Updates from the Arctic energy budget group

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Overview of recent activities

Projects involving Arctic budget and ocean transport analysis:

- **CMEMS - Validation & Intercomparison of Global Copernicus Marine Reanalyses**: Assessment of oceanic transports, including key Arctic gateways (ending 06/2028)

→ Contribution to UN Decade **Marine Environment Reanalyses Evaluation Project** (MER-EP)

- **ESA MOTECUSOMA** (Monitoring the Energy Cycle for Climate Understanding): Work package with Arctic relevance: improved near-surface temperature estimates in the marginal ice zone & evaluation of energy budgets (ending 08/2027)

- IASC Atmospheric Working Group: Michael → Susanna
- Susanna involved with Fresh Eyes on CMIP initiative → If you work with CMIP data or are interested in joining future activities, feel free to contact me

- Collaboration with Geosphere Austria: Master thesis by Anna on Freya Glacier (30-yr surface energy & mass balance reconstruction using reanalysis)

A 30-year reconstruction of the surface energy and mass balance of Freya glacier, Greenland, using reanalysis data

Anna Rohrböck

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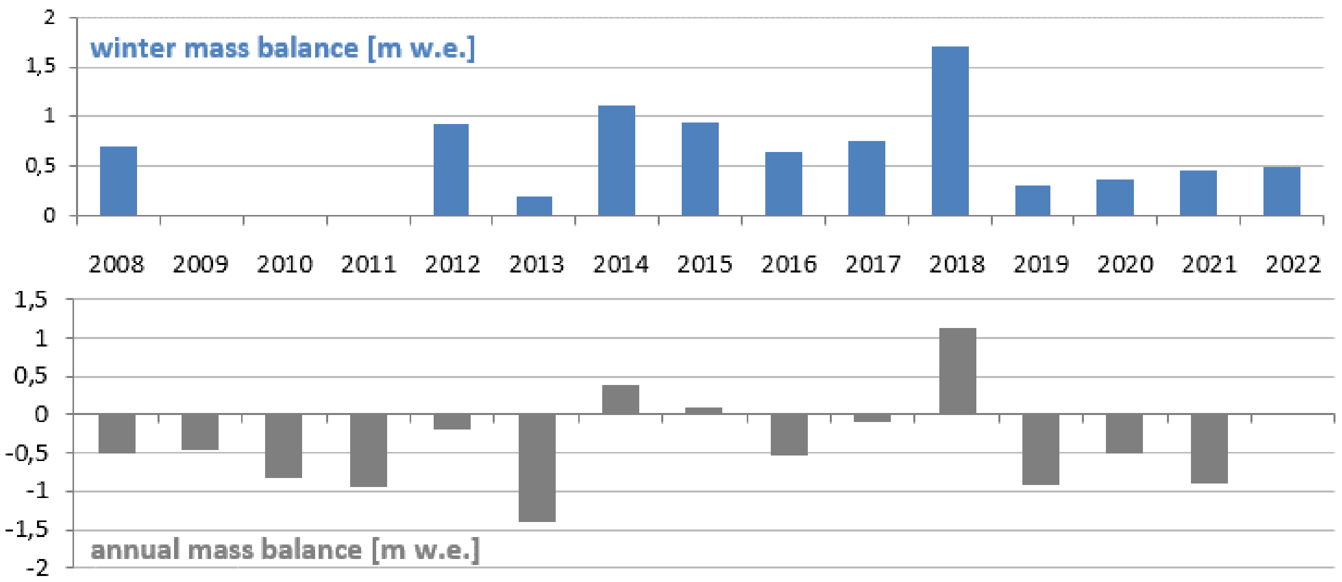
APRI Annual General Meeting

28-11-2025

Research Questions & Motivation

1) How can the understanding of the mass balance on Freya glacier be extended into the past?

2) Are there any machine learning methods that are suitable for determining the mass balance?



