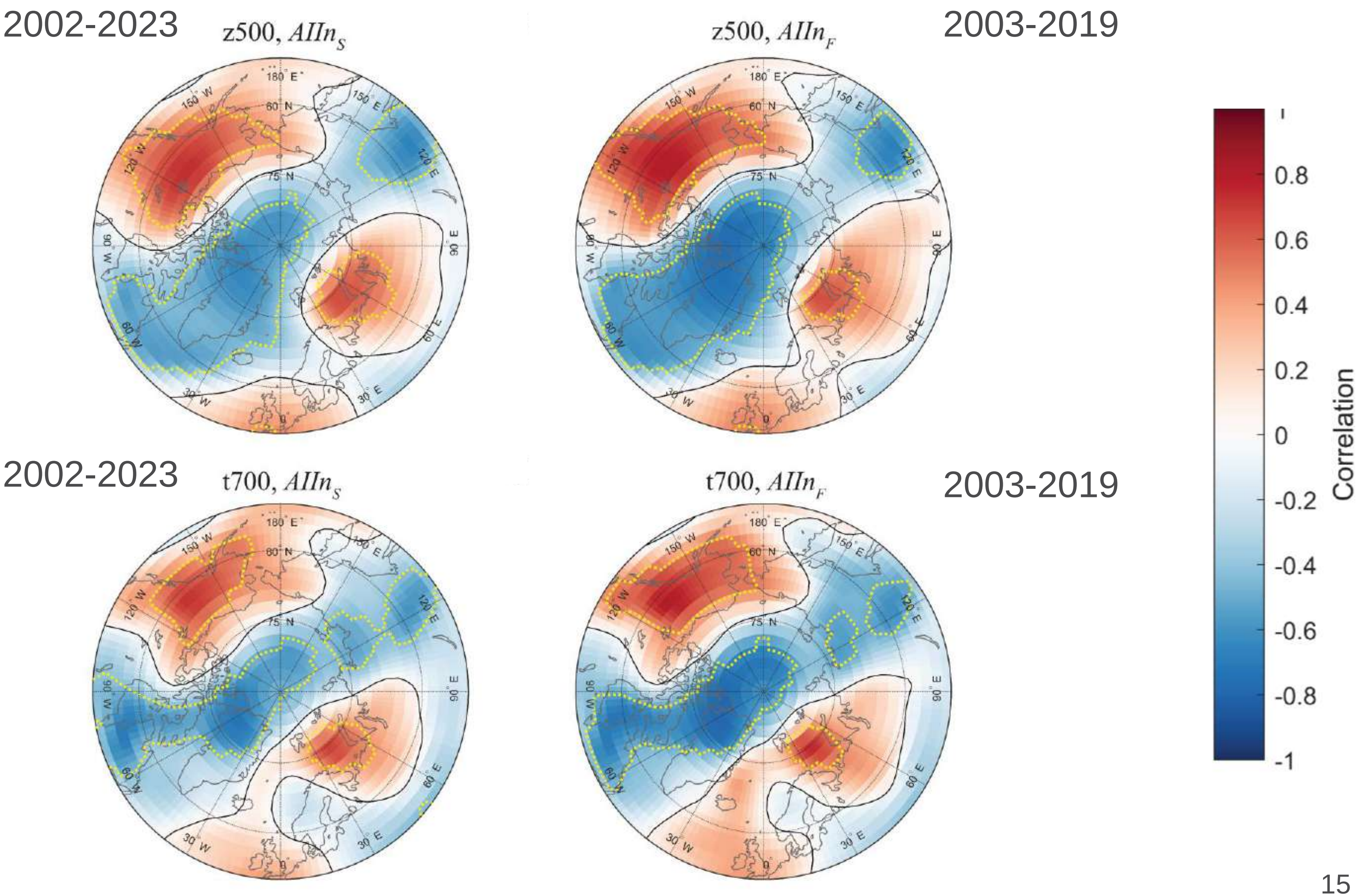
Cold in Svalbard & European Russian Arctic

Uncertainty: observation uncertainties + ensemble spread

Correlation of indices with atmosphere fields

Summer (JJA)
geopotential height
anomaly at 500 hPa

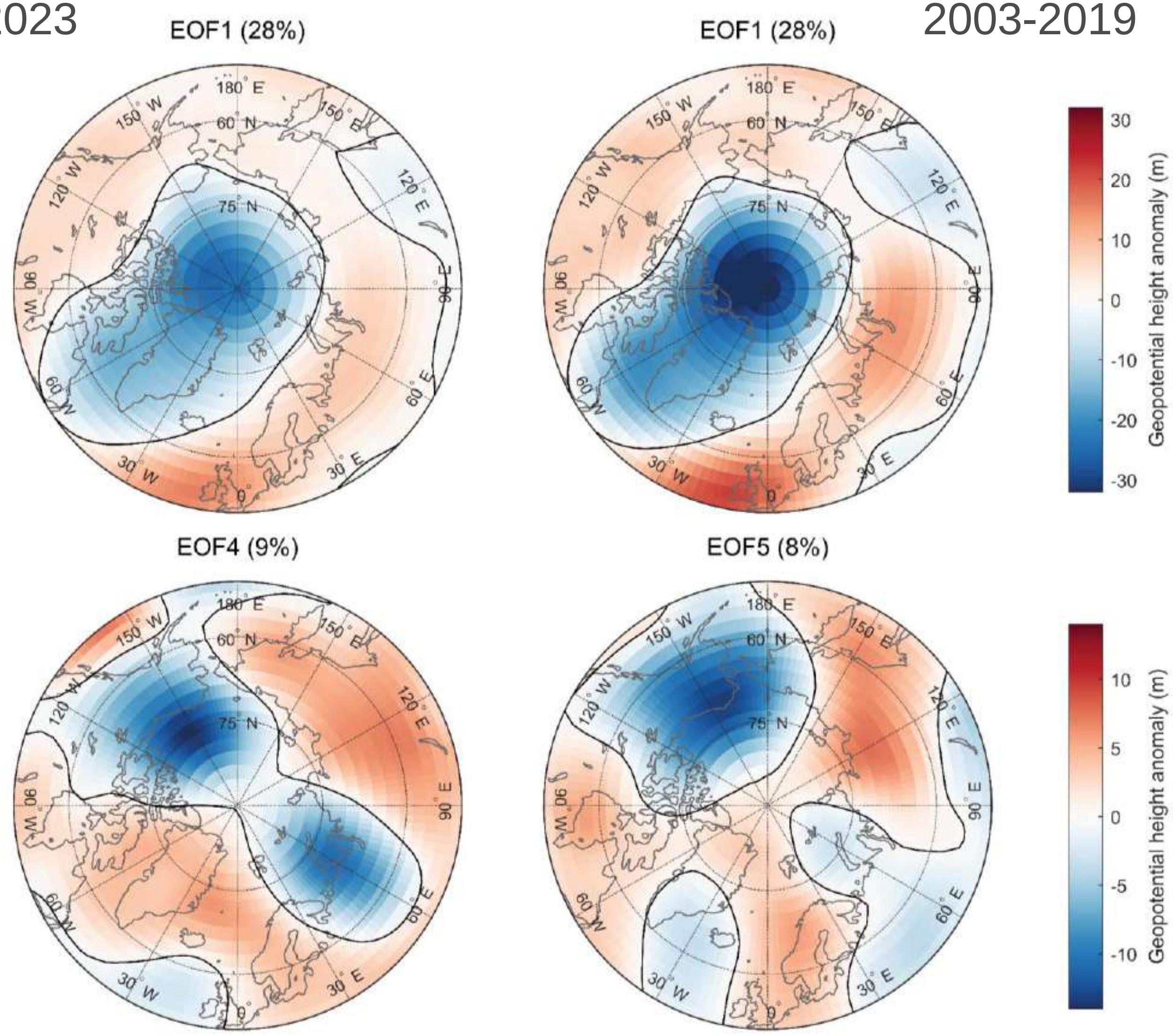
Summer (JJA)
surface-air temperature
anomaly at 700 hPa



