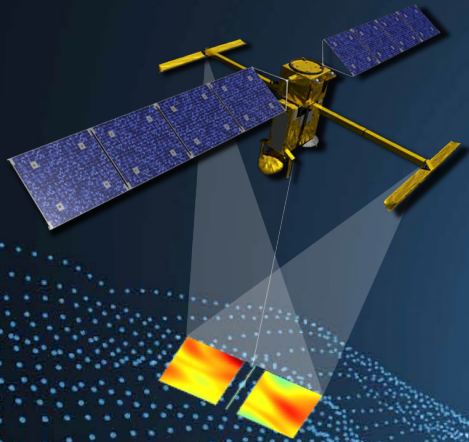


Experimental Mapping of Ocean Surface Topography using SWOT Altimetry: Ongoing and Future Studies



Ballarotta, M., Ubelmann, C., Meda, G., Tréboutte, A., Metref, S., Faugere, Y., Dibarboure, G., Fablet, R.



- **3 month** of Level-3 SWOT Karin data during **1-Day repeat** orbit have been processed in the L3-DUACS system (see *SWOT L3 Overview poster & Gerald's presentation*)
- So far, only **OSSEs** have been used to assess the impact of Karin data in Level-4 gridded products.
- These assessments were based on various mapping algorithms, such as:
 - **DUACS** (*Le Traon et al., 1998*),
 - **MIOST** (*Ubelmann et al., 2021*),
 - **DYMOST** (*Ubelmann et al., 2015*),
 - **BFN-QG** (*Le Guillou et al., 2021*), and
 - **4Dvarnet** (*Fablet et al., 2021*)
 - + other Deep learning based method or assimilated OGCM

=> See for example ocean data challenge [2020a SSH mapping NATL60](#)

=> And [presentation](#) by V. Bellemin-Laponnaz @ 2022 SWOT-ST meeting

Today, we present early mapping analysis based on real SWOT Karin observations with the MIOST and 4Dvarnet methods

- The objectives of these studies were:
 - To **verify** the systems behaviour with real SWOT karin observations
 - To **assess** the performance of mapping systems with real SWOT data (in particular the impact on fine scale ocean structures)
 - To **quantify** the contribution of SWOT Karin during the calval phase in mapping systems

SWOT Level-3 Overview algorithms and examples

Context
 Level-3 products are formally part of the Science Team Project OCSMOS
 Convergence point: Project *SWOT*, ST research and Operational Oceanography

Added-value
 State of the art research-grade upgrades (incl. very recent & submitted papers)
 Multi-mission calibration (SWOT is consistent with other altimeters)
 Noise mitigation for SSWA derivatives (experimental, AI-based)
 Pre-made sophisticated editing procedure
SWOT and nadir instruments blended into a single image
 L3 has new layers (optional) that can blend with L2 fields

SWOT Level-3 algorithm sequence

Uncalibrated L2 SSWA (cm) | Calibrated SSWA | Edited SSWA | Noise-reduced SSWA | Geostrophic velocities | Relative Vorticity

L2 Research-grade standards

The CLS/OSTM Hybrid 2023, as a Mean Sea Surface

| Product | RMSE | RMSE (100km) | RMSE (10km) |
|------------------|------|--------------|-------------|
| SWOT-OSSE | 0.34 | 0.24 | 0.14 |
| OSSE 2022 | 0.25 | 0.20 | 0.10 |
| OSSE 2021 | 0.21 | 0.16 | 0.08 |
| SWOT-OSSE (2023) | 0.20 | 0.17 | 0.07 |

The CHOC/CL33 as a Mean Dynamic Topography

Regional improvements with v2023 model
 - Kinetic 2D/3D analysis based
 - Independent low 10% mean-comparison with delta sea surface height (SSH) model

The FOS 2023 as a tide model

Improved bathymetry partly through the use of regional bathymetry
 - New high resolution mode 8 from ocean observatory data on the FOS21 0.5 grid
 - Assimilation of new observations, IC, extension of the altimetric period, etc.
 - Improved pole accuracy and accuracy

L3 Karin processing sequence : the V0.1 version

Cloning Layers (CL3)

1. Mask non-ocean data out of products
2. Mask data with sea currents above 80% of sea level
3. Mask data with products quality information (combination of quality flags from 24 L2s in SSH, SSWA, etc.)
4. Mask data with 50% uncertainty from 24 L2s in SSH, SSWA, etc.

L3 data-driven calibration

1. Step 1: Use the altimetric uncertainty flag (sea level anomaly)
2. Step 2: Use the altimetric uncertainty flag (sea level anomaly)
3. Step 3: Use the altimetric uncertainty flag (sea level anomaly)
4. Step 4: Use the altimetric uncertainty flag (sea level anomaly)

AI-based noise-estimation algorithm (Treboutte & al 2023)

