

Assessment of multi-mission Sea-Level Anomaly grids in the Baltic Sea using SWOT and In-situ observations

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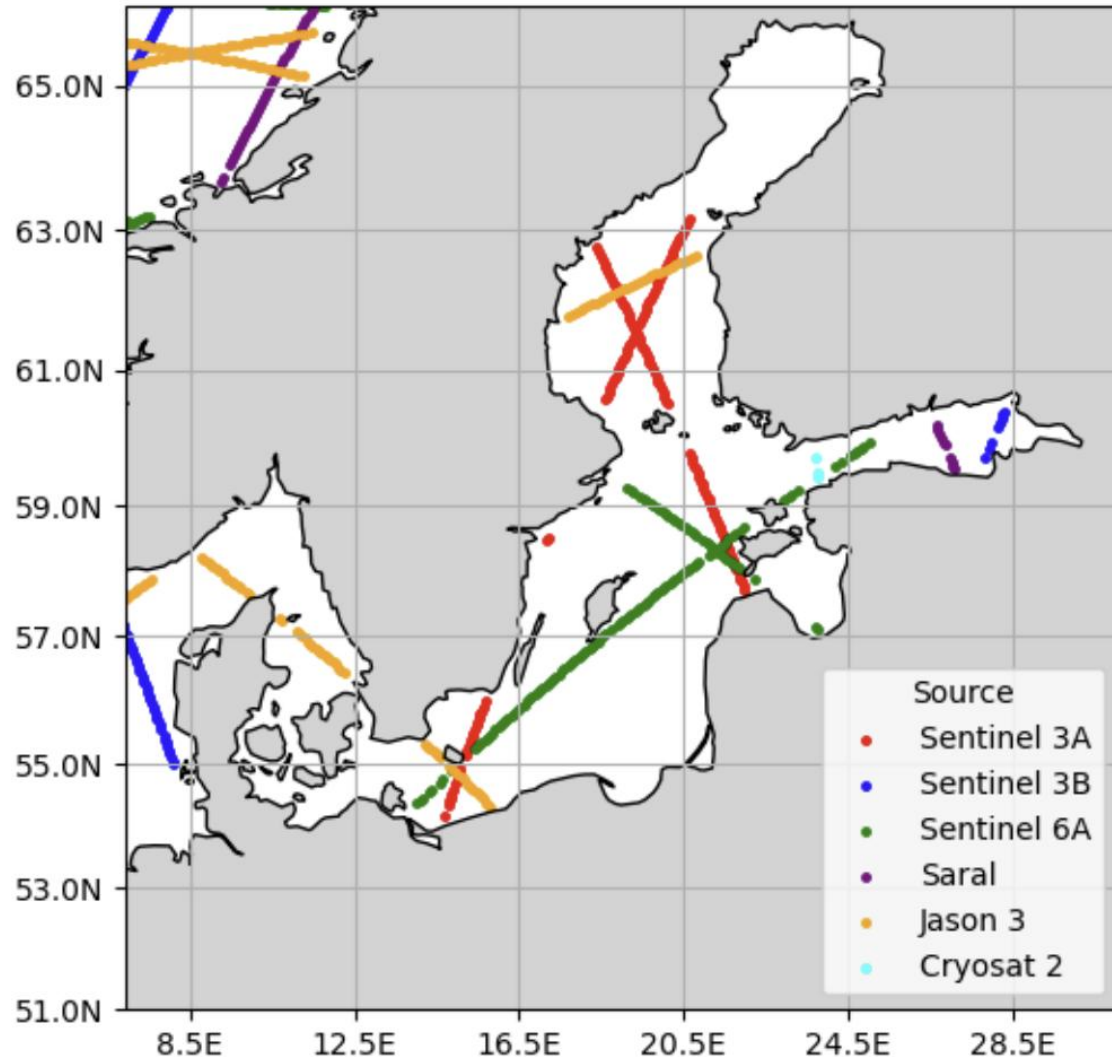
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Nordic Geodetic Commission
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Motivation

Multi-Mission Along Tracks on April 23, 2023



- Nadir altimetry measures sea level only along satellite ground tracks.
- Repeat cycles of 10–27 days, together with drifting orbits, leave large gaps in a single day.
- Interpolation creates continuous daily maps, but it can smooth real variability or preserve track-related artefacts.
- Sea-level anomaly ($SLA = SSH - MSS$) is used to examine sea-level variability relative to the mean sea surface, rather than absolute surface heights.

Research question: How reliably can sparse tracks be converted into daily Baltic Sea SLA maps?

Research Objective

- **Objective:** To assess best method for obtaining daily grids of Sea Surface Height anomaly (SSHa).
 - **Methods (Gravsoft ,Optimal Interpolation)**
 - **CMEMS dataset for validation**
 - **Test spatial and temporal performance of Grids using moorings, tide gauge and SWOT.**

This study is part of the case study " Sea level change in the Baltic Sea on various time scales" within the ESA 4DBALTDYN project <https://4dbaltdyn.albavalor.es/> and of the ADAC-SWOT cruise during the SWOT Cal/Val in 2023 by Uni Bonn and Leibniz Institute for Baltic Sea Research Warnemünde (IOW) <https://www.swot-adac.org>

Sea Level Data Sources

Cal/Val: Apr–Jun 2023 | Science: Aug 2023–May 2024

Type	Dataset	Reference Surface	Main characteristic
Along-track	RADS: Sentinel 3a, 3b, 6a Jason-3, CryoSat-2, SARAL	DTU15 MSS	1 Hz multi-mission along-track SSHa
Gridded	GRAVSOF T RADS	DTU15 MSS	Kriging/LSC, daily, 0.125° x 0.125°
Gridded	OI–RADS GRv2.0	DTU15 MSS	Optimal Interpolation, daily, 0.125° x 0.125°
Gridded	CMEMS DUACS L4 /SEALEVEL_GLO_PHY_L4_MY_008_047/008_060	Hybrid_2023 MSS	Operational daily 0.125° SLA grid, 0.125° x 0.125°, daily,
SWOT Wide – swath	SWOT (L3 Expert v1.0 /L2 v2.0 Expert, L3 unsmoothed v1.0.1)	Product specified MSS Hybrid SIO/CNES_CLS22/DTU21	2-km grid for L2 Expert and L3 Expert 250-m grid for L3 Unsmoothed
In situ Moorings	IOW Moorings: GOCE, GONE, GOSW	Relative water-level anomalies; demeaned before comparison	RBR pressure derived water level; and drift corrected
In situ Tide gauges	Tide gauges: Visby, Landsort Norra, Viken, Klagshamn, Onsala	Local height reference (RH2000 SE), Demeaned water level anomalies	National database SMHI/Sweden. 1-min temporal resolution