Hynek et al. (2021)

Limited long-term observations

Direct mass-balance data at Freya glacier only since 2008

Peripheral glaciers in Greenland are under-monitored

Need to reconstruct past conditions

Effects of climate change on the mass balance

Opportunity to extend mass-balance records back in time with high-resolution reanalysis data

Combining empirical models & machine learning

Classical temperature-index melt models

Data-driven approaches may capture non-linear processes

Data

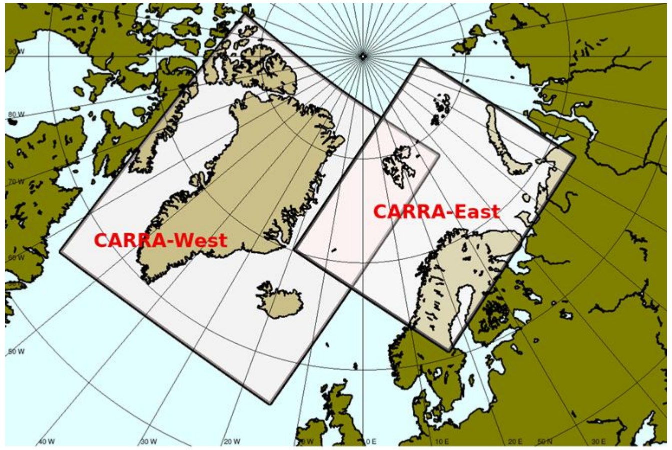
Observational data

- Automatic Weather Station (AWS) on Freya glacier
- Ablation stakes on Freya glacier

Reanalysis data

- Copernicus Arctic Regional Reanalysis (CARRA)
- High-resolution Arctic reanalysis (2.5 km grid vs. 9 km ERA5-Land)
- Combines radiosonde, satellite & local observations (PROMICE, GC-Net, DMI, Asiaq, Zackenberg)
- Covers 1990 - present

The current AWS on Freya glacier was installed in May 2016 at an altitude of 688 m a.s.l. *(Hynek et al., 2016)*



CDS (2025)

PROGRAMME OF THE EUROPEAN UNION | Copernicus | ECMWF | Climate Change Service

Photo: Anton Neureiter, 2025

Glacier mass balance models

Model	Input variables	Equation
Hock (2003)	Air temperature	$M = \begin{cases} f_m\,(T_d - T_{melt}), & T_d > T_{melt} \\ 0, & T_d \leq T_{melt} \end{cases}$
Marzeion (2012)	Air temperature & precipitation	$\sum_{i=1}^{n} (P_i - f_m(\max(0, T_i - T_{melt}))) = MB$
Pellicciotti (2005)	Air temperature, shortwave radiation & albedo	$M = \begin{cases} TF\,T + SRF(1-\alpha), & T > T_{melt} \\ 0, & T \leq T_{melt} \end{cases}$

- Goal: use melt models with lower data requirement than energy-balance models
- Test the influence of increasing model complexity on the reconstructed mass balance and compare results with a data-driven machine learning approach

Support vector regression

<u>SVR</u>: typically applied for classification and regression tasks
<u>Main advantage</u>: computational efficiency

Basic idea

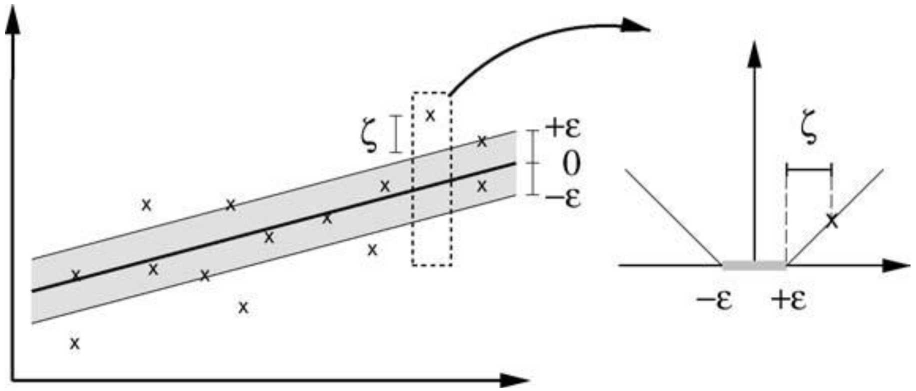
- Fit regression function within ε-tube
- Points within the ε-tube are within the tolerance range → no penalty
- Points on the edge or outside are called support vectors → they determine the position and slope of the regression line

Kernels

- Project data into higher-dimensional spaces
- Model both linear & non-linear relations

Common kernels

- Linear → simple/linear relations
- Polynomial → more complex relationships
- Radial Basis Function (RBF) → well suited for capturing non-linear patterns in the data