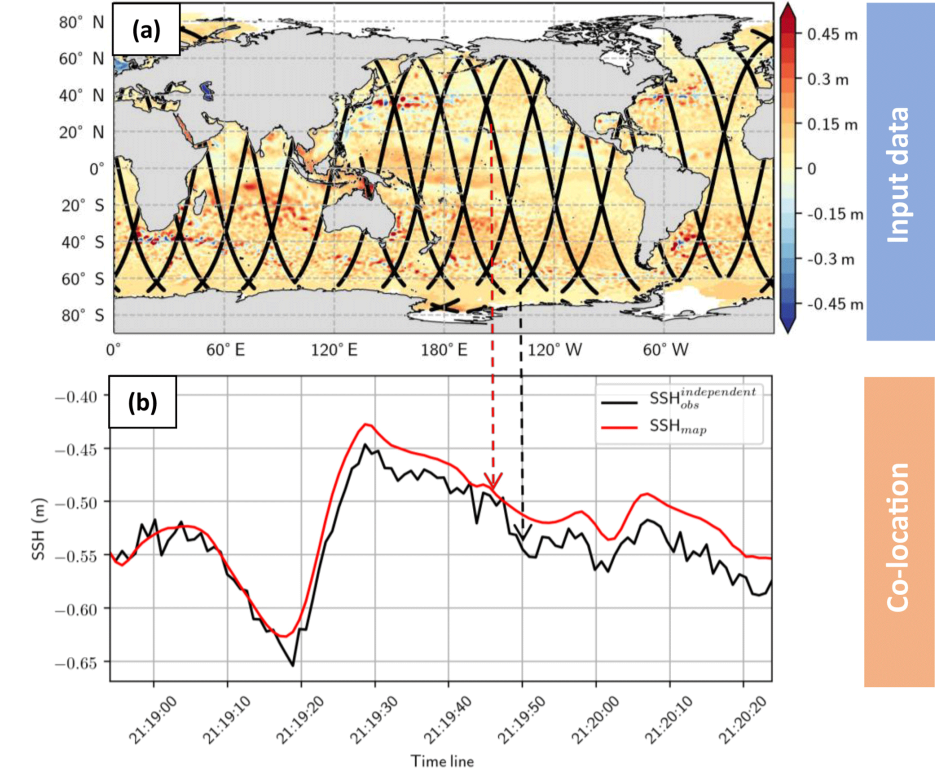
Community feedback & suggestions welcome

Near real time production running since last Spring

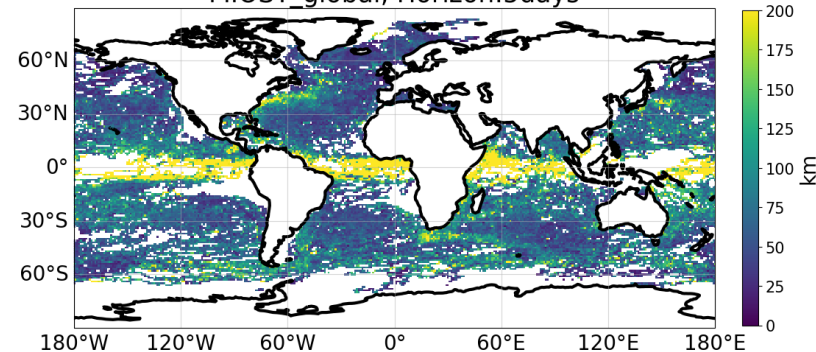


- **Validation** based on the **SSHA comparison** between gridded reconstruction and independent **altimeter** data
 - Apply various along-track filter to isolate the signal of interest
 - Perform spectral analysis
 - Metrics: RMSE, explained variance score, effective resolution
- **Validation** based on sea surface **current comparison** between gridded reconstruction and independent **drifters** data: => *on going work undertaken in the CMEMS Service Evolution SLICING project*
- **Validation** based on Lagrangian method: dispersion at specific time horizons => *on going work undertaken in the CMEMS Service Evolution SLICING project*

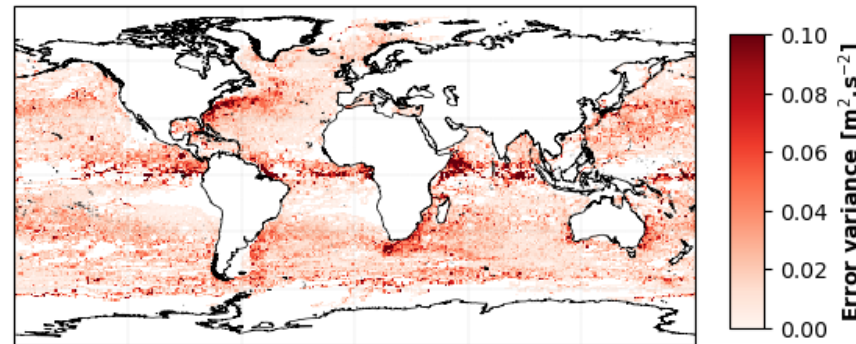
INPUTS: reconstructed maps and independent along-track data



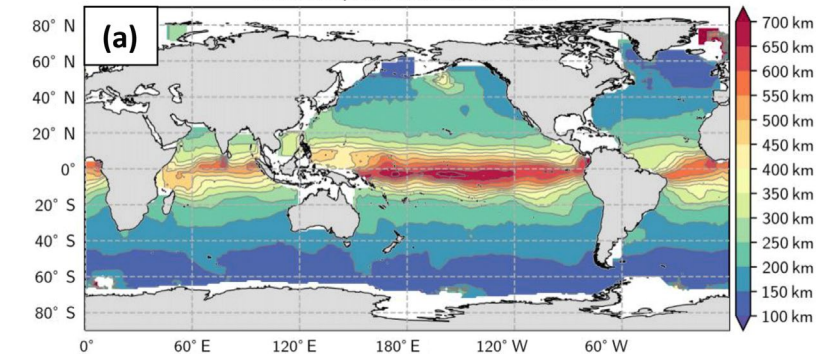
MIOST global, Horizon:5days



Meridional current [All scale]