4

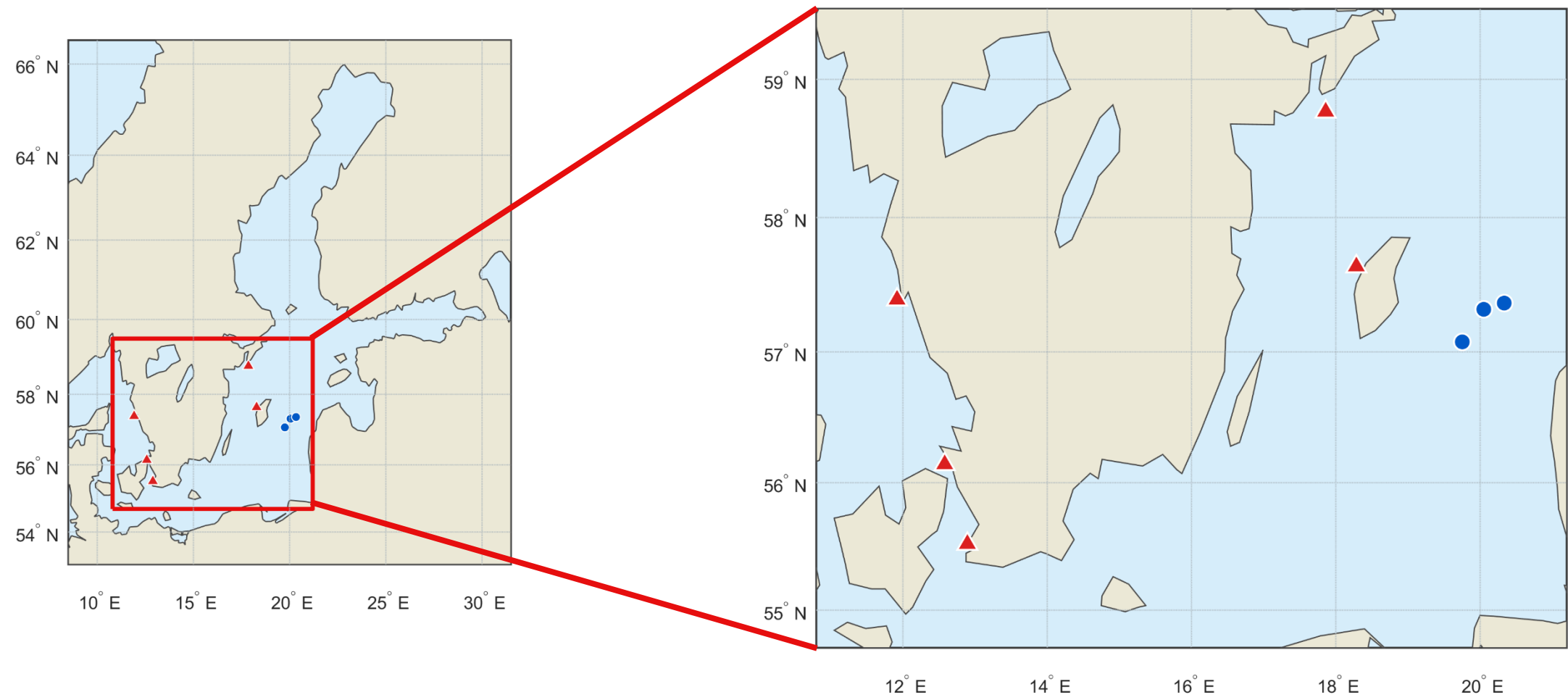
*GRAVSOF T output was generated at 0.1° and resampled to 0.125°. All time series and transects were demeaned; no geoid-based datum transformation was applied.

Study Area – Baltic Sea

Baltic Sea Tide-Gauge and Mooring Network

A. Baltic Sea overview

B. Tide-gauge and mooring locations



METHOD 1: GRAVSOFT GEOGRID KRIGING

Input: RADS 1 Hz SSHA from Sentinel-3A/B, Sentinel-6A, Jason-3, CryoSat-2 and SARAL/AltiKa

1

Prepare and align tracks
aline_rads.f filters and aligns the daily multi-mission observations.

2

Adjust crossover differences
crsadj_ad.f estimates mission-dependent bias and tilt corrections.

3

Kriging at two spatial scales
geogrid.f uses least-squares collocation with a second-order Gauss–Markov covariance. Correlation lengths: 100 km for the long field and 14 km for the residual field.

4

Local neighborhood
Up to 20 nearest observations are selected in each quadrant around a prediction point.

5

Merge and standardise
Long- and short-wavelength grids are combined, exported to NetCDF and resampled from 0.1° to 0.125° .

Configuration used here: ± 15 -day observation window | daily output | final resolution 0.125°

Method characteristic: flexible two-scale reconstruction, but sparse coverage can leave gaps and track imprints.

METHOD 2: OPTIMAL INTERPOLATION (OI)

OI estimates a daily grid by weighting observations according to covariance and expected error.

1

Observation vector, y
Filtered RADS 1 Hz SSHA within a ± 15 -day window.

2

Observation operator, H
Maps the target grid state to each along-track observation location: $y = Hx + \epsilon$.

3

Covariance and errors
 B describes space-time signal covariance; R describes observation-error covariance. Gaussian correlations decay with longitude, latitude and time separation.

Optimal weighting

$$K = B H^T (H B H^T + R)^{-1}$$

$$x_a = x_\beta + K (y - Hx_\beta)$$

Parameters used

Spatial scales: $L_x = L_y = 2^\circ$

Temporal scale: $L_t = 15$ days

Observation noise: 5%

Output: daily $0.125^\circ \times 0.125^\circ$ NetCDF grid

Interpretation: nearby, temporally relevant and lower-error observations receive greater weight. This produces a continuous field, although the covariance scales smooth some fine structure.