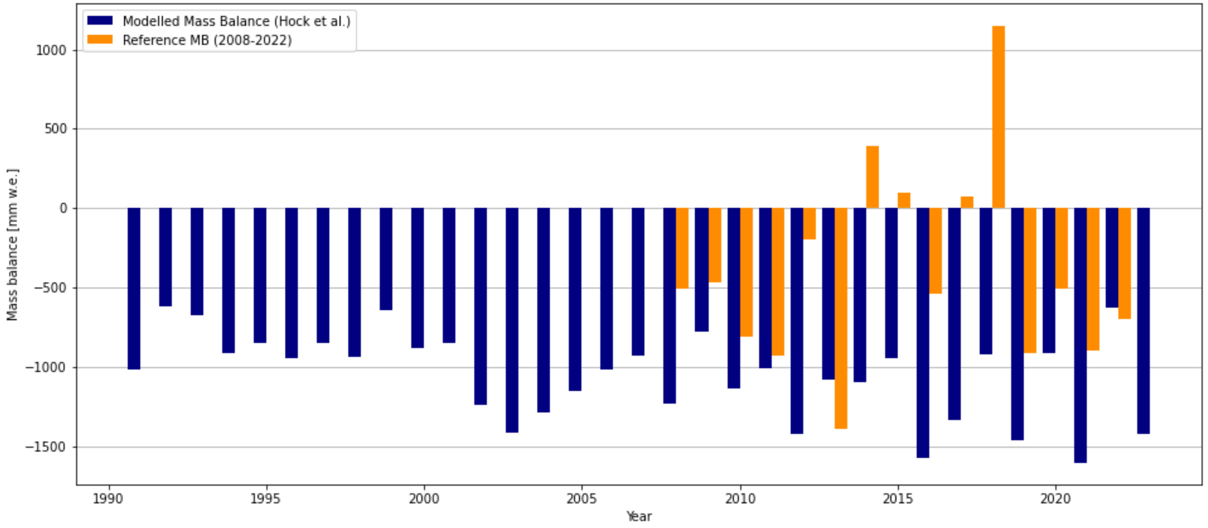


Schölkopf and Smola (2004)

- ➢ ***<u>Predictors</u>***: CARRA summer temperature, winter precipitation, summer shortwave radiation
- ➢ ***<u>Target/Predictand</u>***: observed annual mass balance of Freya glacier