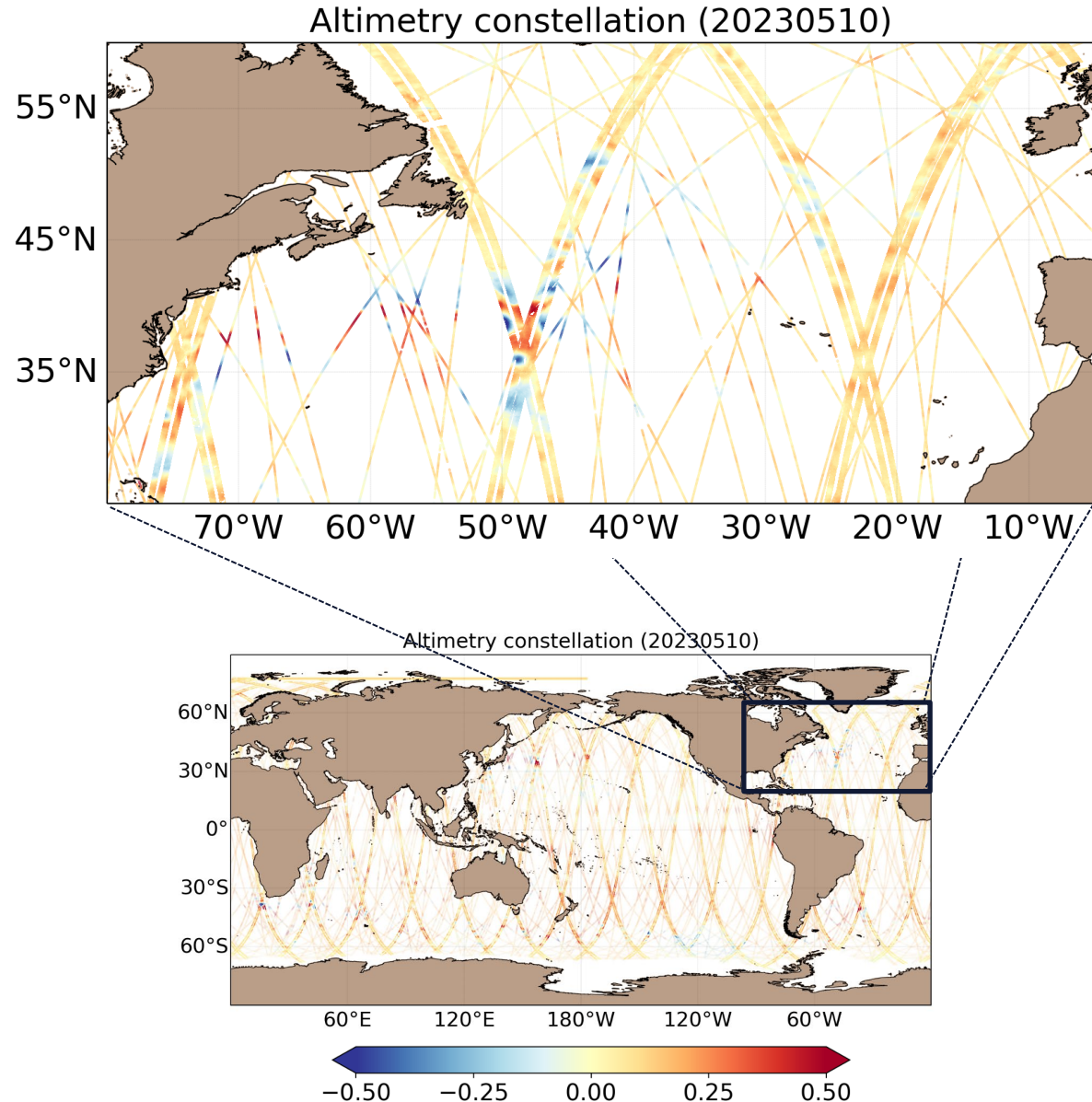


Effective spatial resolution DT2018





- With MIOST:
 - **Global** mapping conducted for the period from 2023-05-01 to 2023-07-01.
- With 4Dvarnet:
 - **North Atlantic** mapping conducted for the period from 2023-05-01 to 2023-07-01.
- Experiments carried out in Delayed-Time mode (DT: past & future observations):
 - **EXP#1:** Cryosat-2, HaiYang-2B, Sentinel-3A, Sentinel-3B, Sentinel-6, Jason-3: => **nadirs only reference exp.**
 - **EXP#2:** Cryosat-2, HaiYang-2B, Sentinel-3A, Sentinel-3B, Sentinel-6, Jason-3 + **SWOT Karin: to quantify the contribution of Karin**
- SARAL/Altika kept aside for validation
- **Resources:** Mapping & Validations are undertaken on the CNES Computing Center (see Cyril presentation on CNES computing facilities)



- Two mapping methods (MIOST (OI based) & 4Dvarnet (data-driven)) were tested to reconstruct the ocean surface topography using Level-3 SWOT Karin data and nadirs observations.
- The experiments indicate that the **systems behave well for assimilating Karin data** in addition to the current **nadir constellations**.
- Currently, the key message regarding the **contribution of Karin in mapping** is a **reduction of 15-20% in RMSE (Root Mean Square Error)** in energetic regions, and approximately **8% reduction elsewhere**.

=> Science results presented in Guillaume's Poster:
4DvarNet: Data-driven mapping of Ocean Surface Topography using SWOT altimetry

4DVarNet : Data-driven mapping of Ocean Surface Topography using SWOT altimetry
 G. Malet, M. Bellenger, A. Truesdale, Y. Pichot, R. Paillet, G. Dibarboure

Introduction & Context
 Until now, only OI-based methods have been used to assimilate and refine the impacts of Karin data in mapping systems. These experiments included various mapping algorithms such as DUACS (Le Traouegoulec et al., 2008), MIOST (Laguarda et al., 2021), 4DVARNet (Laguarda et al., 2021), 4DVARNet (Laguarda et al., 2021) and 4DVARNet (Laguarda et al., 2021). Here we present the first mapping study conducted using real SWOT Karin observations with 4DVARNet and MIOST methods. The main objectives of these studies were to assess the performance of mapping systems with real SWOT data, especially on fine-scale ocean structures, and to quantify the contribution of SWOT Karin during the 4DVARNet phase in experimental mapping method 4DVARNet. The altimetry constellation used in this study spans from March 2023 to July 2023 and includes Track 1 (Crossed 2), 1 (along 20, Sentinel-3B, Sentinel-3C, Jason 3, SWOT nadir) and 1 Karin instrument (SWOT).