Results

Comparison

Daily spatial fields

Independent time-series validation

Gotland spatial transect

December 2023 MBI event

Evidence

GRAVSOF, OI and CMEMS

Three moorings and Landsort Norra tide gauge

IOW CTD steric height and SWOT L2/L3

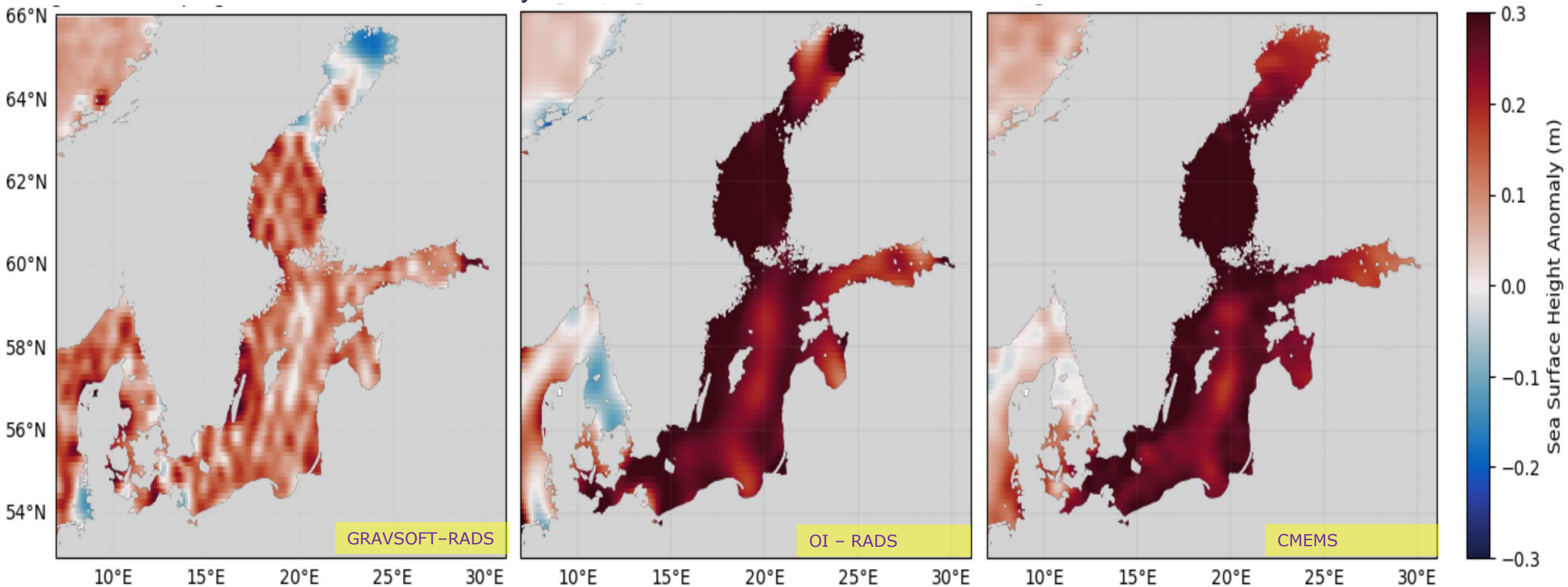
SWOT L3 compared with all three grids

Metrics: correlation (r), standard deviation of differences (STDD). Profiles and time series were demeaned before comparison.

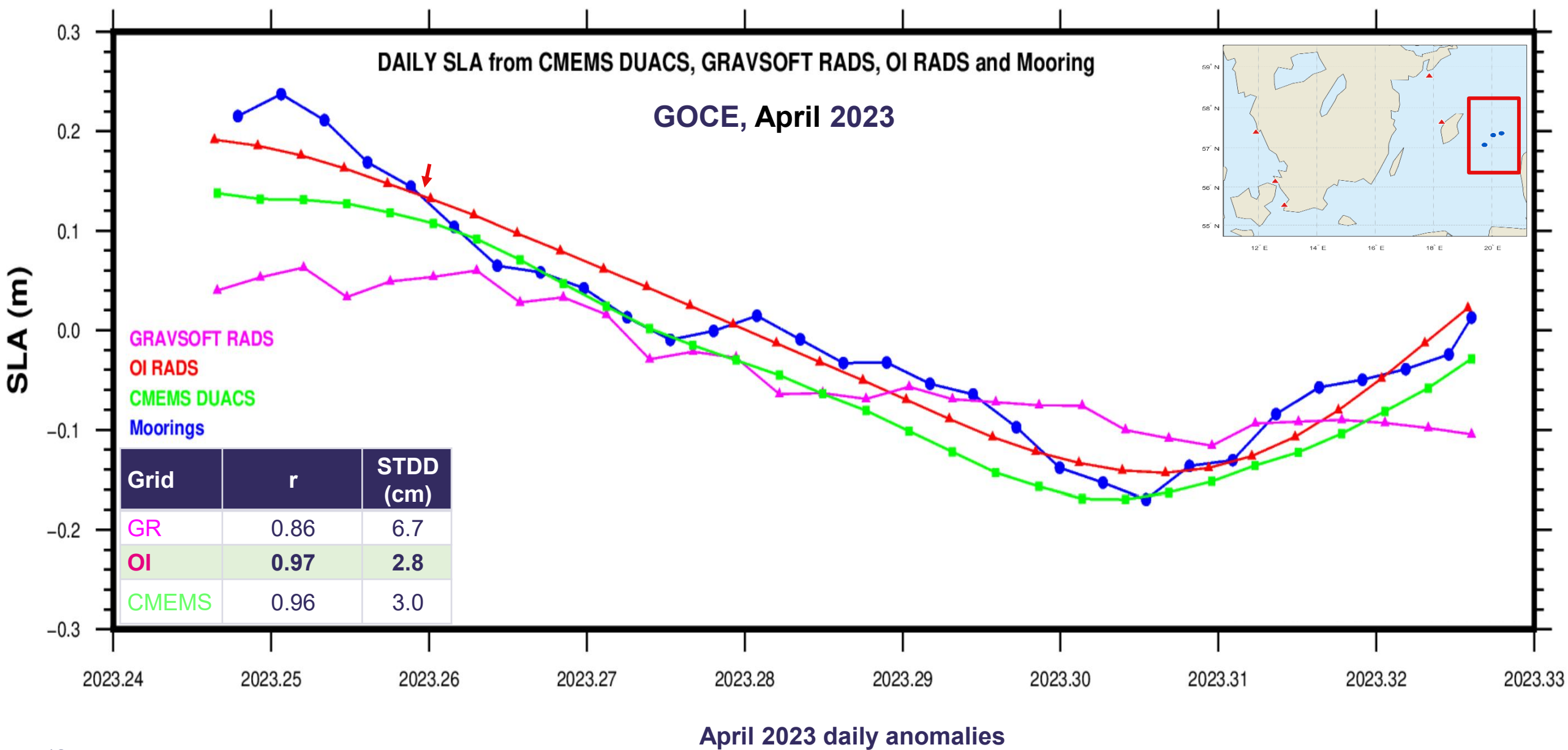
Results: Spatial Fields

GRAVSOFr retains track imprints and gaps; OI and CMEMS produce smoother, spatially coherent fields.