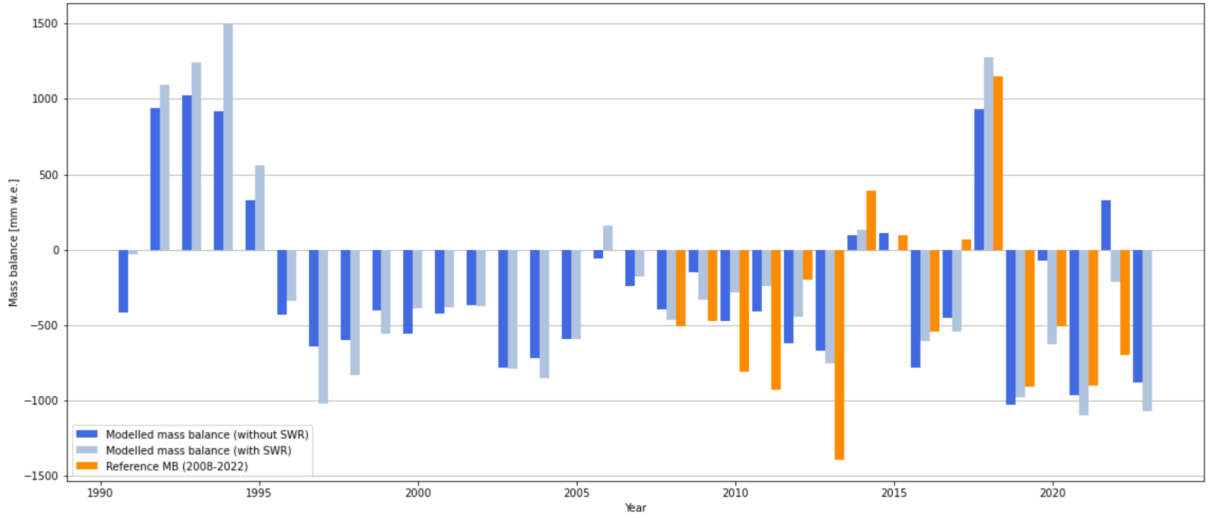
Results

Hock model: RMSE = 965 mm w.e./yr; MAE = 784 mm w.e./yr

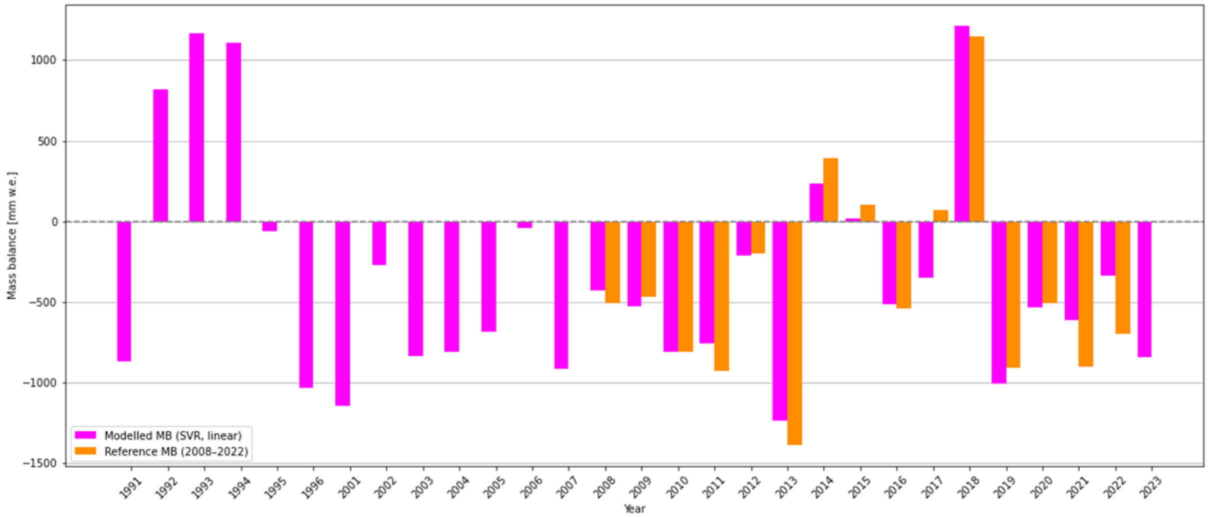


Marzeion model: RMSE = 442 mm w.e./yr; MAE = 358 mm w.e./yr

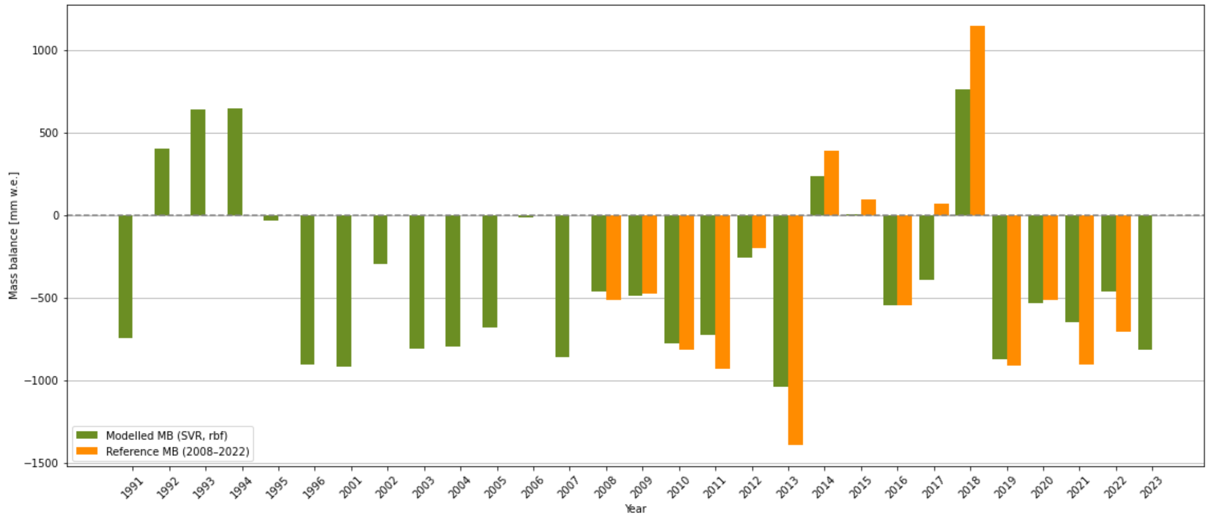
Marzeion model + SW rad: RMSE = 365 mm w.e./yr; MAE = 288 mm w.e./yr