Input data & Methods
Supervised training of 4DVARNet using CHL160 data
 In this study, we use the 4DVARNet framework introduced by Laguarda et al. (2021) relying on a neural network architecture based on a variational formulation. The framework consists of an end-to-end trainable architecture to which we apply a supervised learning strategy. This model is trained on a training set between the true state (ground truth) and its reconstruction made by the neural network. We use the same 4DVARNet-NN parameterization and training strategy as those presented by Laguarda et al. (2021).

Key results
Impact of SWOT Karin in 4DVARNet
 Figure 1: Comparison of RMSE (cm) for 4DVARNet with and without SWOT Karin data. The figure shows two maps of the North Atlantic region. The left map is labeled '4DVARNet (without SWOT Karin)' and the right map is '4DVARNet (with SWOT Karin)'. The right map shows a significant reduction in RMSE, particularly in the energetic regions (indicated by red and orange colors).
 Table 1: RMSE (cm) for 4DVARNet with SWOT Karin data.

| Scale | RMSE (cm) [low sensitivity (0.1-10 m)] | | |
|-----------|--|----------------|-------------------|
| | In swath [%] | Near swath [%] | Outside swath [%] |
| All Scale | -0.24 | -0.23 | -0.04 |
| 05-500 km | -0.22 | -0.22 | -0.05 |
| 05-200 km | -0.22 | -0.22 | -0.05 |

Impact of SWOT Karin in MIOST
 Figure 2: Comparison of RMSE (cm) for MIOST with and without SWOT Karin data. The figure shows two maps of the North Atlantic region. The left map is labeled 'MIOST (without SWOT Karin)' and the right map is 'MIOST (with SWOT Karin)'. The right map shows a reduction in RMSE, particularly in the energetic regions.
 Table 2: RMSE (cm) for MIOST with SWOT Karin data.

| Scale | RMSE (cm) [low sensitivity (0.1-10 m)] | | |
|-----------|--|----------------|-------------------|
| | In swath [%] | Near swath [%] | Outside swath [%] |
| All Scale | -0.24 | -0.23 | -0.04 |
| 05-500 km | -0.22 | -0.22 | -0.05 |
| 05-200 km | -0.22 | -0.22 | -0.05 |

Inference on real climatic dataset
 The trained 4DVARNet model is ready to be used to perform SSM reconstructions with real altimetry data in real-time. SSM reconstructions are being generated over the CHL160 dataset as the algorithm is still in development and not yet ready for global use. We also compare the MIOST reconstructions (Laguarda et al., 2021) over the same dataset. As a result of Level 3 SWOT Karin (1-day repeat orbit) have been processed in the 4DVARNet system (see MIOST in overview poster, Y. Pichot), we use a constellation spanning from March 2023 to July 2023, including 7 nadirs (CS-1, 103, 53A, 53B, 5C, 1), SWOT nadir) and 1 Karin (SWOT) nadir. Figure 3: Comparison of RMSE (cm) for 4DVARNet and MIOST over the CHL160 dataset. The figure shows two maps of the North Atlantic region. The left map is labeled '4DVARNet (with SWOT Karin)' and the right map is 'MIOST (with SWOT Karin)'. The 4DVARNet map shows a significant reduction in RMSE compared to MIOST, particularly in the energetic regions.

Conclusion & Perspectives
 As the first 8 months of Level 3 SWOT Karin (1-day repeat orbit) have been processed in the 4DVARNet system, we were able to produce the first SSM mappings using real SWOT Karin observations. Two experimental mapping methods were tested to reconstruct the ocean surface topography using SWOT data. The experiments indicate that the systems are ready to assimilate Karin data in addition to the current nadir constellation, even though 4DVARNet reconstructions could only be carried out at the scale of the North Atlantic basin (the algorithm is still in development and not yet ready for global use). We can draw various useful conclusions regarding the impact of Karin. For both MIOST and 4DVARNet methods, Karin data resulted in a reduction of 15-20% in RMSE (Root Mean Square Error) in energetic regions, and approximately 8% reduction elsewhere. As the SWOT satellite transition to a 21-day repeat, it will offer swath data coverage across all regions within the basin (with, however, a reduced repeat rate). Consequently, it is reasonable to anticipate that the 21-day SWOT data will lead to a more consistent enhancement in the basin-scale performance of the mapping algorithm than 4DVARNet or MIOST. Moreover, developments are currently underway to apply 4DVARNet at a global scale in the near future, later allowing for the quantification of SWOT's contribution to the method on a global scale. This will also help address an ongoing question that remains unanswered: which method of mapping ocean height will be the most suitable to make the best use of the revolutionary swath data provided by the SWOT satellite's data acquisition. It could be considered to structure data challenges focusing on the contribution of Karin data in regional and global mappings on this different working groups. Mapping methods can compare their approaches (see for example CSRSV and CSRSV funded projects: <https://ocean-2023.challenge.gatech.edu/>).