Daily SSHa on 30th December 2023

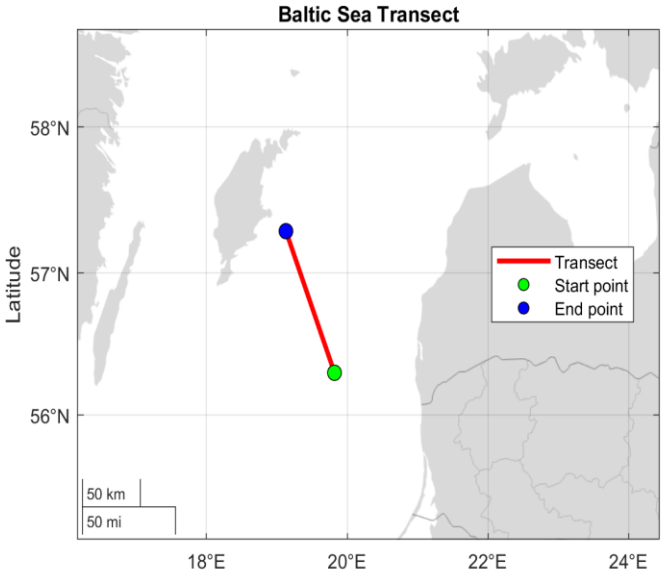


Results: Validation of Grids with Moorings

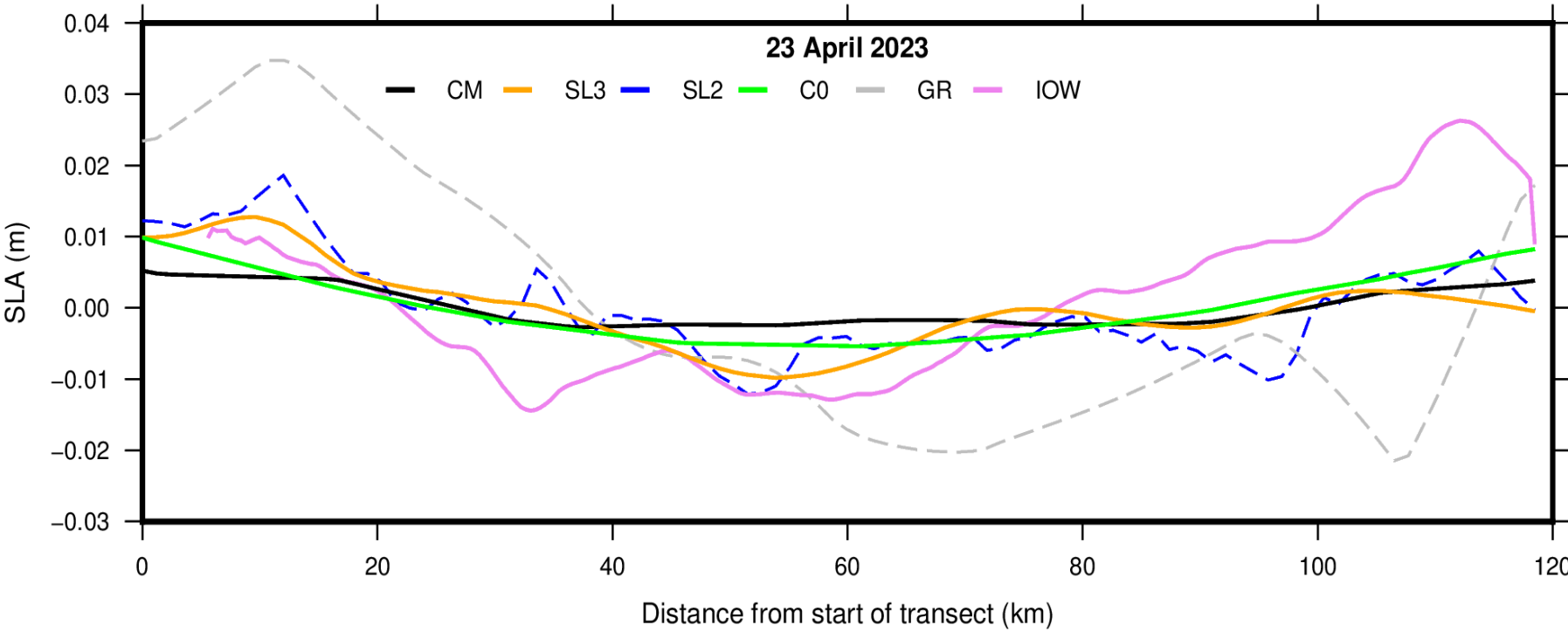


Results: Gotland Transect

- IOW cruise 18-30 April 2023.
- CTD steric heights against SWOT and grids (GRAVSOFT, OI and CMEMS).
- GRAVSOFT worst, OI and CMEMS smooth, SWOT L2/L3 expert best to resolve finer structure.

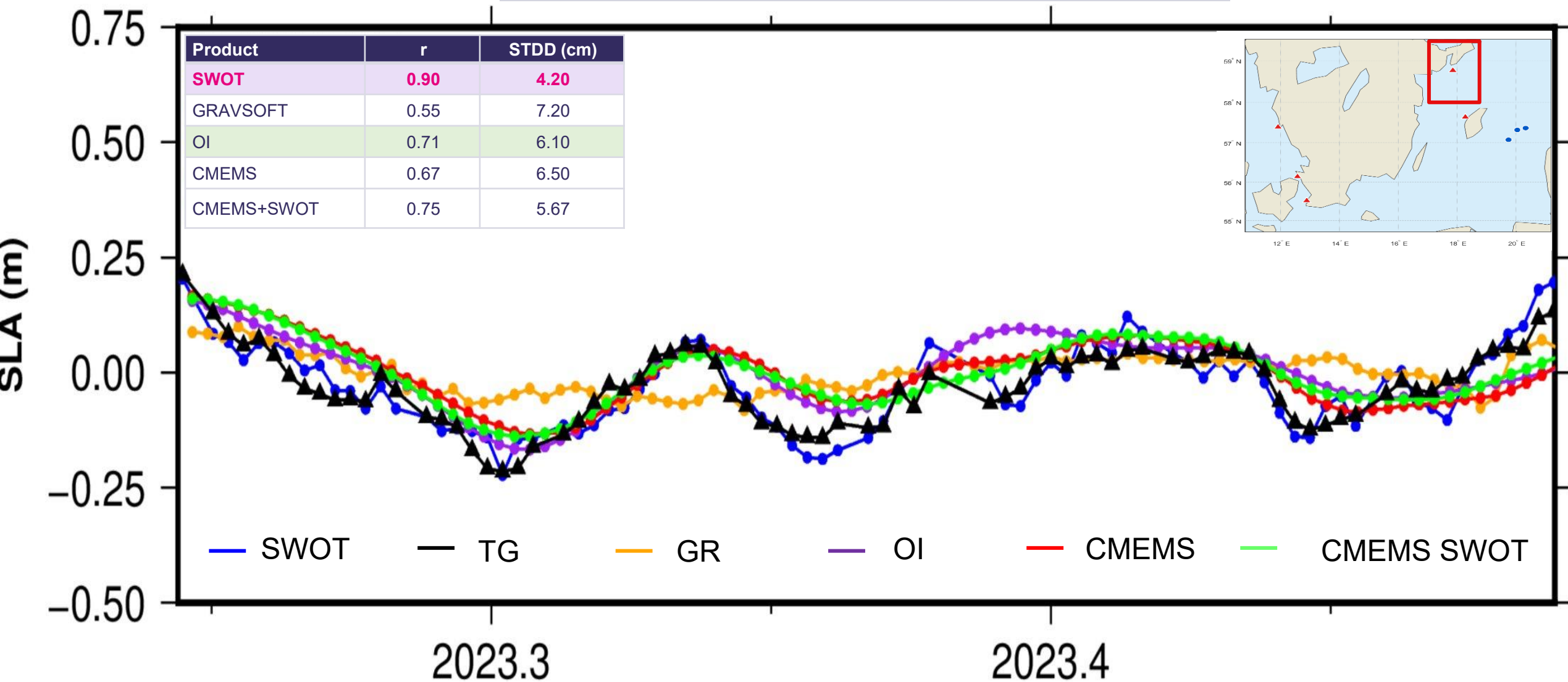


Product	Reference	STDD (cm)	r
CMEMS	IOW	0.95	0.71
SWOT L3	IOW	0.93	0.55
SWOT L2	IOW	0.97	0.49
OI C0	IOW	0.77	0.89
GRAVSOFT	IOW	1.87	0.15