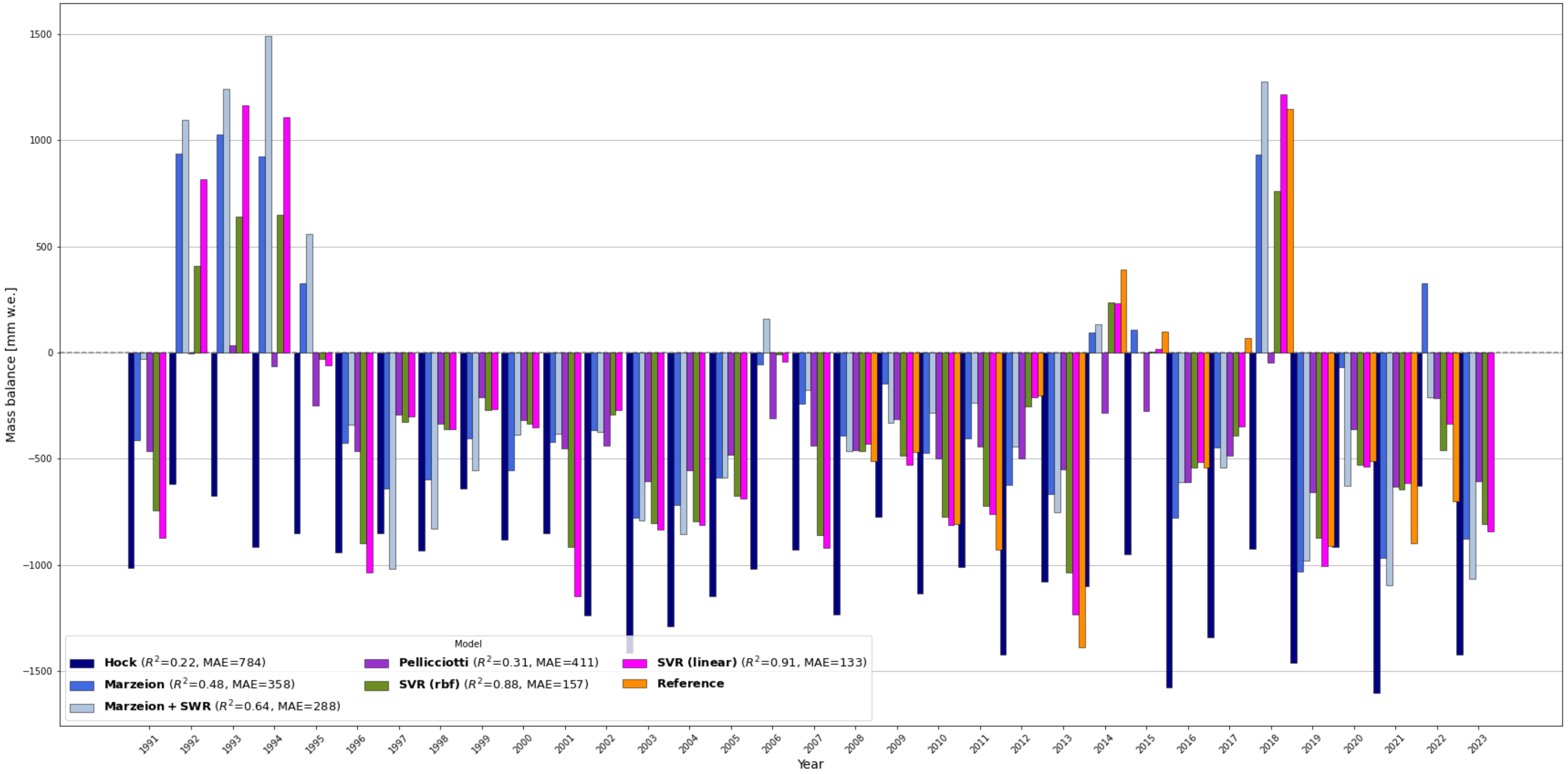
Linear SVR model: RMSE of 182 mm w.e./yr; MAE = 133 mm w.e./yr



RBF SVR model: RMSE = 215 mm w.e./yr; MAE = 157 mm w.e./yr



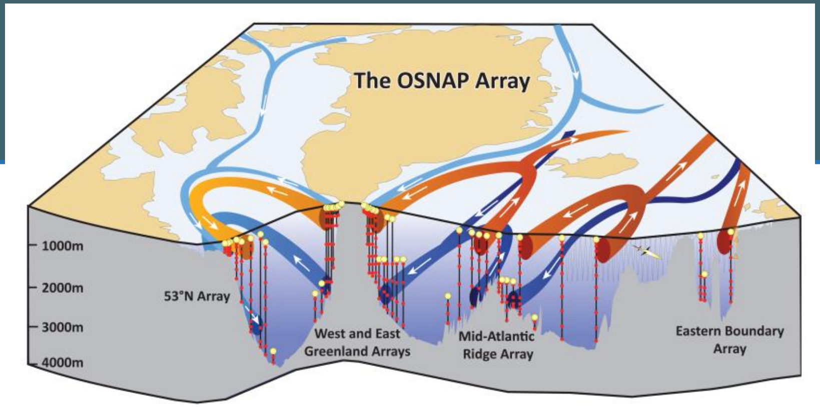
Summary



Comparison of the different mass balance models*. Modelled annual mass balance on Freya glacier according to the different mass balance models that were tested in this thesis and the reference mass balance from 2008 to 2022. The legend also contains the values of R^2 and the MAE of each model.*