- **Data sharing:** experimental L3 & L4 datasets presented here may be distributed (e.g., AVISO+, CNES HPC ?)
- **Sharing Validation method:** structuring data challenge for Global/Regional mapping focused on Karin's contribution, so that different mapping groups can intercompare their mapping and validation methods
 - => Ongoing work through CMEMS Service Evolution SLICING project, as well as CNES funded projects

<https://ocean-data-challenges.github.io/>

- **Improved mapping & validation plans:**
 - Towards a globalization of the 4dvarnet method
 - Result consolidation: Validation and refinement of mapping for SWOT Science orbit with MIOST & 4Dvarnet
 - Test mapping with **dynamical methods** such as BFN-QG, DYMOST, and 4Dvar-QG (F. Le Guillou), etc.. at the regional scale => Next presentation & posters
 - **Validation** with independent data (along-track and in-situ) => Possible synergy with fields campaign (validation with insitu data)



THANK YOU !!!





BACKUP

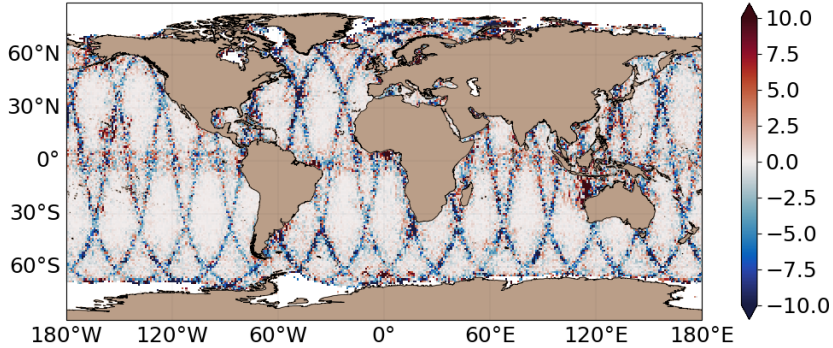


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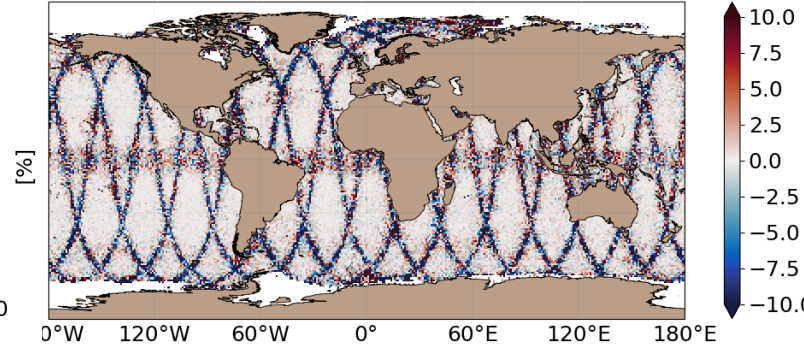
FOR ALL SPATIAL SCALE

Δ RMSE MIOST with SWOT Karin vs MIOST without SWOT Karin (all scale)



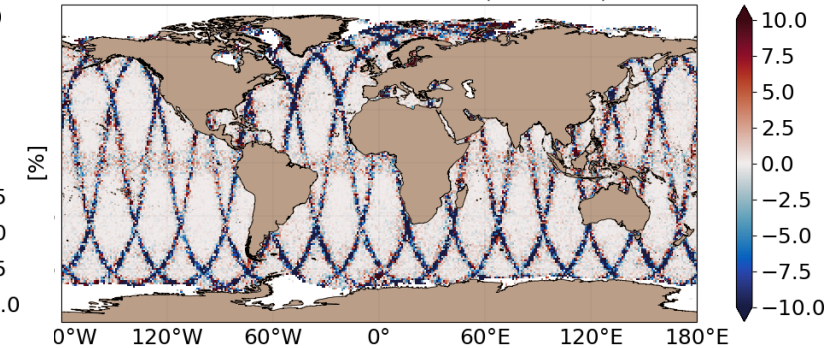
FOR SPATIAL SCALE < 500km

Δ RMSE MIOST with SWOT Karin vs MIOST without SWOT Karin (65-500km)



FOR SPATIAL SCALE < 200km

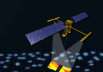
Δ RMSE MIOST with SWOT Karin vs MIOST without SWOT Karin (65-200km)



Improved with Karin
 Degraded with Karin

| | offshore (>200km) <u>low</u> var (<0.02m ²) | | |
|-----------|--|----------------|-------------------|
| | In swath [%] | Near swath [%] | Outside swath [%] |
| ALL SCALE | -2.05 | -1.03 | 0.06 |
| 65-500km | -5.79 | -1.98 | 0.12 |
| 65-200km | -5.97 | -2.34 | 0.06 |
| | offshore (> 200km) <u>high</u> var (> 0.02m ²) | | |
| | In swath [%] | Near swath [%] | Outside swath [%] |
| ALL SCALE | -9.83 | -4.03 | -0.05 |
| 65-500km | -15.91 | -6.21 | 0.03 |
| 65-200km | -16.85 | -6.89 | 0.06 |