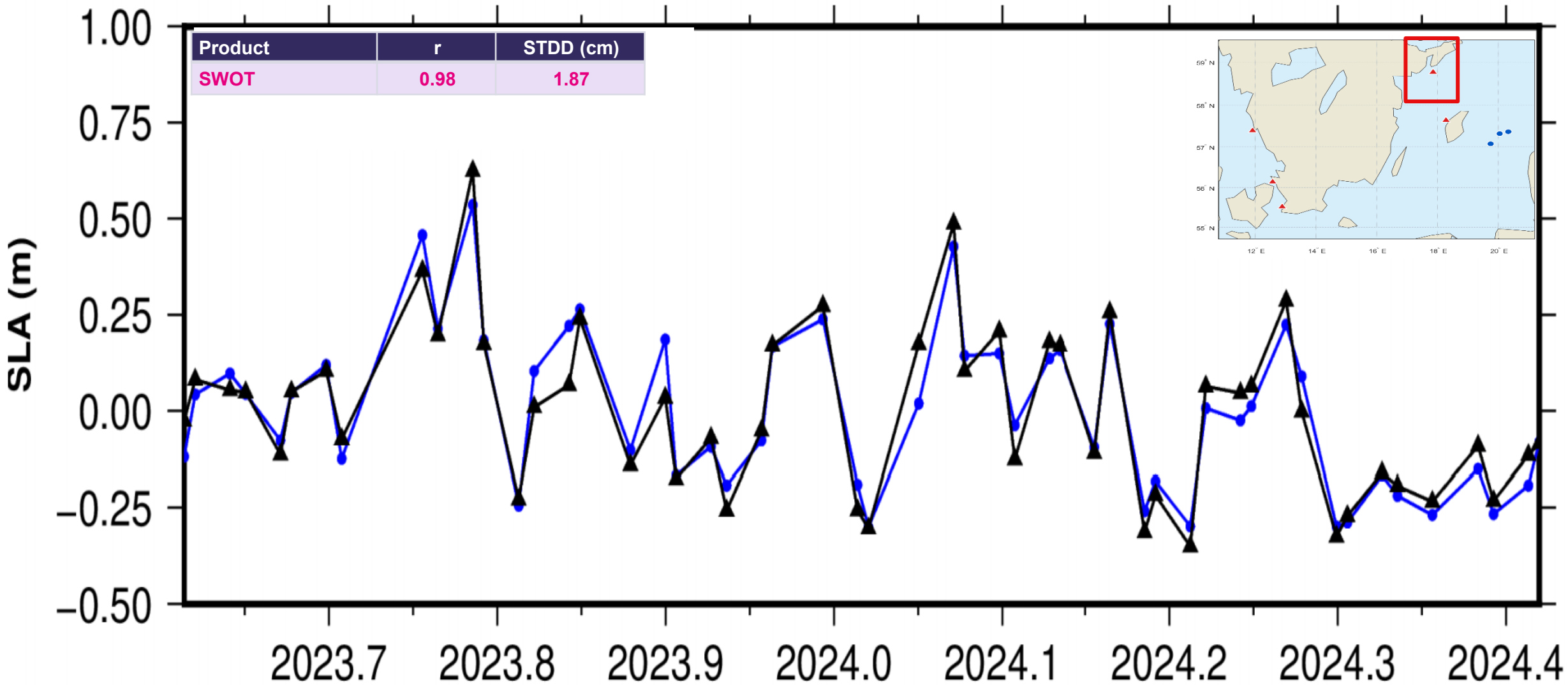
Results: Time Series TG vs SWOT

Landsort-Norra during Cal/Val (April–June 2023)



Results: Time Series TG vs SWOT

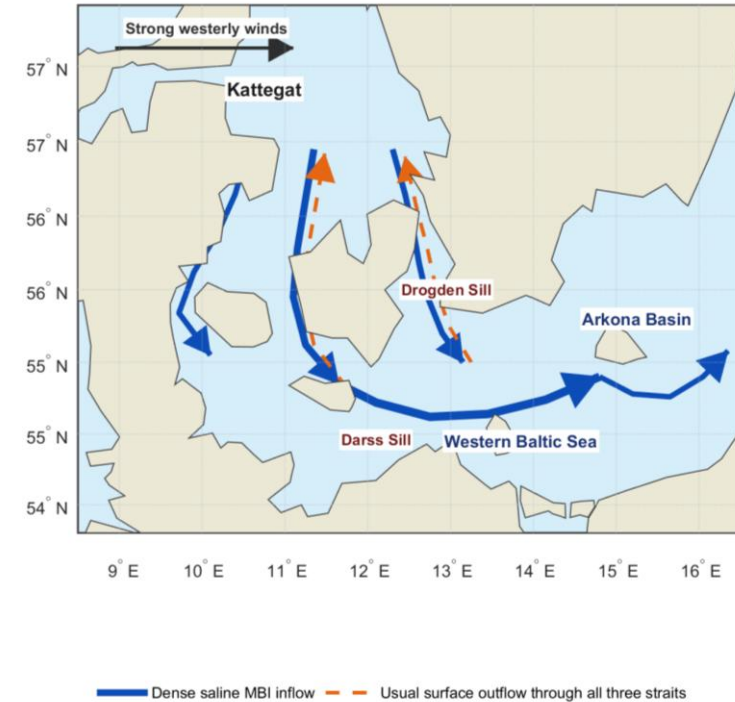
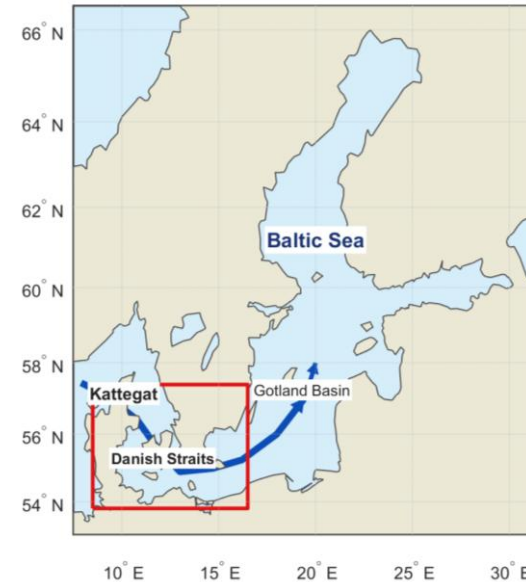
Landsort-Norra during the Science phase (Aug 2023 –May 2024)



Results: Case Study on December 2023 Major Baltic Inflow

Test whether daily gridded SLA captures the rapid sea-level evolution observed by SWOT during an inflow event.