- **Mass balance** on Freya glacier mostly **negative** (1991–2023)
- **High year-to-year variability**, no clear long-term trend
- **Precipitation is crucial** → models without it (e.g. Hock) fail to reproduce positive MB years
- **Marzeion model** performs **best** among **empirical models,** improved further with radiation
- **Pellicciotti model** accounts for radiation and albedo but shows **large errors**
- **SVR models** (linear & RBF) **outperform empirical models**
- **Linear SVR slightly better** than rbf kernel for this dataset

OSNAP https://doi.org/10.5194/egusphere-2025-4093



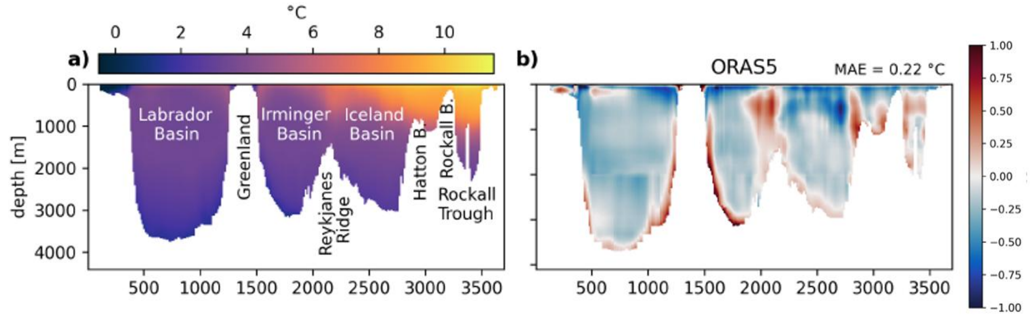
https://www.o-snap.org/

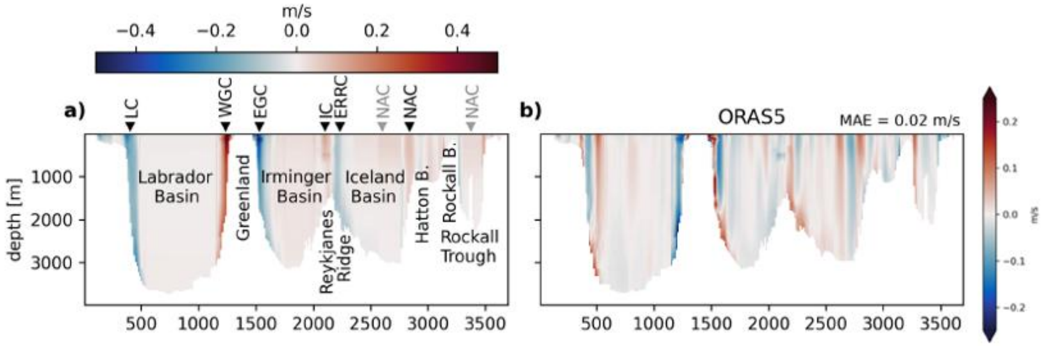
OSNAP (Overturning in the Subpolar North Atlantic Program, Lozier et al., 2017) provides:

- Observation-based estimates of AMOC and oceanic transports in the subpolar North Atlantic (moorings, floats, gliders)

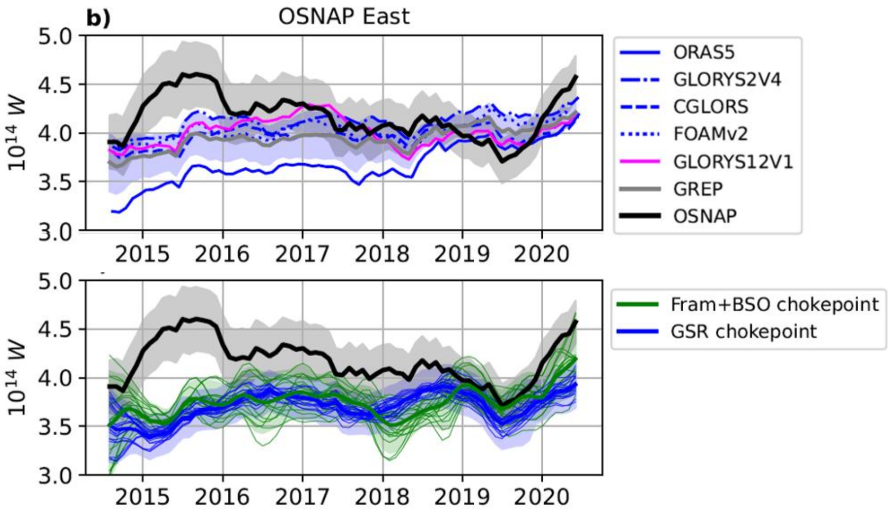
Comparison to reanalyses:

- **Cross-sections:** broadly similar circulation & temperature structures, but with biases: cold interiors, warm along slopes, misplaced currents
- **Heat transport**: similar long-term average across observations & reanalyses, but big differences in terms of variability





Largely independent estimates derived from ocean heat budget
→ variability more consistent with reanalyses transports



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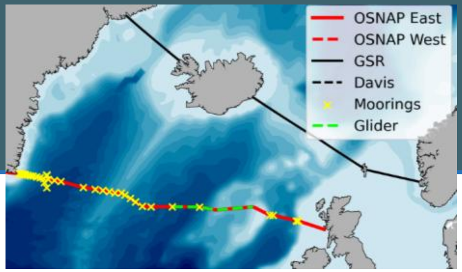
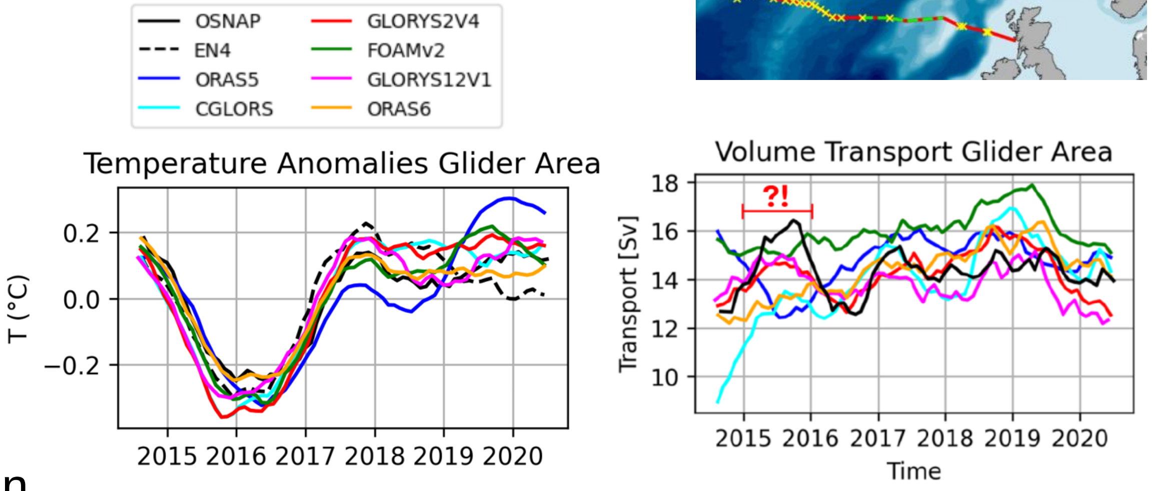
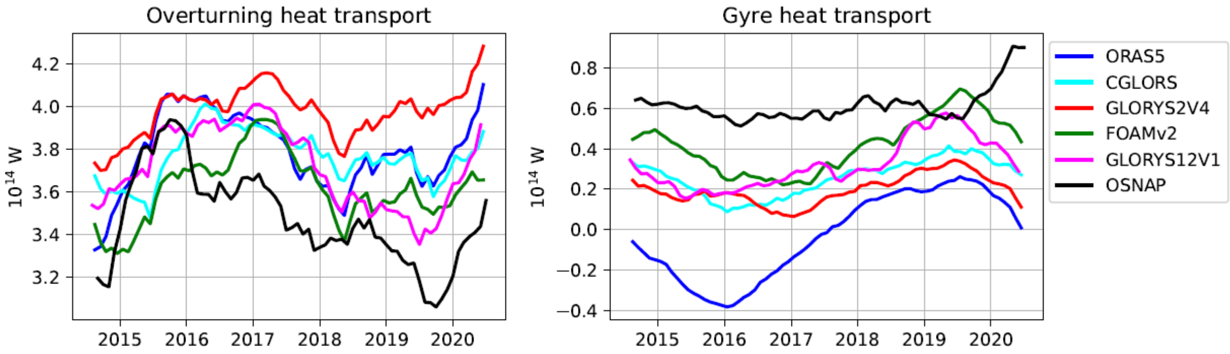