Modes of atmosphere variability

2002-2023

2003-2019

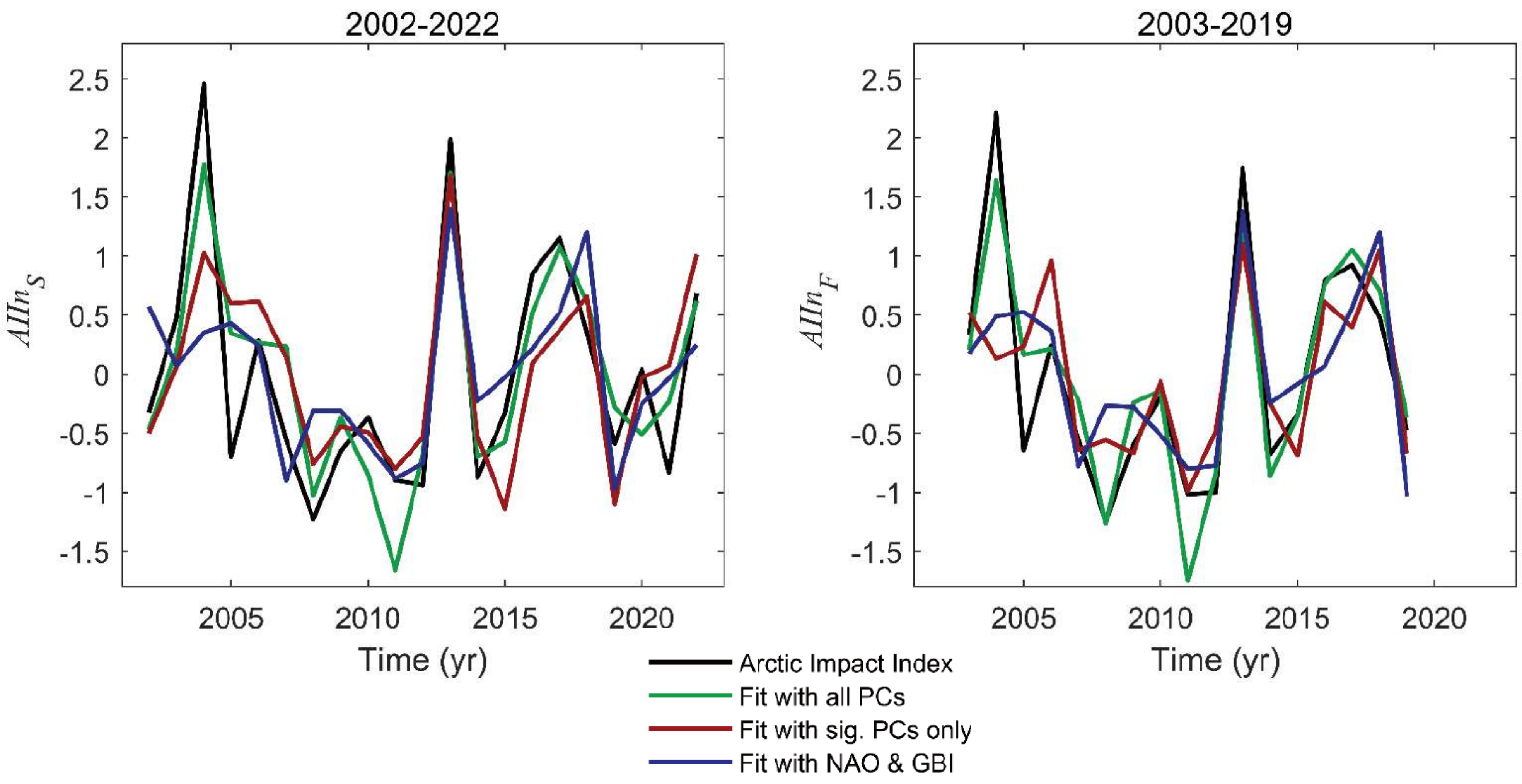


Summer (JJA) **geopotential height** anomaly at 500 hPa

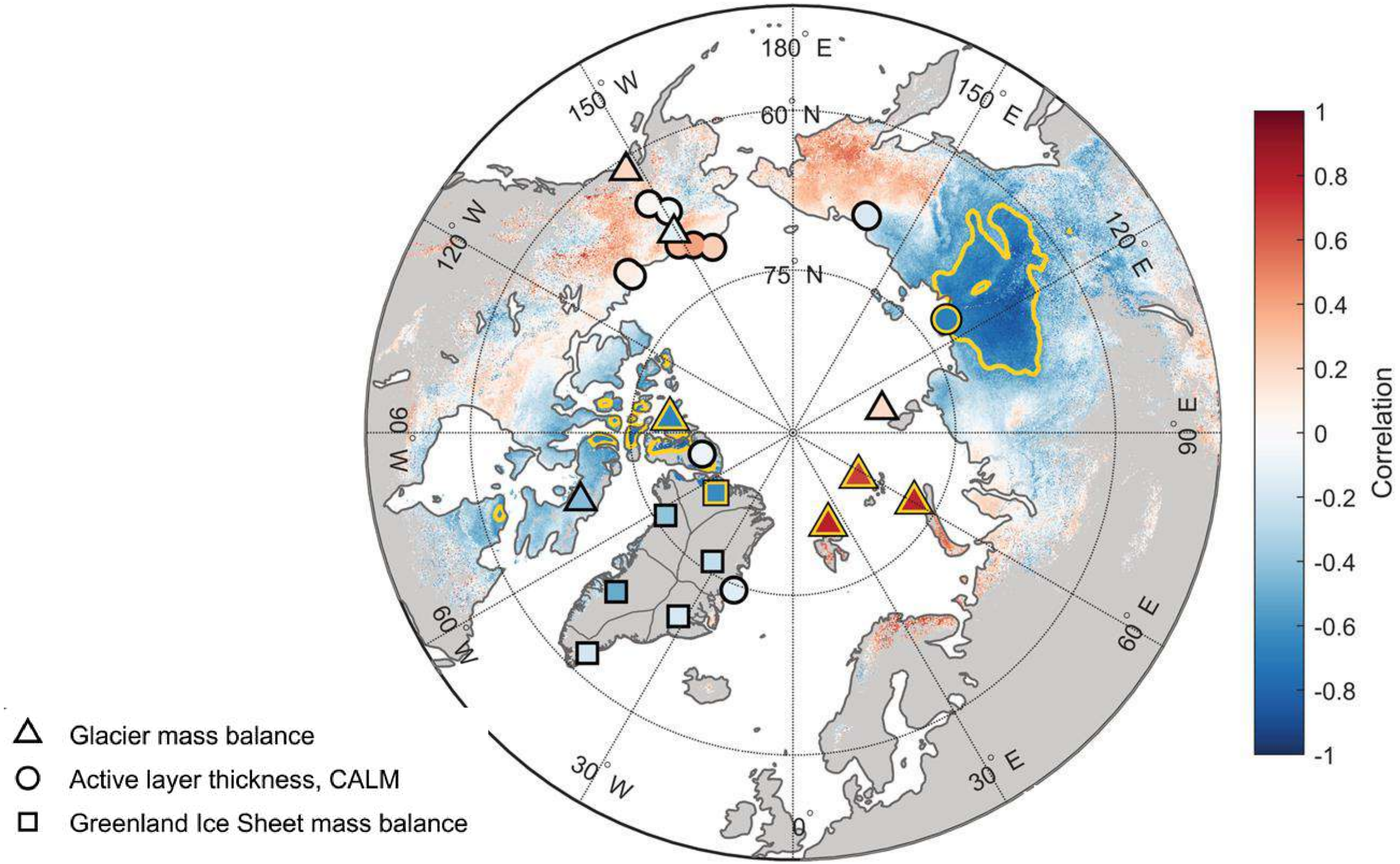
Two modes covary with Arctic Impact indices

- EOF1 correlates with North Atlantic Oscillation and Greenland Blocking index
- EOF4/5 represents variations of higher spatial scale

Representing the indices by atmosphere modes



Regression of impacts observations onto index



Poster announcement

97	Next Generation Gravity Mission design: will new satellite constellations be able to resolve sub-monthly mass change events in Greenland?	Mariia Usoltseva	Technical University of Munich

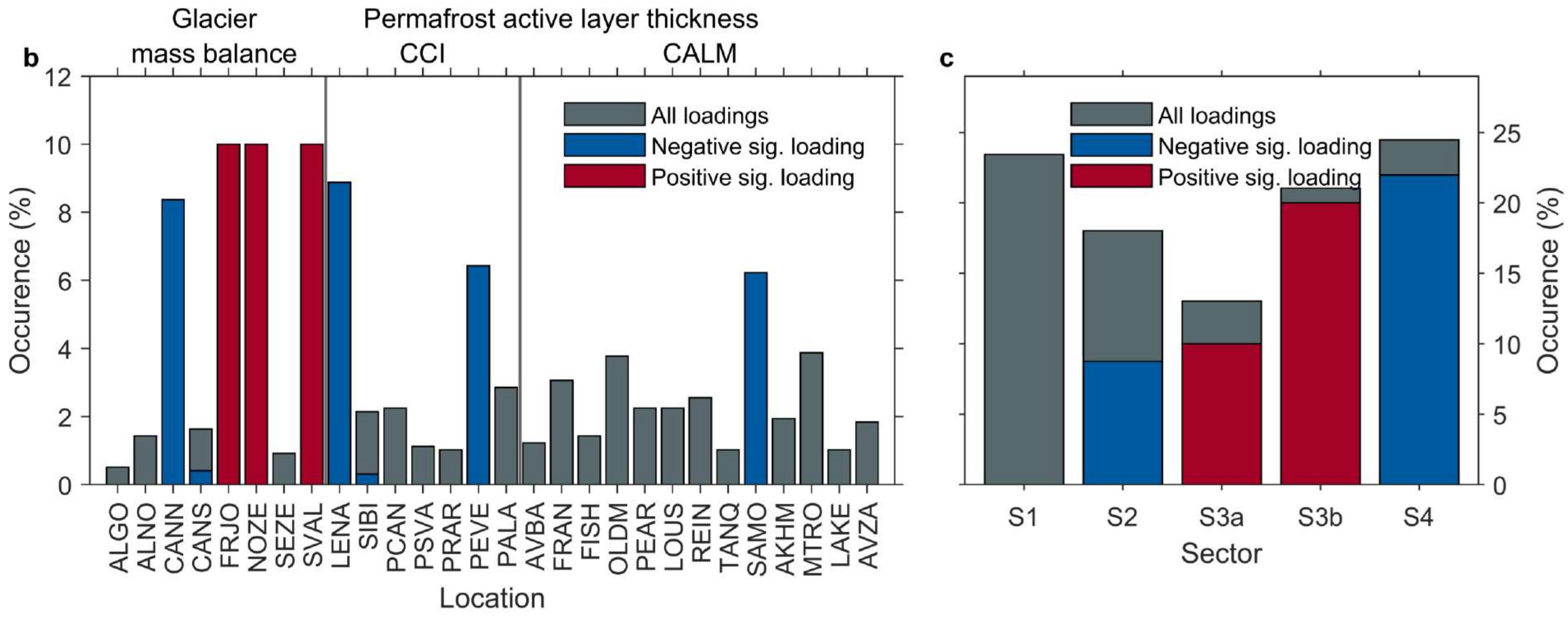
Next Generation Gravity Mission design: will new satellite constellations be able to resolve sub-monthly mass change events in Greenland?