- Mapping is improved under SWOT Karin



FOR ALL SPATIAL SCALE

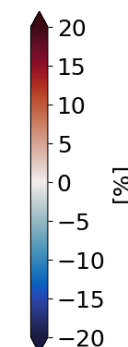
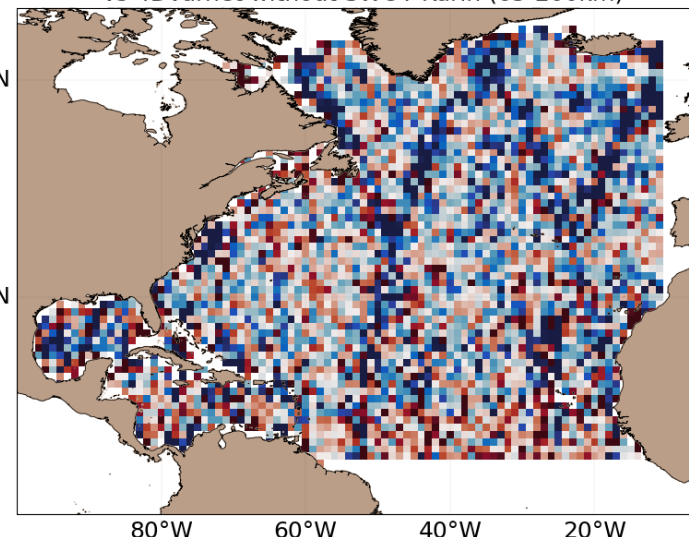
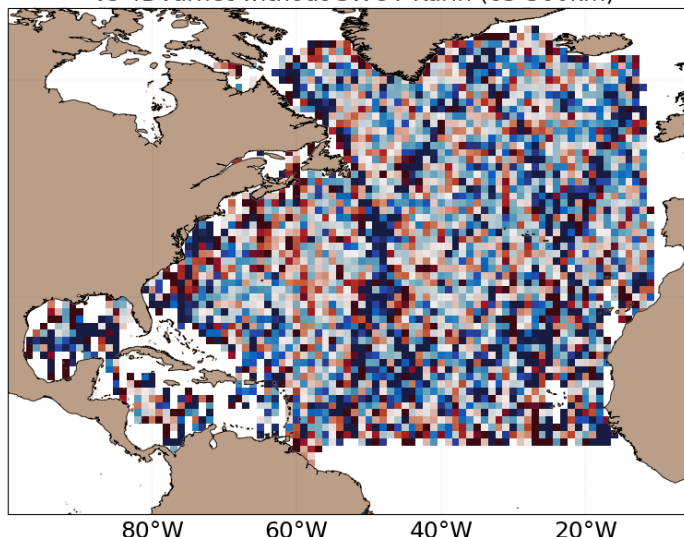
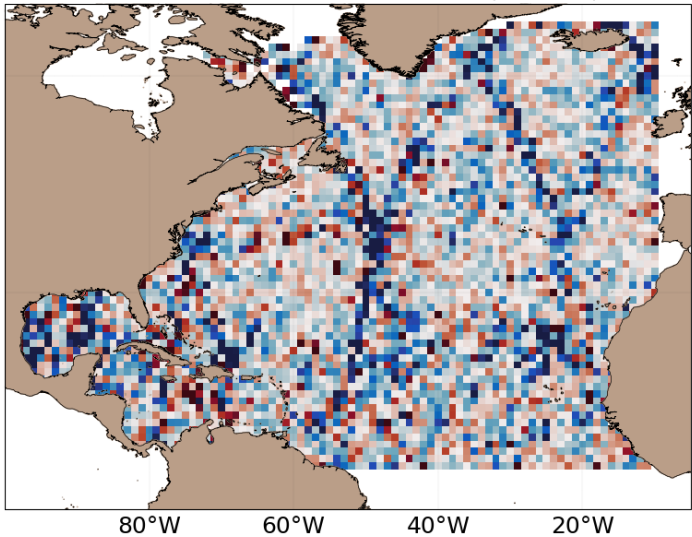
Δ RMSE 4Dvarnet with SWOT Karin vs 4Dvarnet without SWOT Karin (all scale)

FOR SPATIAL SCALE < 500km

Δ RMSE 4Dvarnet with SWOT Karin vs 4Dvarnet without SWOT Karin (65-500km)

FOR SPATIAL SCALE < 200km

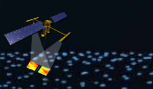
Δ RMSE 4Dvarnet with SWOT Karin vs 4Dvarnet without SWOT Karin (65-200km)



| | offshore (>200km) <u>low</u> var (<0.02m ²) | | |
|-----------|---|----------------|-------------------|
| | In swath [%] | Near swath [%] | Outside swath [%] |
| ALL SCALE | -5.34 | -3.92 | -1.67 |
| 65-500km | -7.13 | -7.12 | -1.89 |
| 65-200km | -6.79 | -6.74 | -1.36 |

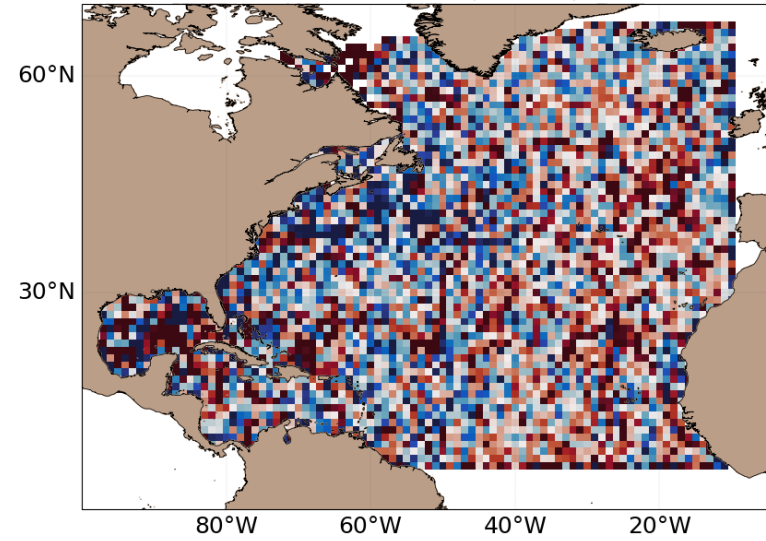
| | offshore (> 200km) <u>high</u> var (> 0.02m ²) | | |
|-----------|--|----------------|-------------------|
| | In swath [%] | Near swath [%] | Outside swath [%] |
| ALL SCALE | -17.46 | -4.79 | -0.07 |
| 65-500km | -17.88 | -3.12 | 0.37 |
| 65-200km | -18.09 | -6.45 | -0.77 |