→Discrepancies in heat transports traced back to glider area
- Temperature anomalies similar
- positive velocity anomaly in observations (absent in reanalyses) drives heat transport anomaly

Overturning vs. gyre contributions:
- OSNAP: 2015 max & 2019 min are overturning-driven
- Reanalyses: overturning anomalies muted, gyre contribution too weak → flattened OHT variability likely due to reduced/shifted T

→ 2015 peak may be a genuine event, but missing in independent estimates +no clear sea-level signature → **Interpret with caution!**

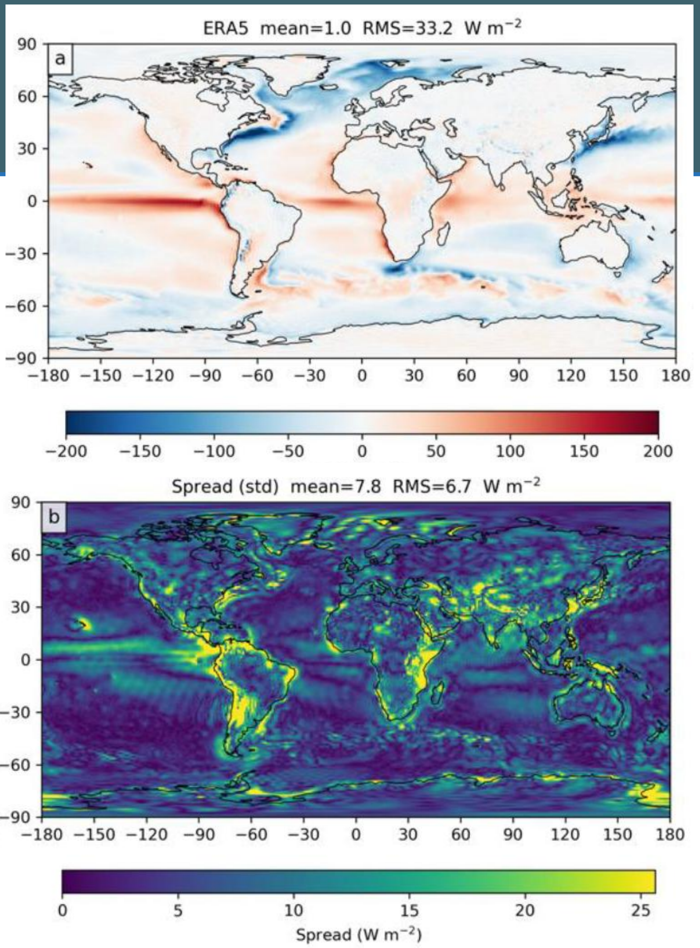




Outlook

CLOSE-EOB: Improving Global Surface Energy Fluxes *(ESA LPF submitted)*

- What we have:
  - Mass-consistent surface energy flux derived from CERES TOA radiation and atmospheric reanalyses
  - Current limitations: Small global land bias (1-2 W/m²) but still too large for precise EEI; regional uncertainties up to several tens of W/m², especially in complex terrain
  - Poorly constrained land heat storage → compensating errors over the ocean
- Improvement using ESA EO:
  - Use ESA multi-mission datasets to derive observation-based constraints on land heat uptake
  - Adjust atmospheric energy divergence over land to match EO-derived land heat uptake
  - Propagate consistent adjustments over the ocean improving inferred Fs globally
  - **Result:** EO-anchored, globally consistent surface energy fluxes



ESA CCI data	
Snow	**Permafrost**
Antarctica + GL Ice Sheet	**Glaciers**
Land Surface Temperature	Soil Moisture

Outlook toward the Polar Year 2032/33

- Improving inferred surface energy fluxes (Fs):
  - Update Fs using ERA6 (expected Arctic improvements due to better sea-ice physics & coupling)
  - Re-assess Arctic biases seen in ERA5 and quantify changes with ERA6
- Evaluation using (upcoming) observations and reanalyses:
  - CARRA2 pan-Arctic reanalysis (expected 2026)
  - MOSAIC data (available)
  - In-situ campaigns planned for the Polar Year
  - Greenland Ice Sheet

General goal:
Leverage all available and forthcoming cryospheric and polar observations (EO + in-situ + reanalysis) to evaluate, constrain and improve our inferred surface energy flux dataset.

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