Mariia Usoltseva, Ingo Sasgen
(mariia.usoltseva@tum.de)

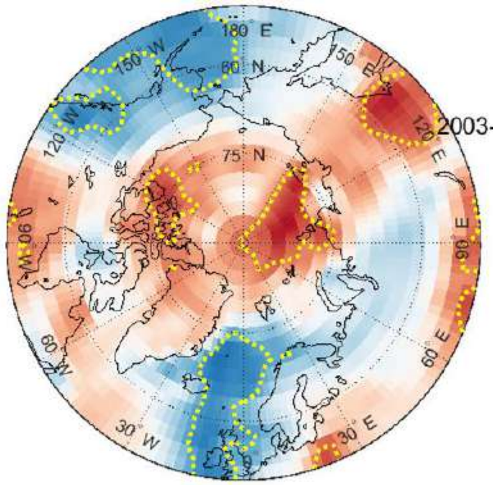
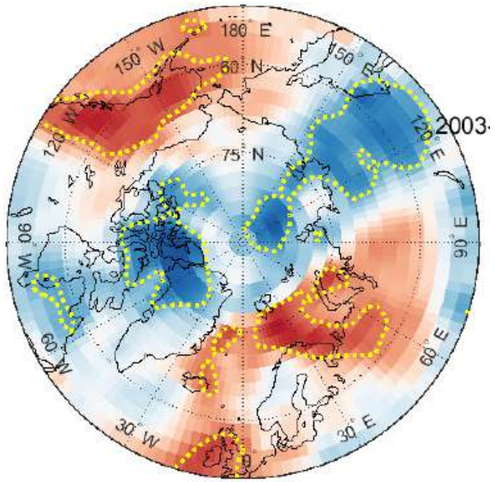
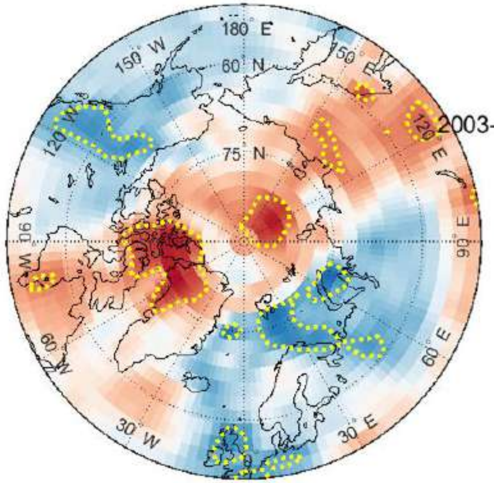
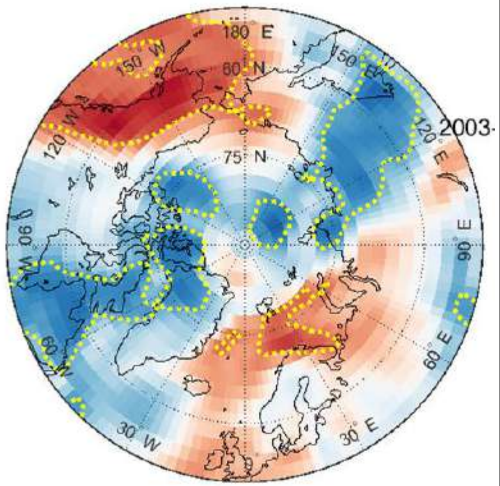
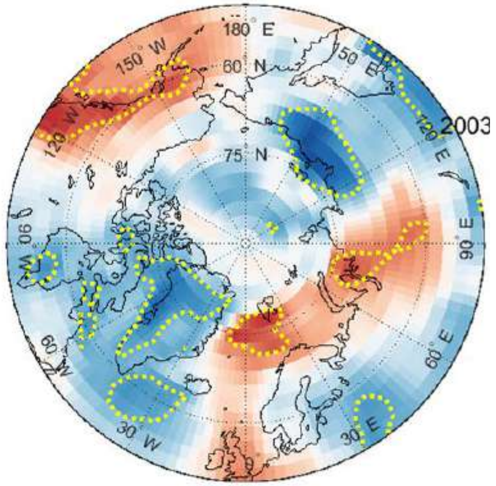
Sasgen, I., Steinhoefel, G., Kasprzyk, C. *et al.*
Atmosphere circulation patterns synchronize pan-Arctic glacier melt and permafrost thaw.
Commun Earth Environ **5**, 375 (2024)
https://doi.org/10.1038/s43247-024-01548-8

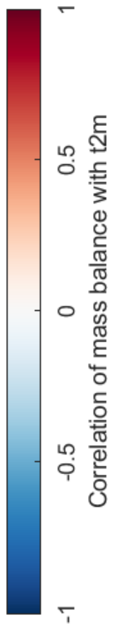
Photo: Carsten Falck, GFZ Potsdam

Statistics of impact index



Correlation with atmosphere variables: t2m

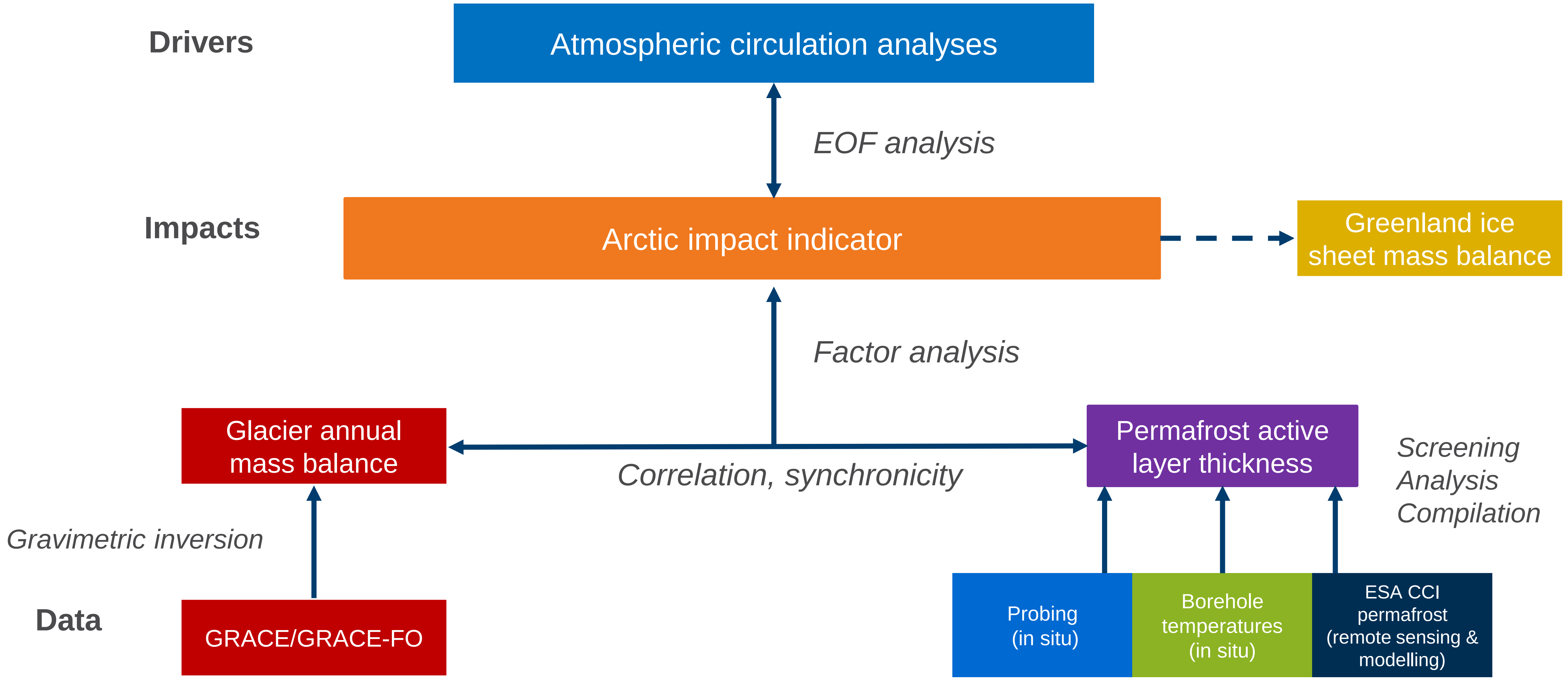
Region 1	Region 2	Region 3	Region 4
ALGO 	CANN 	SVAL 	LENA  SIBI 



Mean 2 m air temperature (JJA) variability &
Annual mass balance variability (2003-2016)