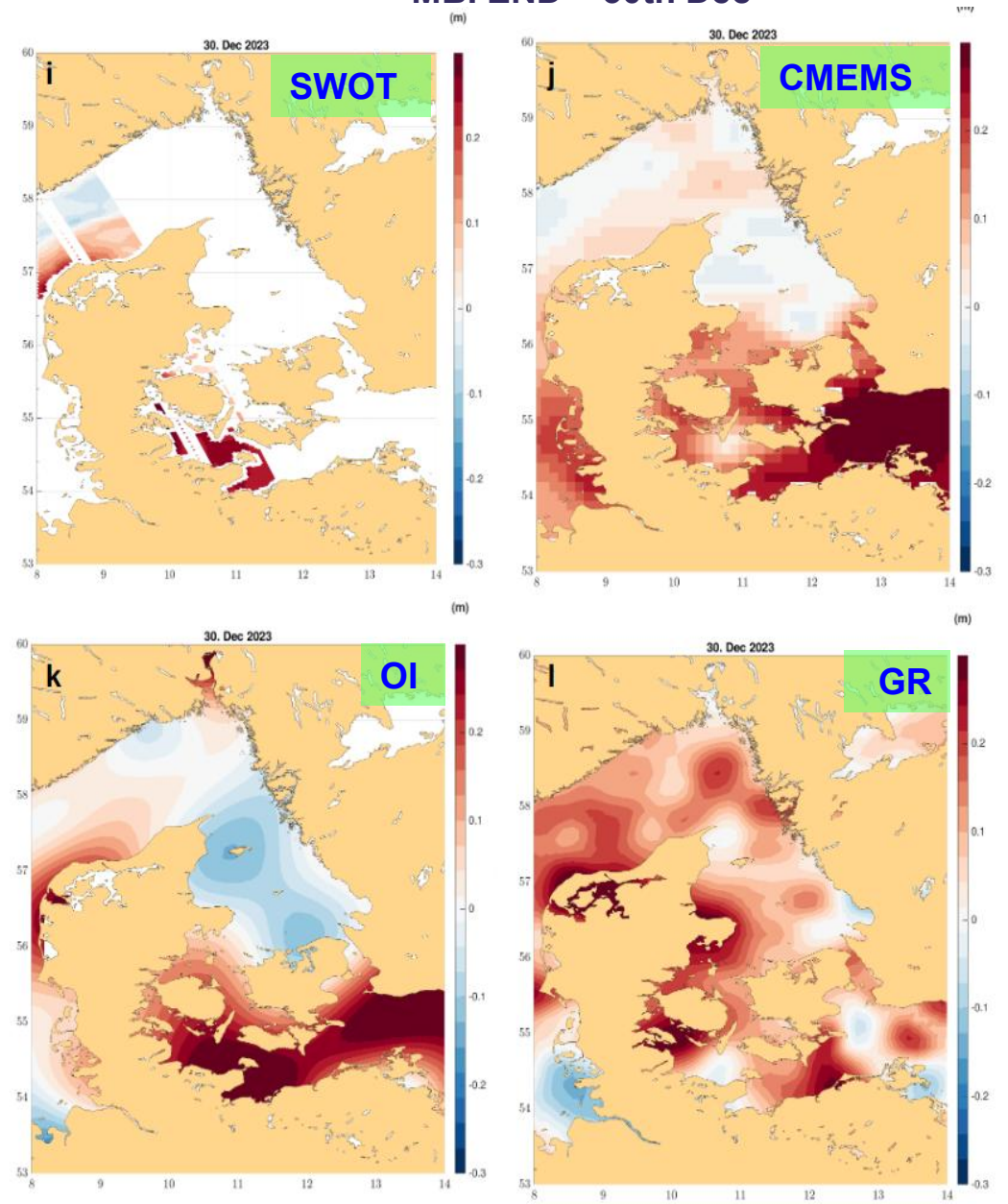
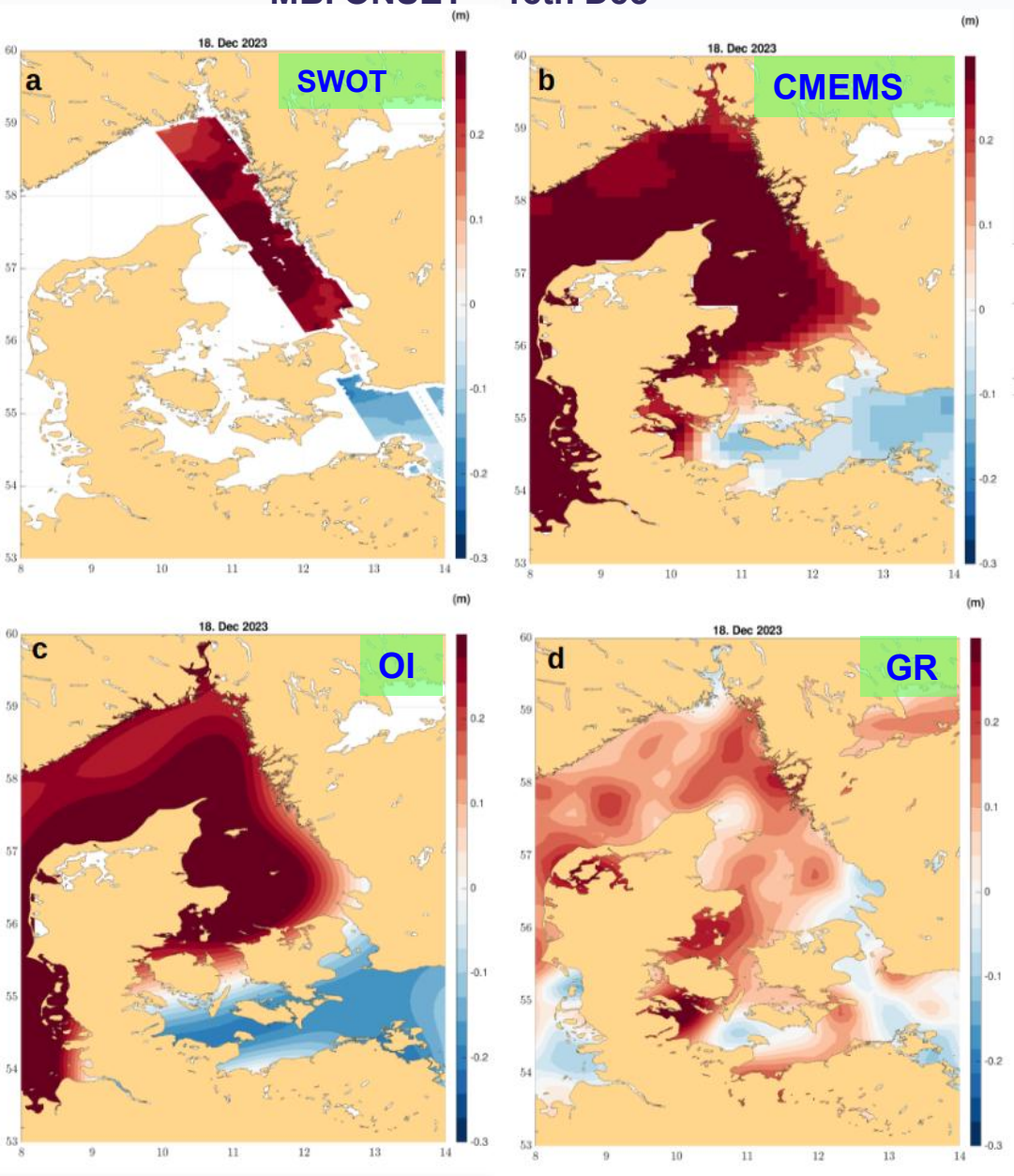
- North Sea water enters the Baltic through the Danish Straits.
- 18 December represents the onset
- 30 December represents the event end.
- SWOT L3 is compared with CMEMS, OI and GRAVSOFT using spatial r and std .