Improved with Karin
 Degraded with Karin



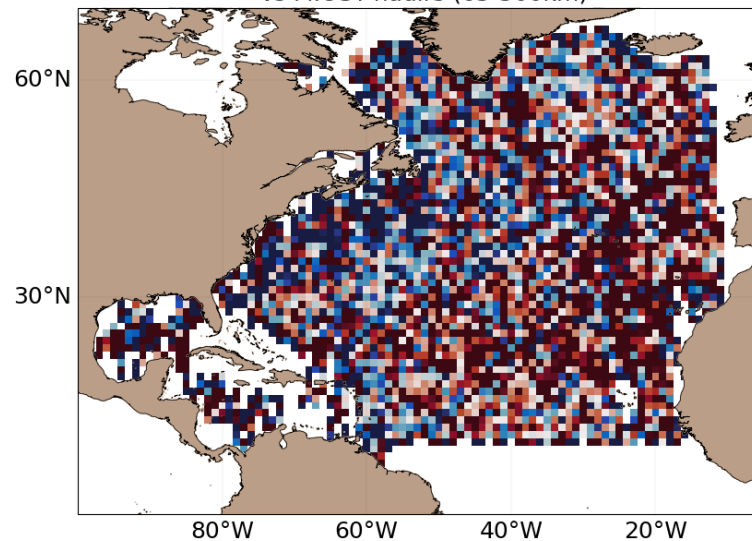
FOR ALL SPATIAL SCALE

Δ RMSE 4Dvarnet-nadirs vs MIOST-nadirs (all scale)



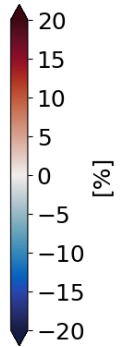
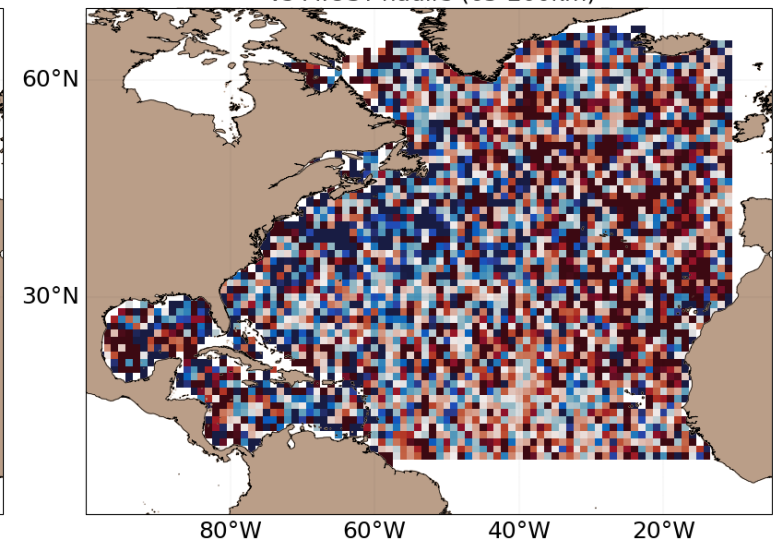
FOR SPATIAL SCALE < 500km

Δ RMSE 4Dvarnet-nadirs vs MIOST-nadirs (65-500km)

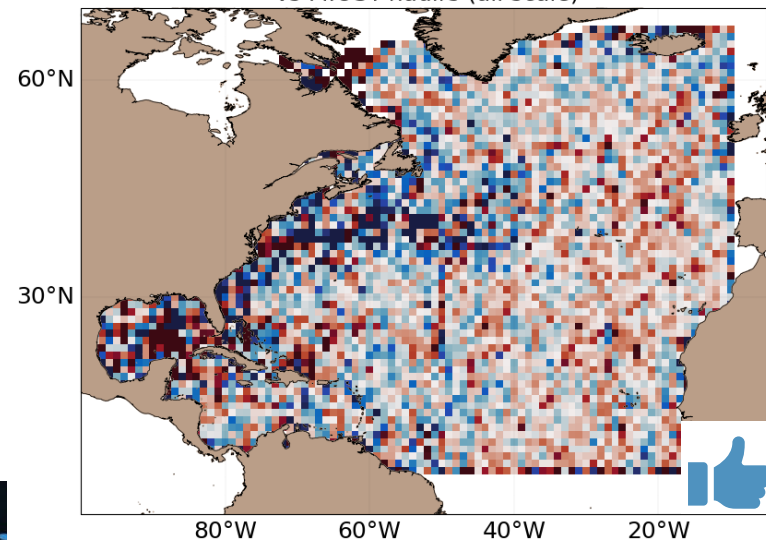


FOR SPATIAL SCALE < 200km

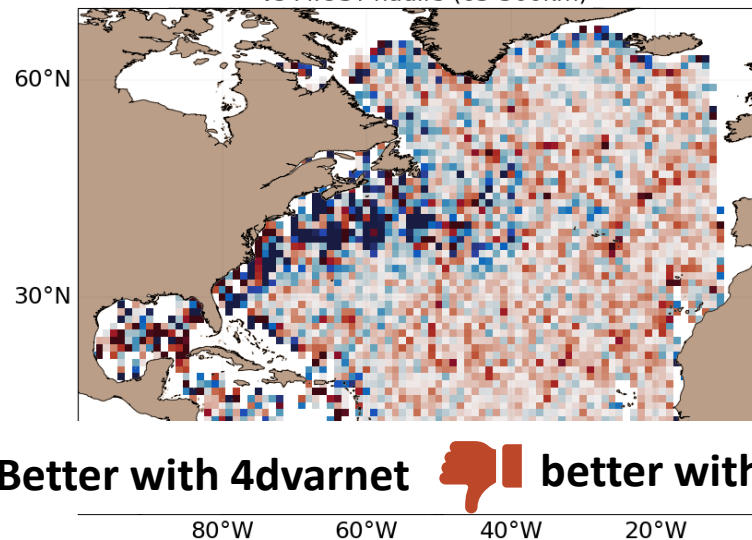
Δ RMSE 4Dvarnet-nadirs vs MIOST-nadirs (65-200km)