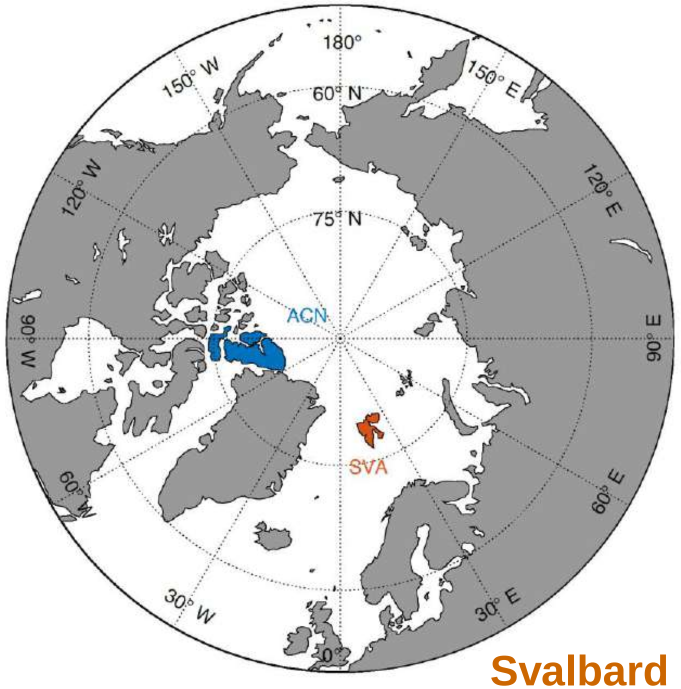
BLUE – negative (cold) temperatures
e.g. BLUE over CANN → cold t2m air temperature → low melting → positive mass balance anomaly (less loss)

Project structure



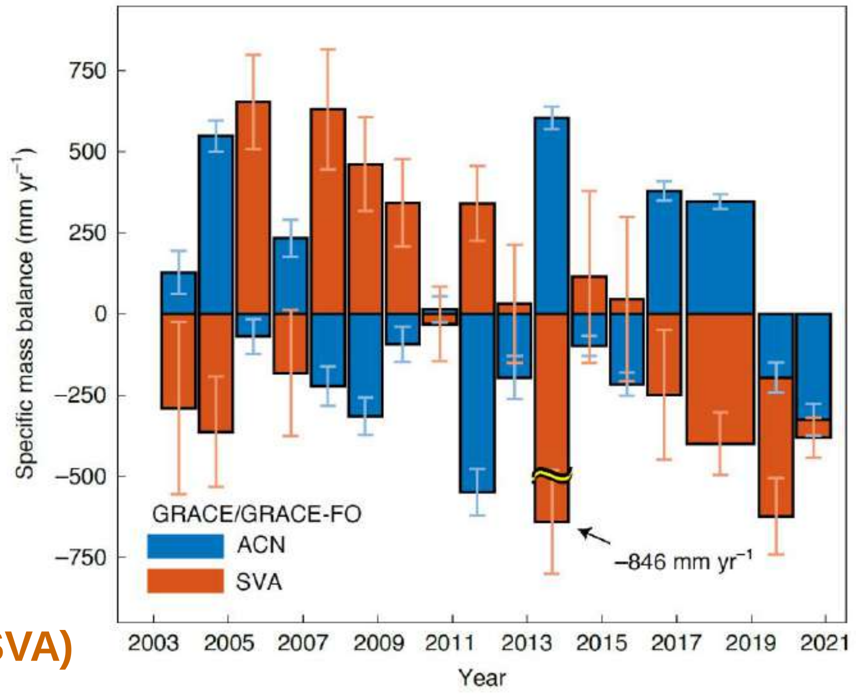
Artic mass change & large-scale weather patterns

Arctic Canada North (ACN)

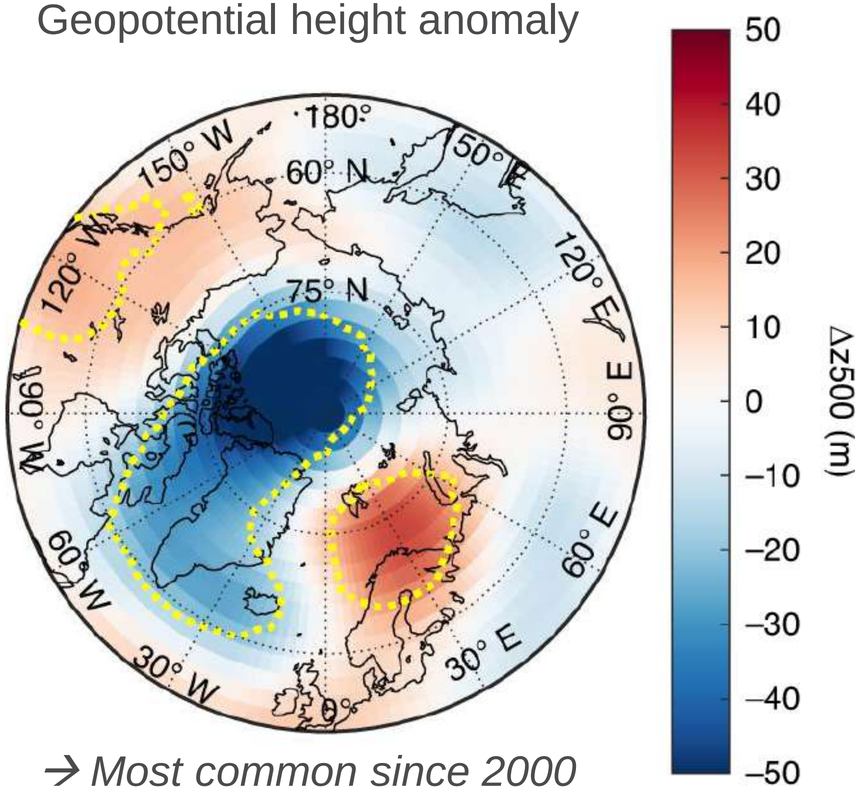


Svalbard (SVA)

Annual mass balance anomaly

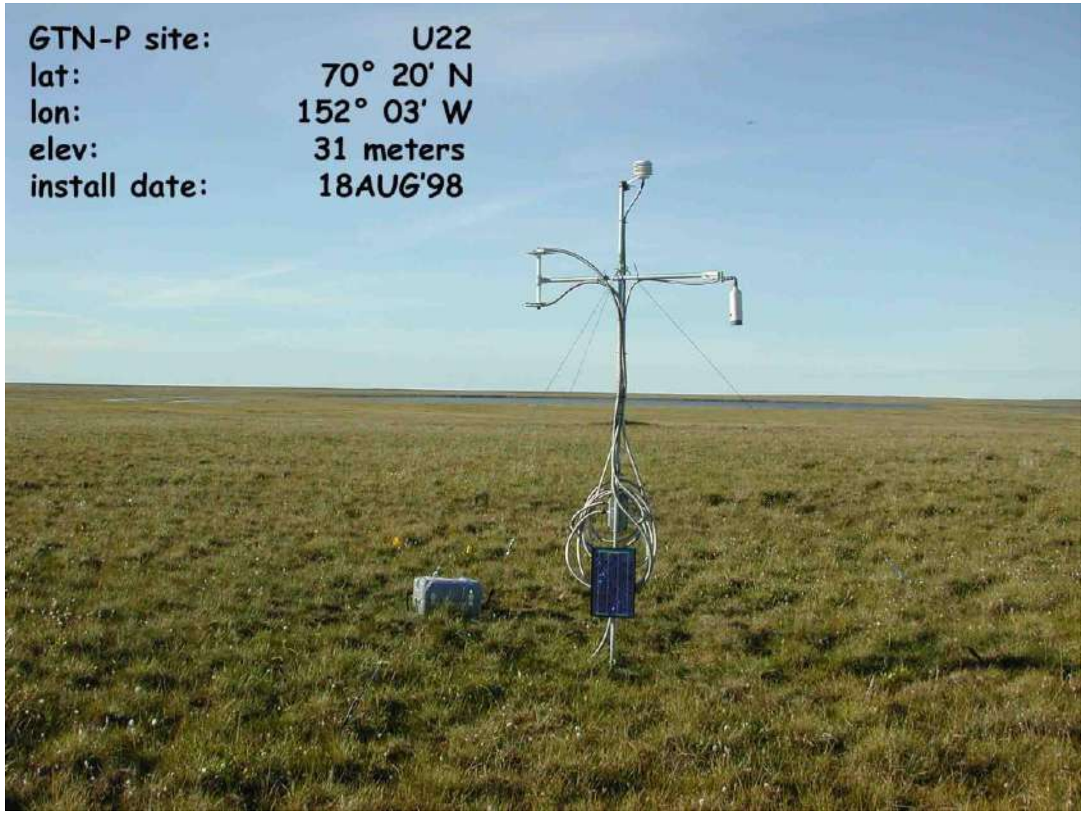


Geopotential height anomaly



→ *Most common since 2000*

Sasgen et al. 2022



CALM SITE U2

BARROW CRREL

Site code

U2

Site name

Barrow

26

Arctic Impact Indices

Type 1 (2003-219)

Standardized Factor 1

$$AIIn_F = f_1/std(f_1)$$

F - Factor analysis

Advantage: Robustness

Disadvantage: Requires continuous and congruent time series for all observation

Type 2 (2002-2023)