Results: Major Baltic Inflow in Dec 2023

MBI ONSET – 18th Dec

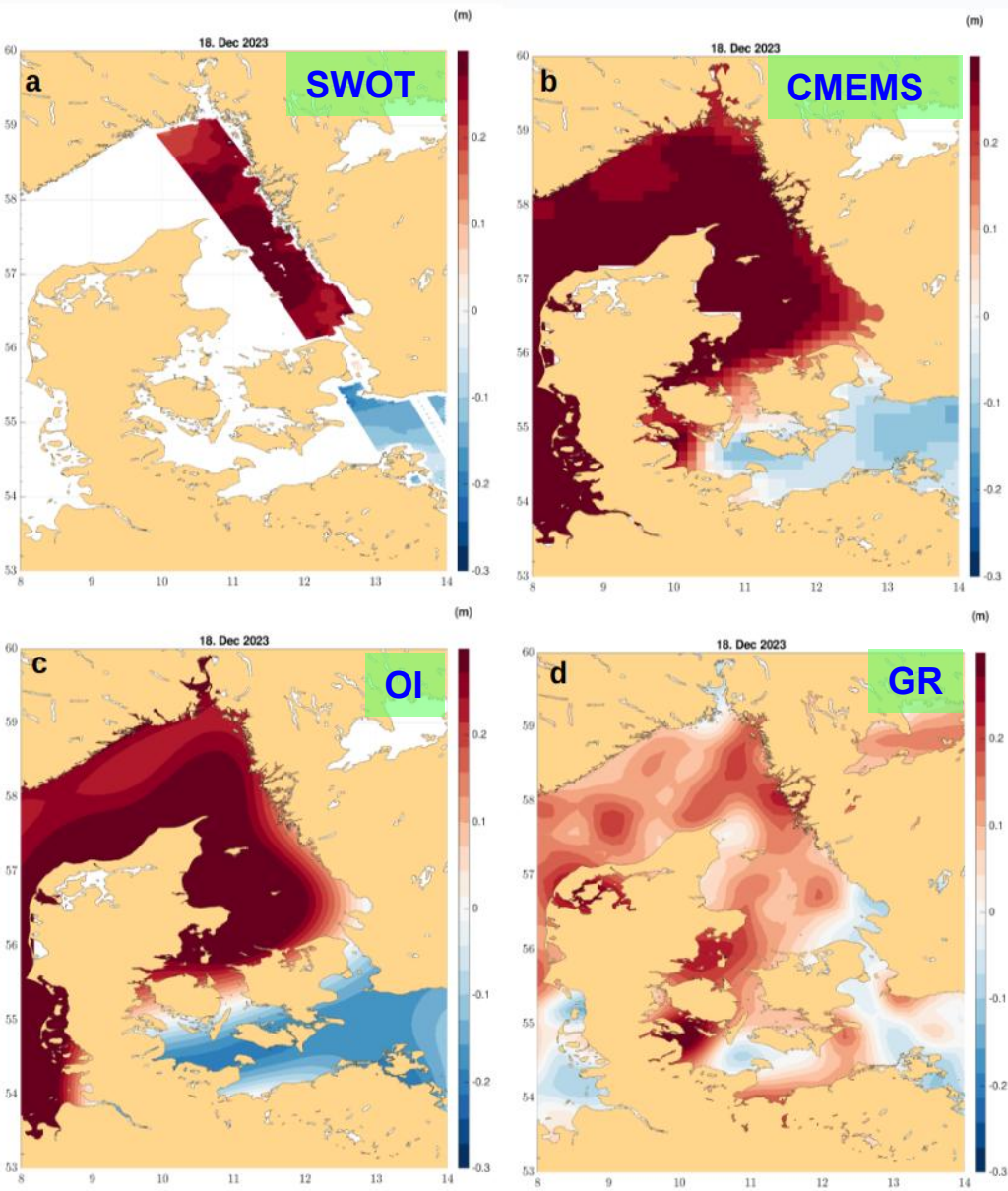
MBI END – 30th Dec



Results: Major Baltic Inflow in Dec 2023

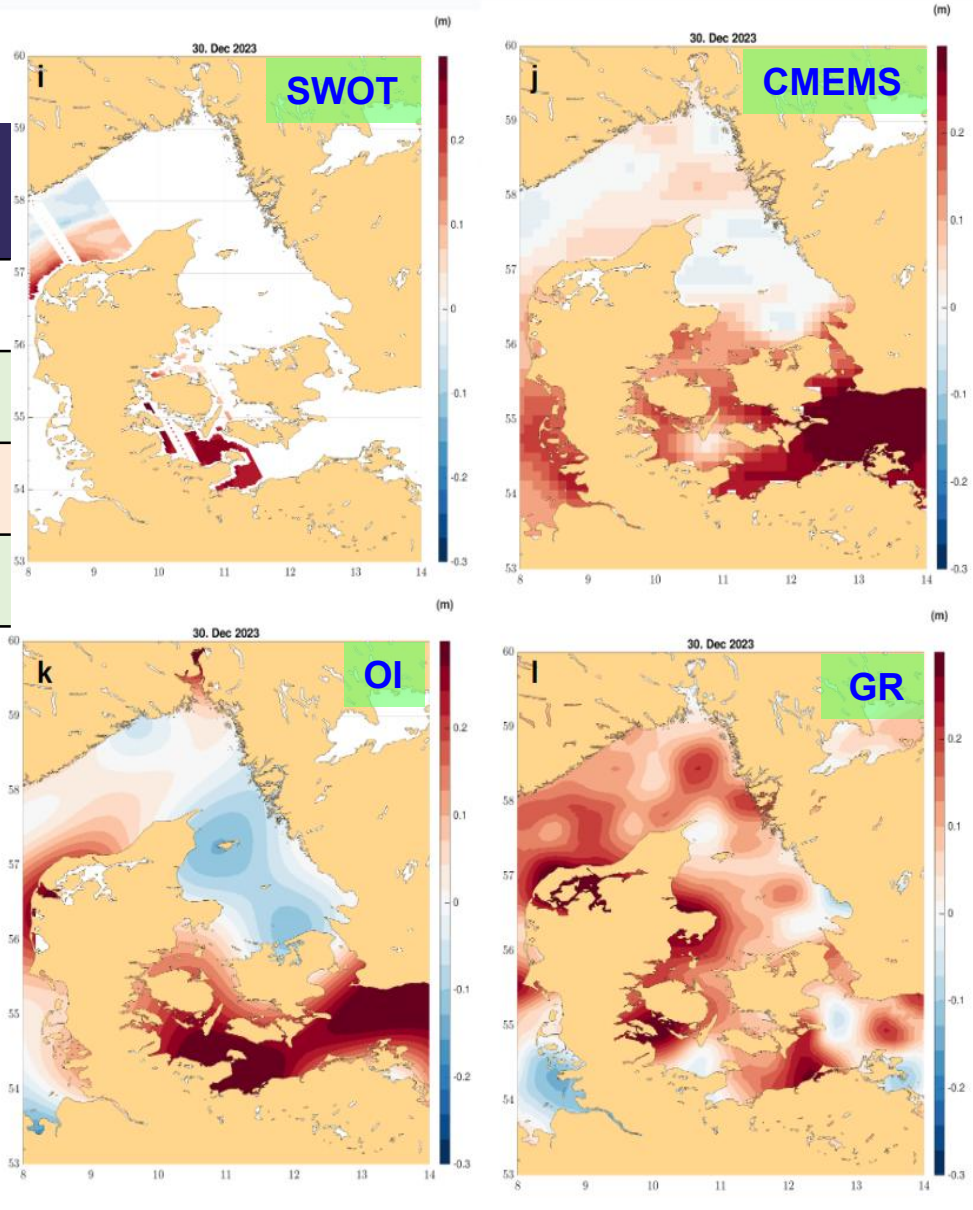
MBI ONSET – 18th Dec

MBI END – 30th Dec



Grid	18 Dec r / stdd (cm)	30 Dec r / stdd (cm)
CM	0.97 / 2.68	0.70 / 5.62
OI	0.97 / 3.28	0.89 / 4.22
GR	0.66 / 6.81	-0.37 / 6.42
Best	CM & OI	OI

At onset, CMEMS has the lowest STDD. At event end, OI retains the highest correlation.



Conclusions

OI consistently outperforms the tested GRAVSOFTE configuration and is marginally stronger than CMEMS in most independent comparisons.

Evaluation	OI	CMEMS	GRAVSOFTE	Main result
GOCE mooring	0.97 / 2.8	0.96 / 3.0	0.86 / 6.7	OI marginally best
Gotland vs IOW	0.89 / 0.77	0.71 / 0.95	0.15 / 1.87	OI strongest spatial agreement
Landsort Cal/Val	0.71 / 6.10	0.67 / 6.50	0.55 / 7.20	OI best grid; SWOT best overall