Significance and attribution to +/- using Factor 1

Double-standardized observation time series directly

$$z = \sum \frac{x_p}{std(x_p)} - \sum \frac{x_n}{std(x_n)}$$

p: observations with significant positive loading

n: observations with significant negative loading

$$AIIn_S = \frac{z}{std(z)}$$

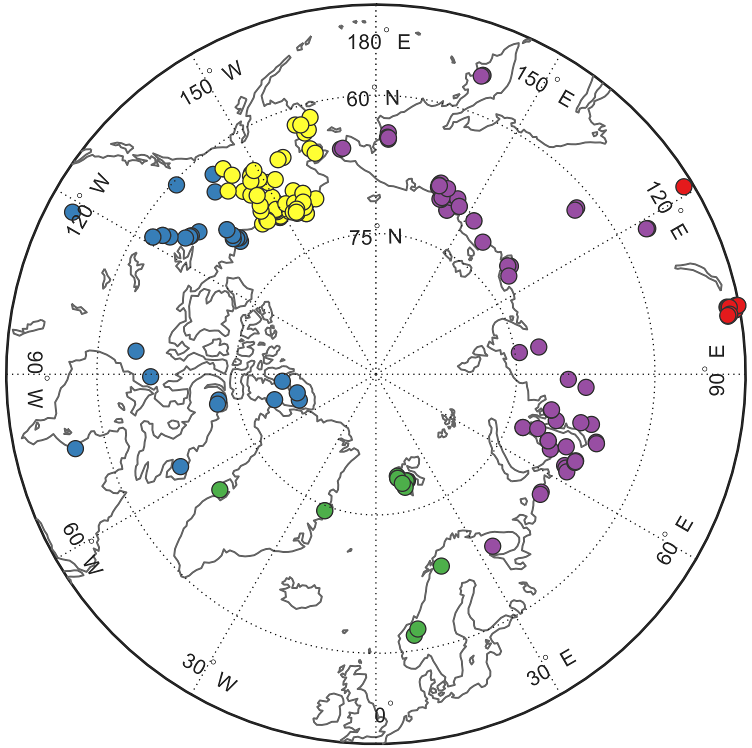
S – Selection of observations

Based on single set of discontinuous key observation

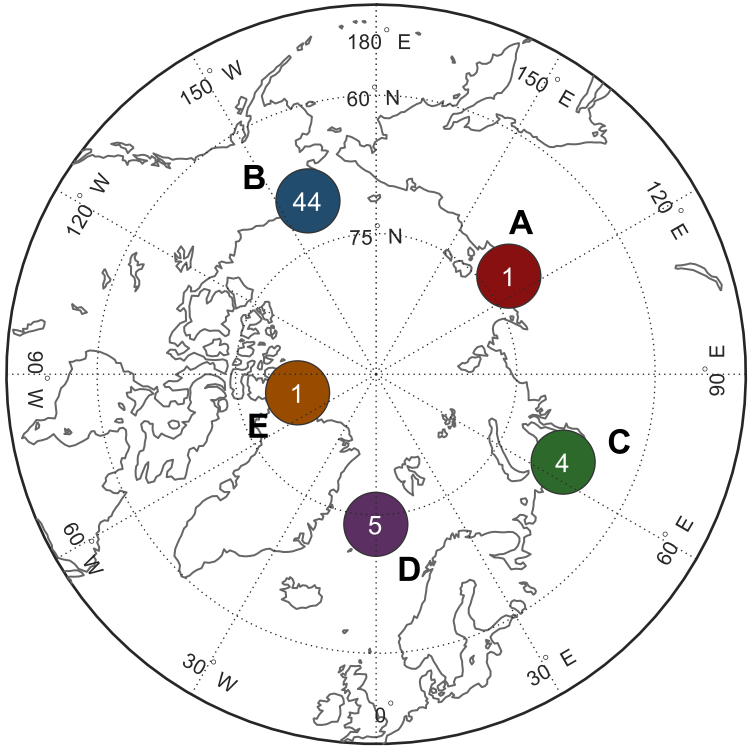
Less representative

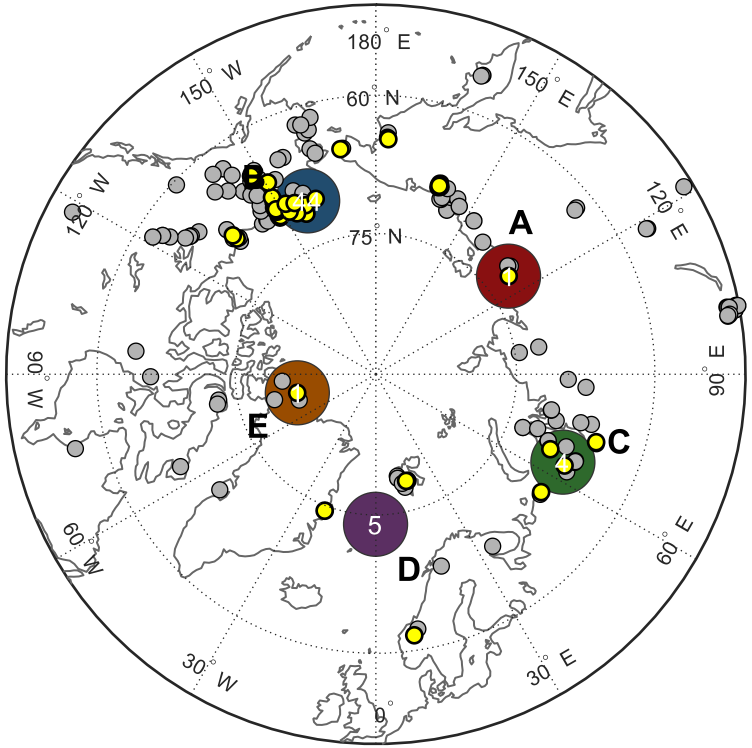
Distribution of CALM measurements

Regional clusters

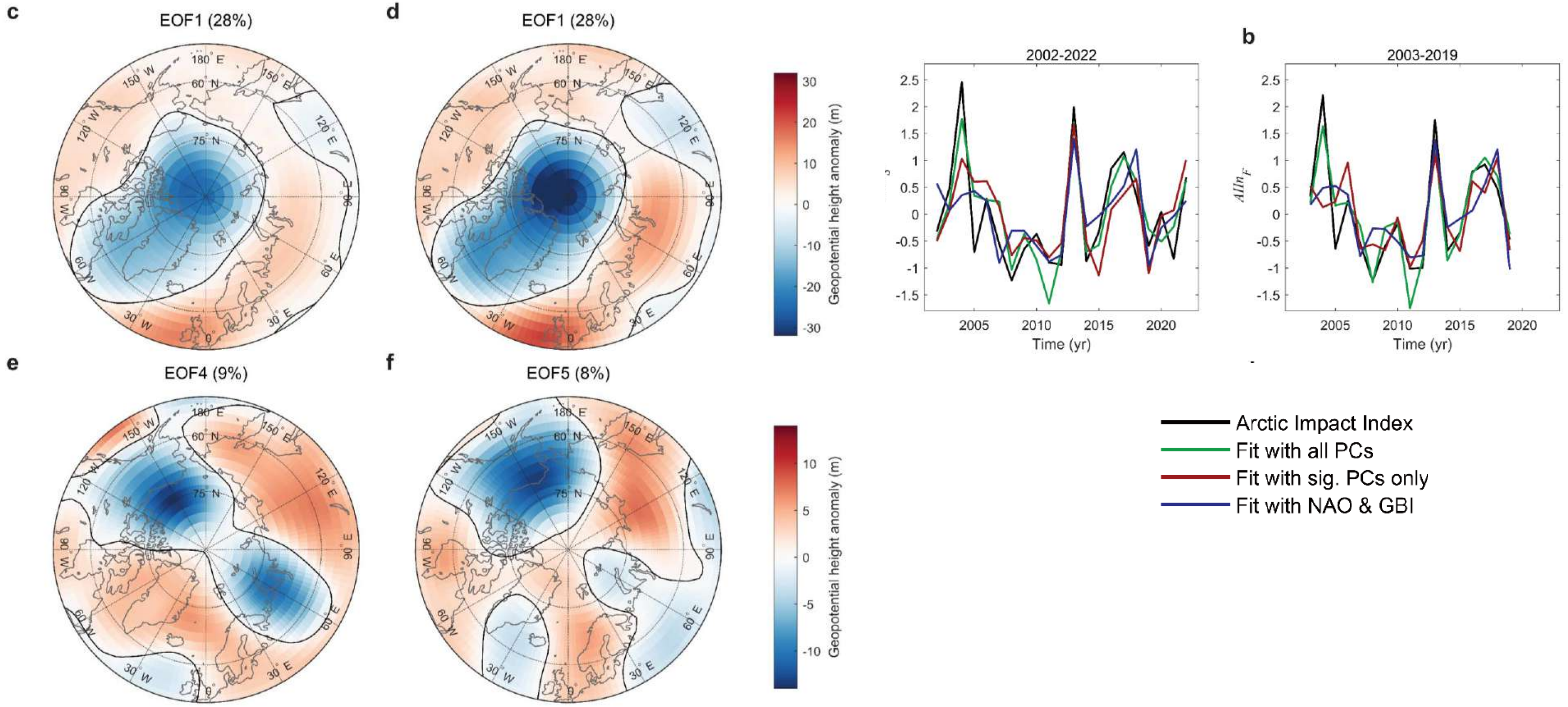


Regional clusters

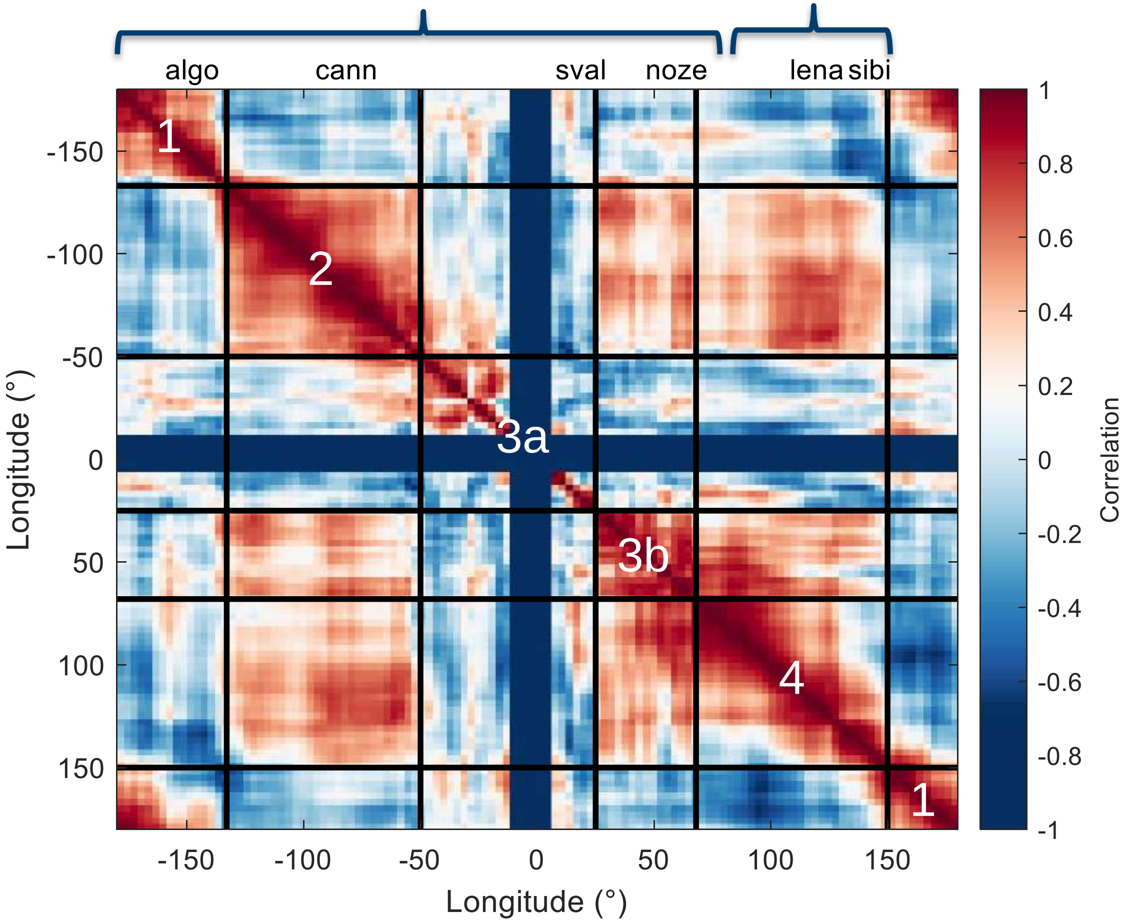




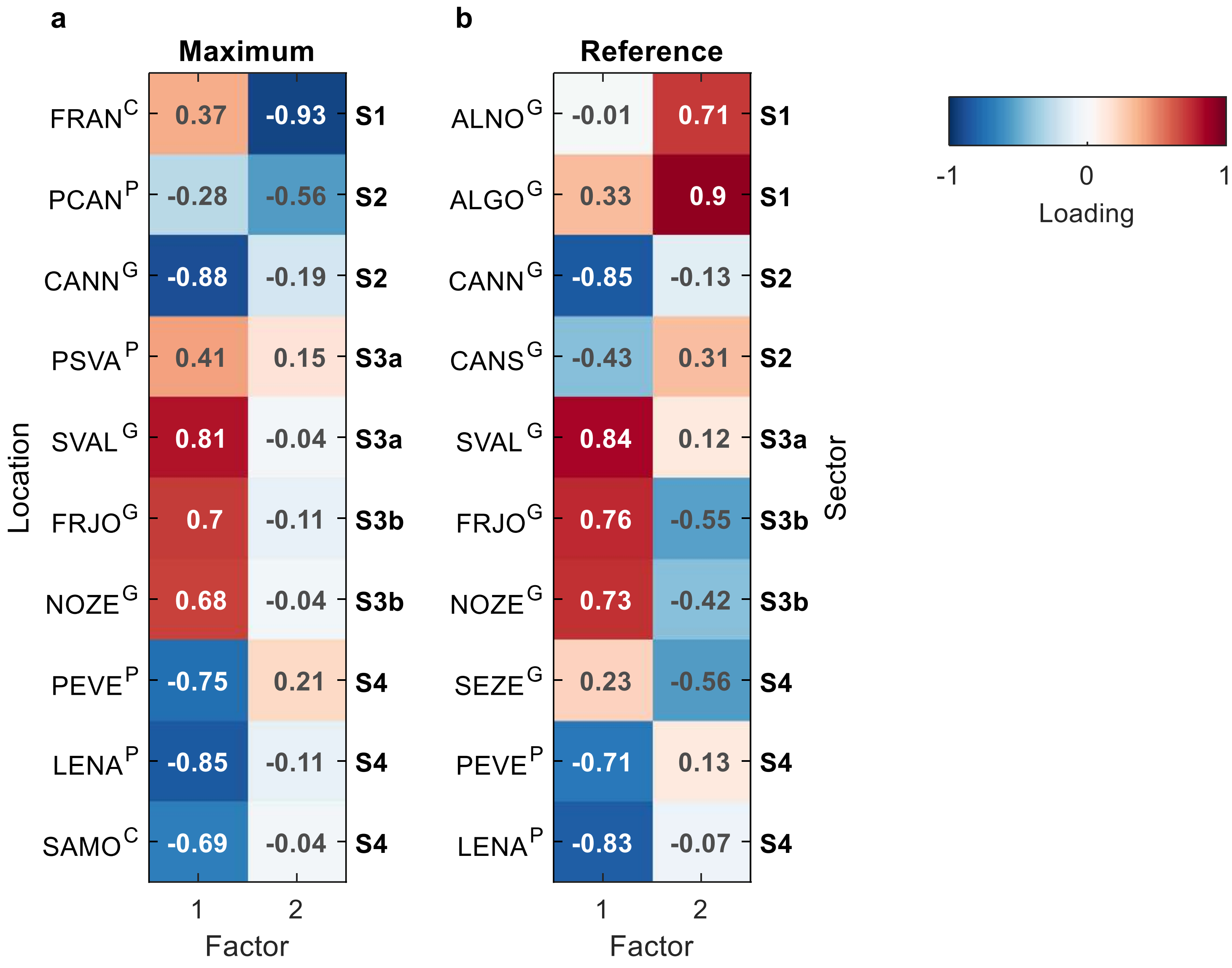
Regression of index with principal components



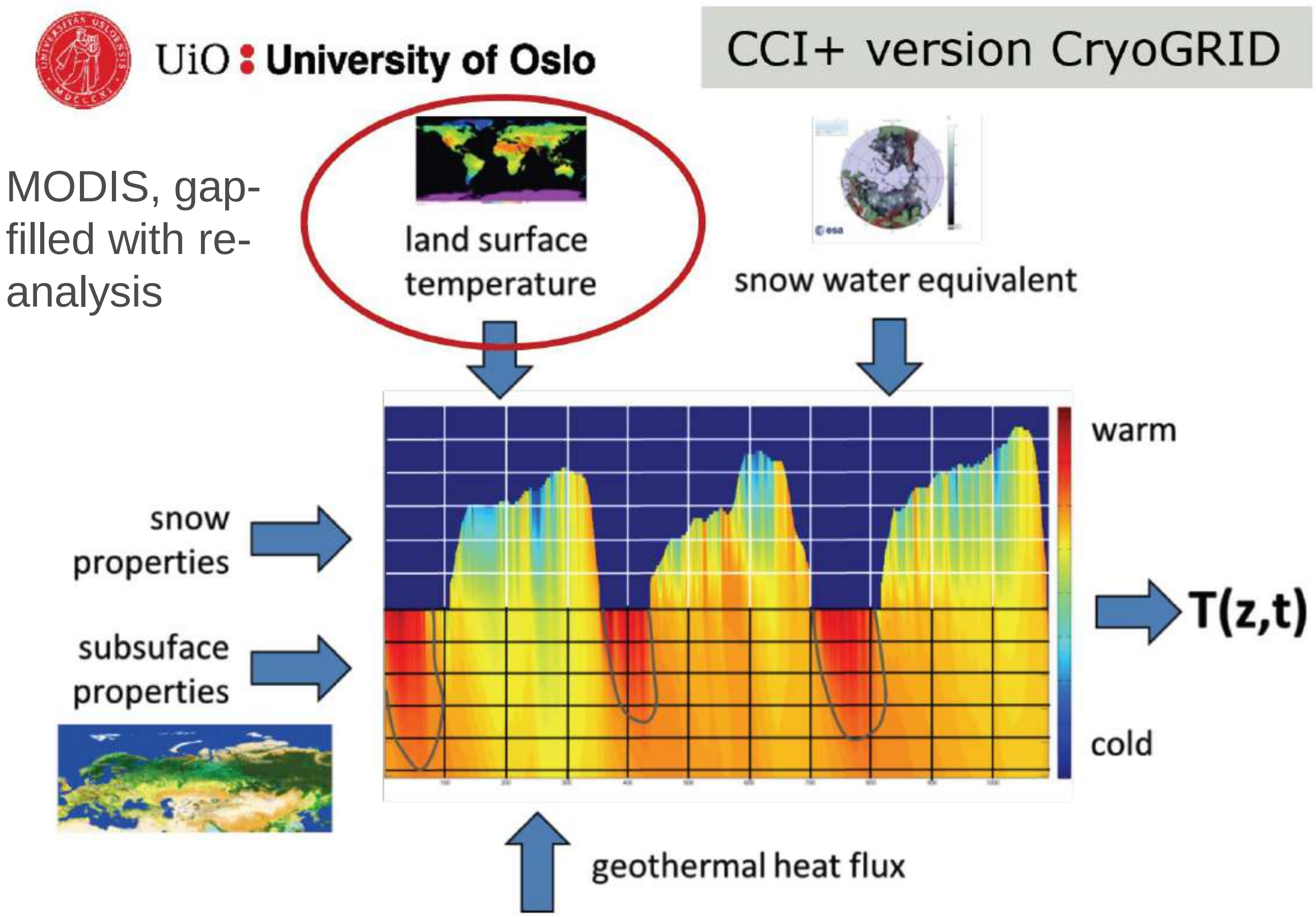
Correlation of meridional means of ALT



Maximum and reference ensemble



ESA permafrost remote sensing / modelling product



- Climate Change Initiative (CCI+), AWI Potsdam, Univ. Oslo
- CryoGRID ground thermal model (CCI+ version)
- Transient modelling of ground temperature – T(z,t)
- Time period 2003-2019 (currently being updated)
- *1 km x 1 km estimates of annual maximum active layer thickness*