MBI onset	0.97 / 3.28	0.97 / 2.68	0.66 / 6.81	CMEMS has lower STDD
MBI end	0.89 / 4.22	0.70 / 5.62	-0.37 / 6.42	OI clearly best

Table entries show r / STDD (cm). Lower STDD and higher correlation indicate closer agreement.

Future Work

1

SWOT-informed gridding

Integrate SWOT observations into improved OI and data assimilation. Evaluate machine learning for gap filling.

2

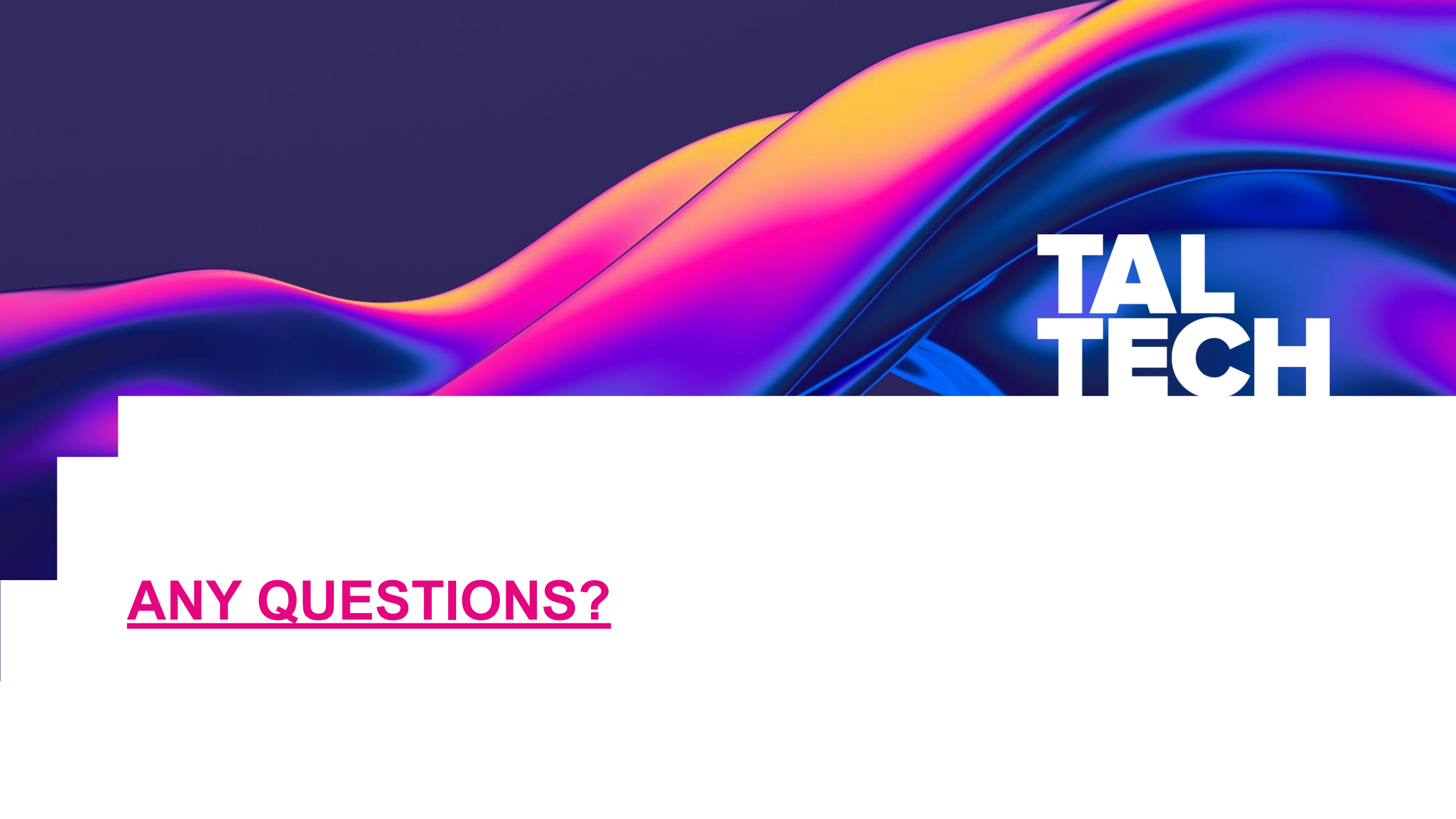
Examine MBI progression into Baltic Sea using Dynamic Topography (referred to the Baltic Sea Chart Datum2000)

Extend the MBI analysis over a longer period using Dynamic Topography from tide gauges, hydrodynamic-model and SWOT KaRin.

3

Calculate the Volume Transport using Dynamic Topography

Investigation of volume variation for the sub-basins of the Baltic Sea during the MBI



**TAL
TECH**

ANY QUESTIONS?