Development: Sebastian Westermann, Univ. Oslo (form. AWI)

Comparison of *in situ* and remote sensing data

In situ CALM observations

- 266 field measurements
- 185 north of 60°N (120 continuous permafrost)
- 57 with only one missing year 2003-2017
- Removed 1 record from Abisco area, Sweden
- Merged 4 co-located sites at Mt. Rodinka, Russia

→ 53 in situ records of permafrost change

CCI+ remote sensing observations

- Interpolated to 5km x 5km
- Detrended
- Standardized anomalies

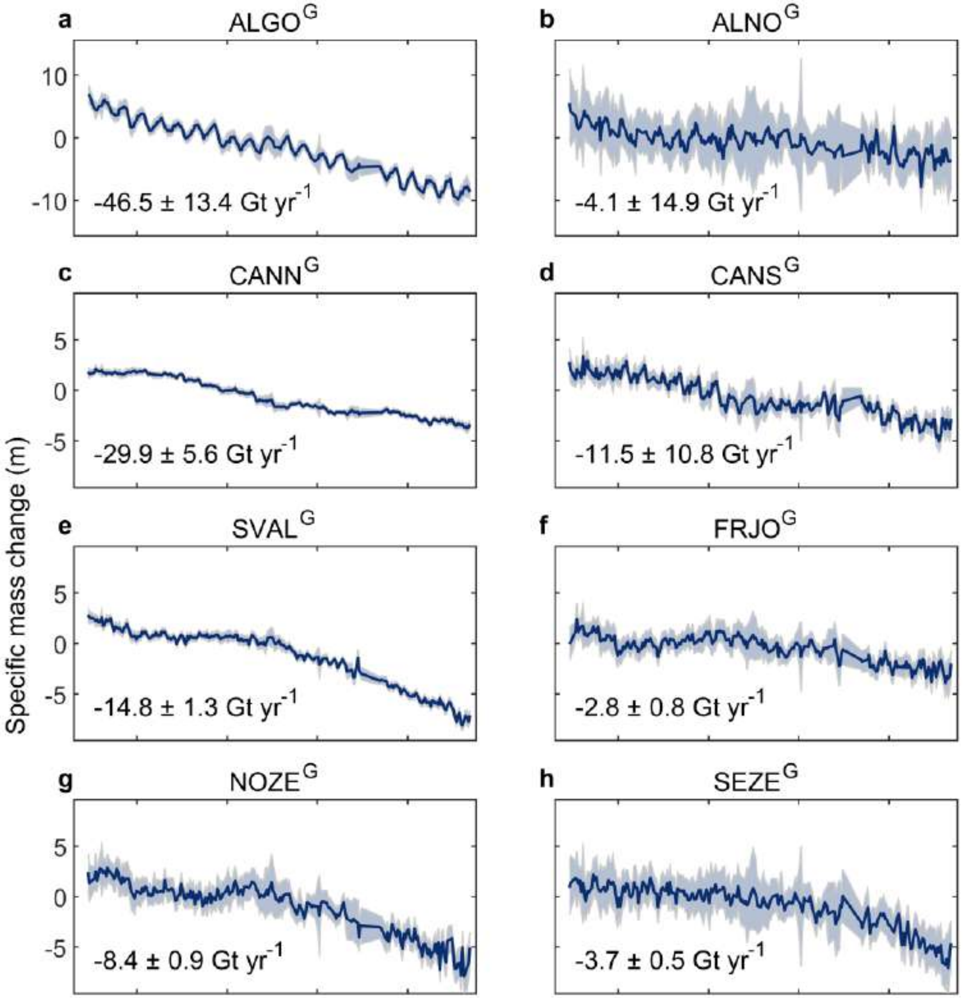
→ Regional/sectoral averages

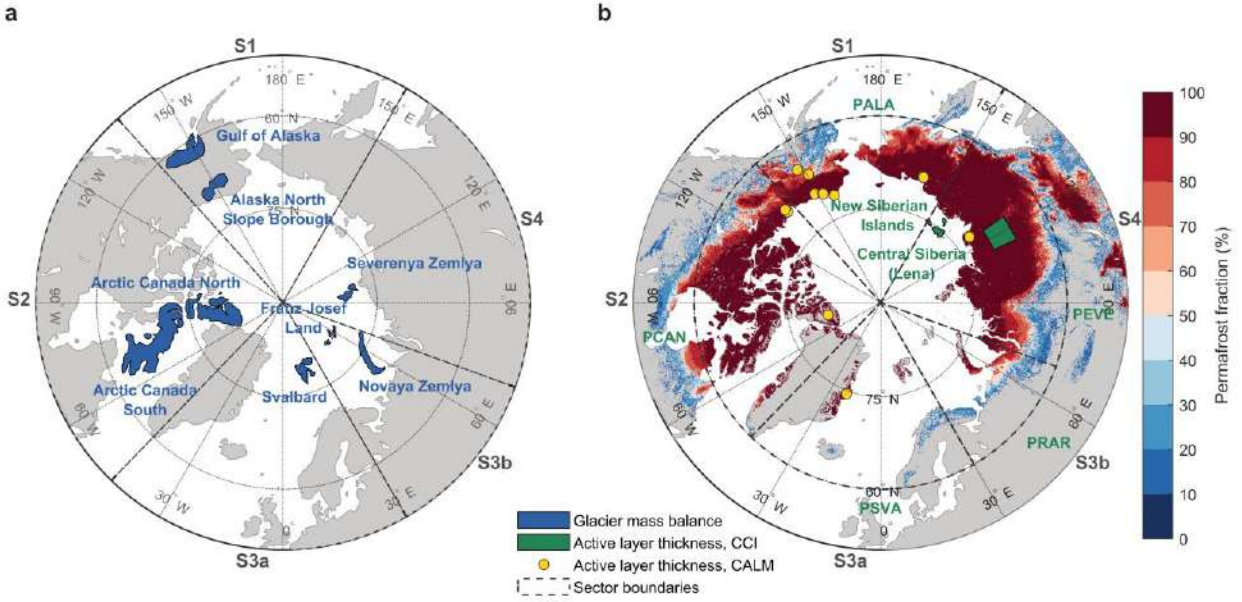
To find CALM stations recording larger regional signals

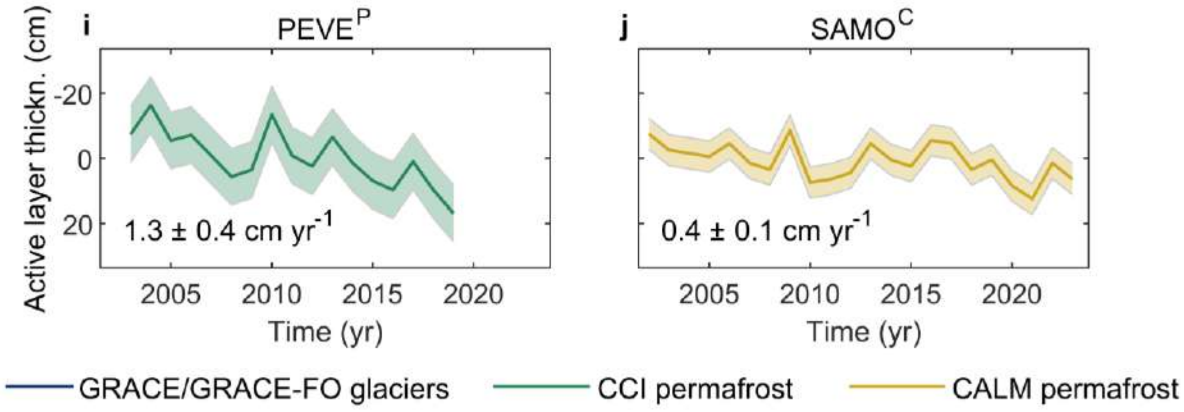
- Correlation of CALM record with nearest grid point in CCI
- Adopt stations where correlation is significant
- Estimate uncertainty from CALM / CCI differences

→ 13 in situ records likely carrying regional signals

Glacier mass and permafrost change







Scheme

Atmosphere drivers

Modes

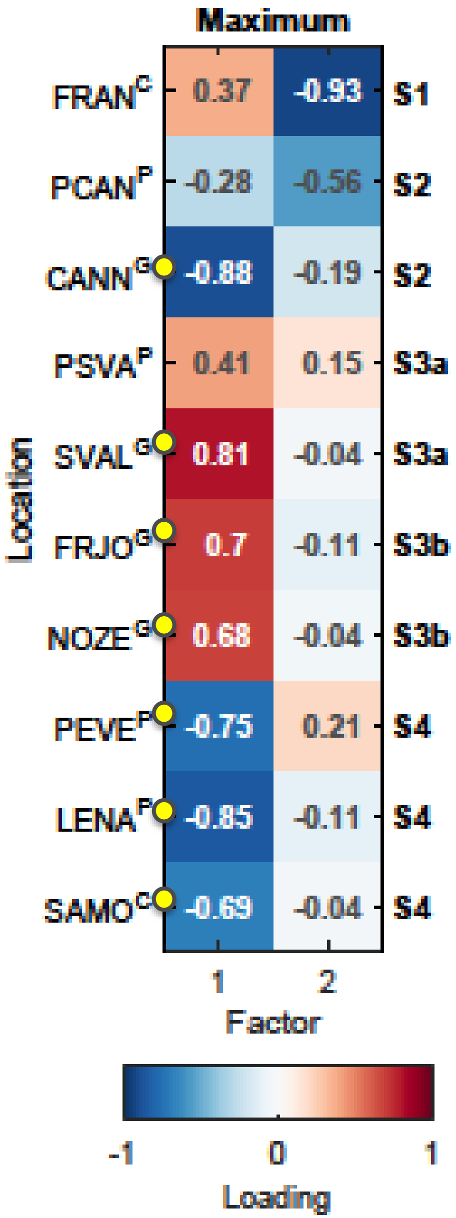
Covariations

GRACE/GRACE-FO mass change

In situ active layer thickness

Remote sensing active layer thickness

Factor analysis and derived impact index



Maximum: $\sum_n |\lambda_{1,n}|\,! = max.$

C: CALM *in situ* measurement

P: CCI remote sensing sectorial / regional average

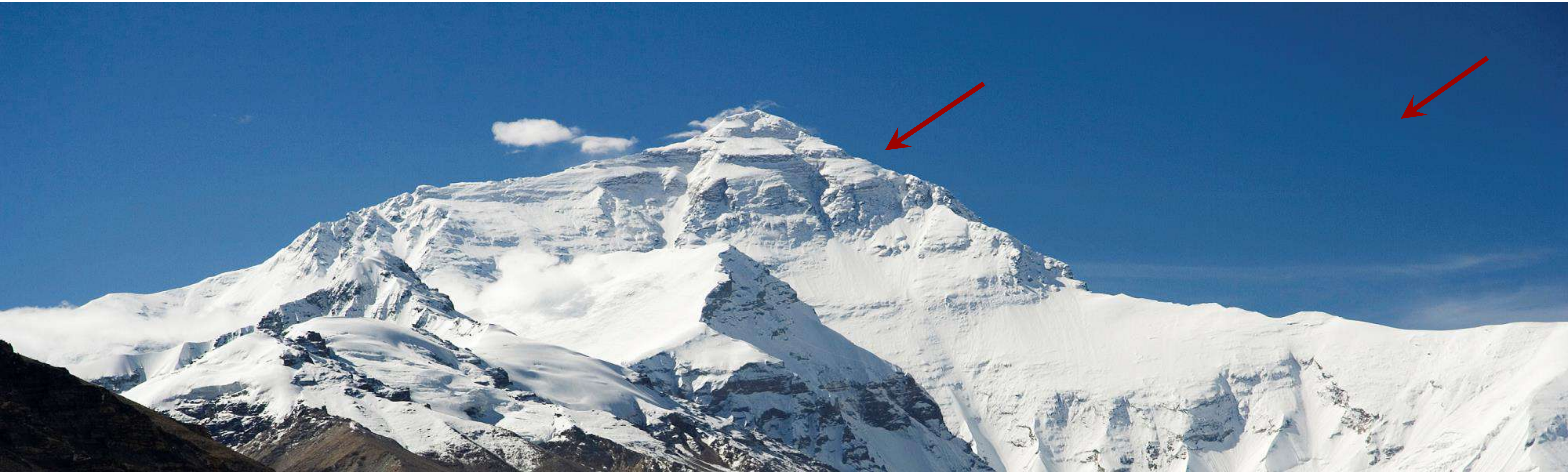
G: GRACE/GRACE-FO glacier mass change

Criterion of significance: $|\lambda_{1,n}| > 0.5$ & $|\lambda_{1,n}|$ - $|\lambda_{2,n}| > 0.3$

Factor analysis

- Random set of 10 observations
- All five sectors have to be represented
- No constraint on data type
- Ensemble with $N \approx 14000$ members
- Significance screening

Mass change from GRACE/GRACE-FO satellites



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Courtesy: D. Schütze (AEI Hannover)

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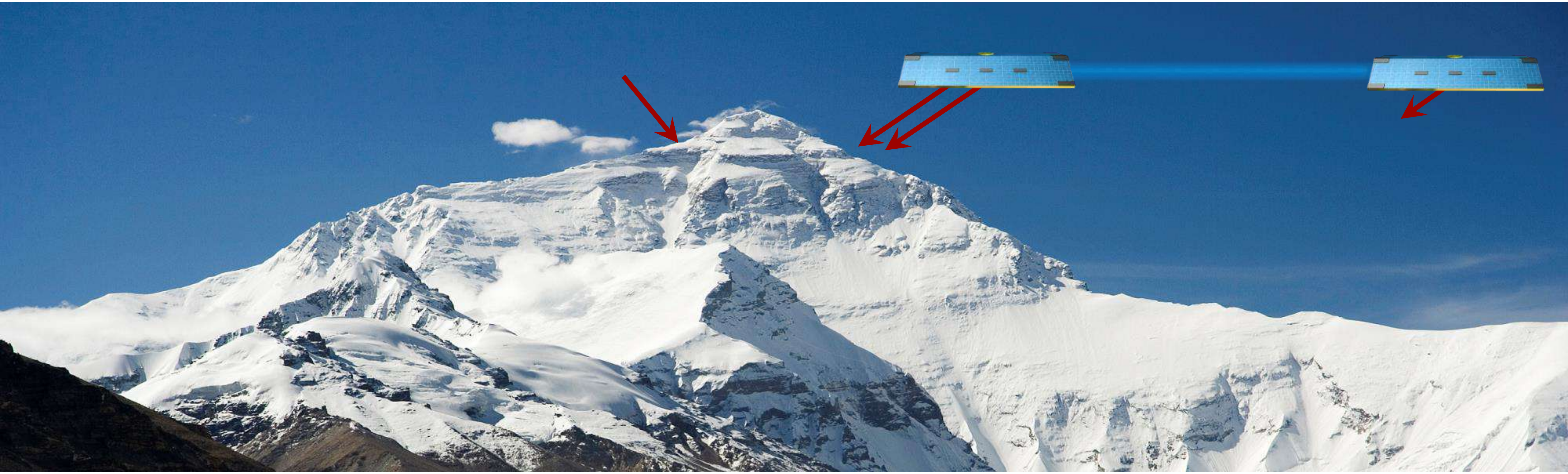

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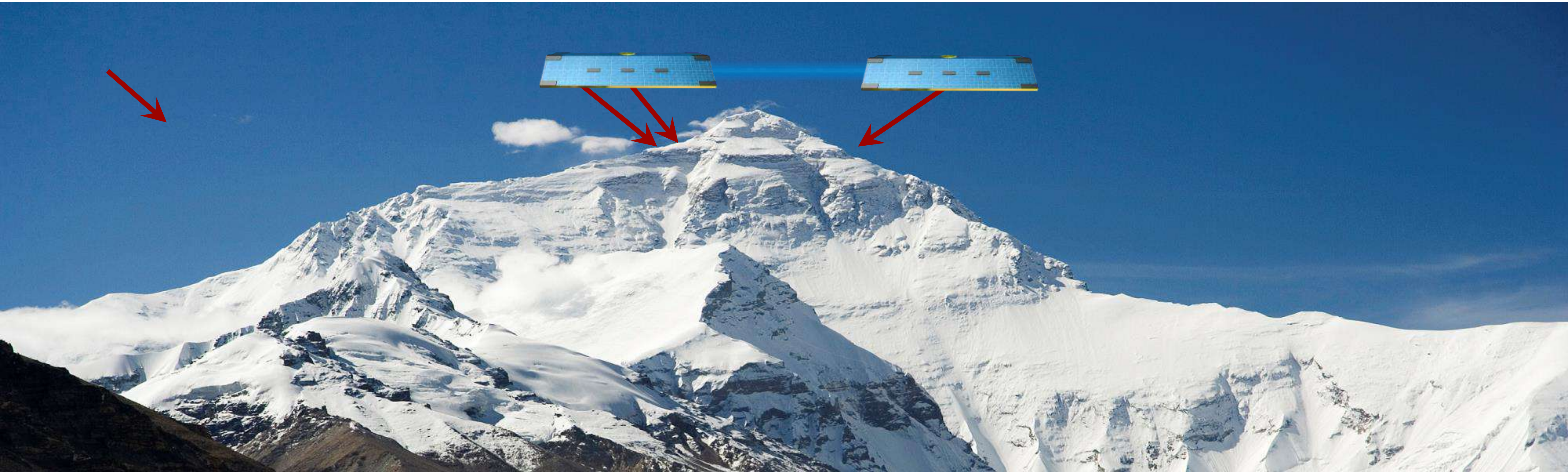

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Courtesy: D. Schütze (AEI Hannover)