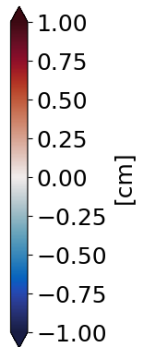
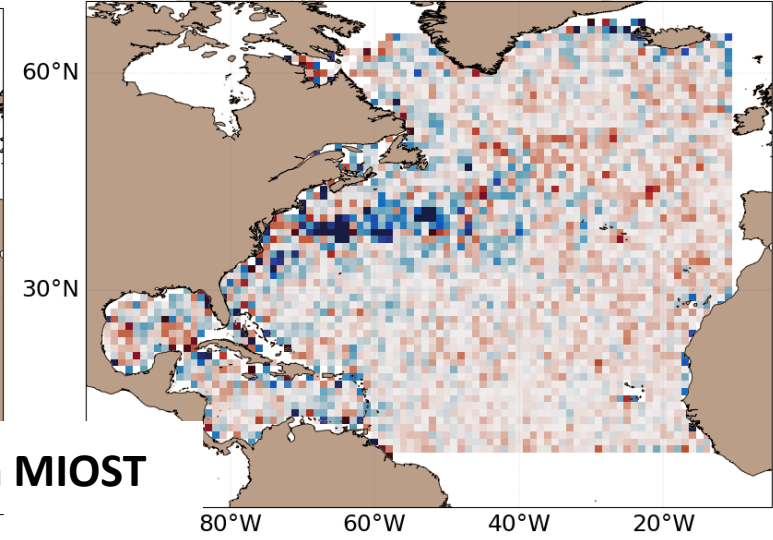
Δ RMSE 4Dvarnet-nadirs vs MIOST-nadirs (all scale)



Δ RMSE 4Dvarnet-nadirs vs MIOST-nadirs (65-500km)



Δ RMSE 4Dvarnet-nadirs vs MIOST-nadirs (65-200km)



Better with 4dvarnet

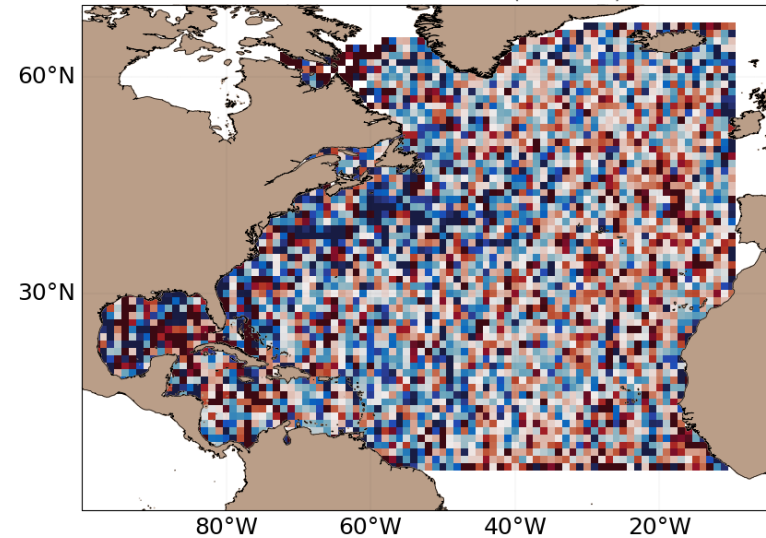


better with MIOST



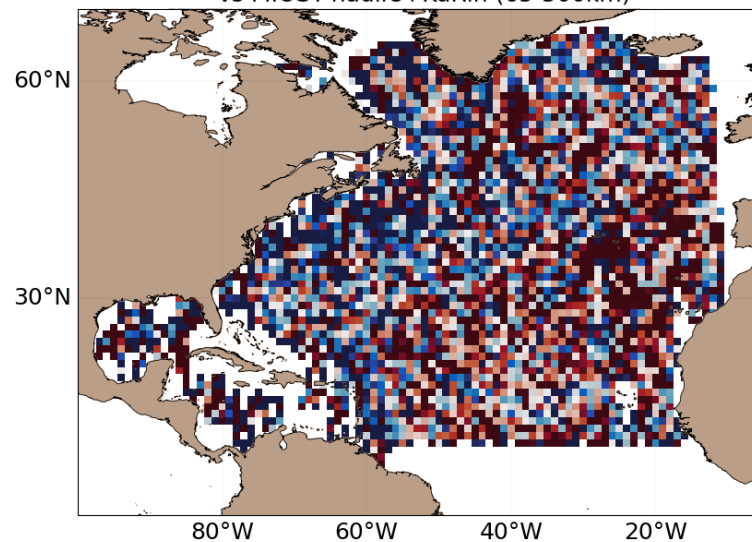
FOR ALL SPATIAL SCALE

Δ RMSE 4Dvarnet-nadirs+KaRin vs MIOST-nadirs+KaRin (all scale)



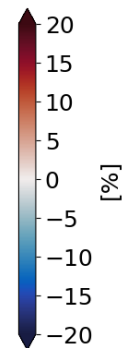
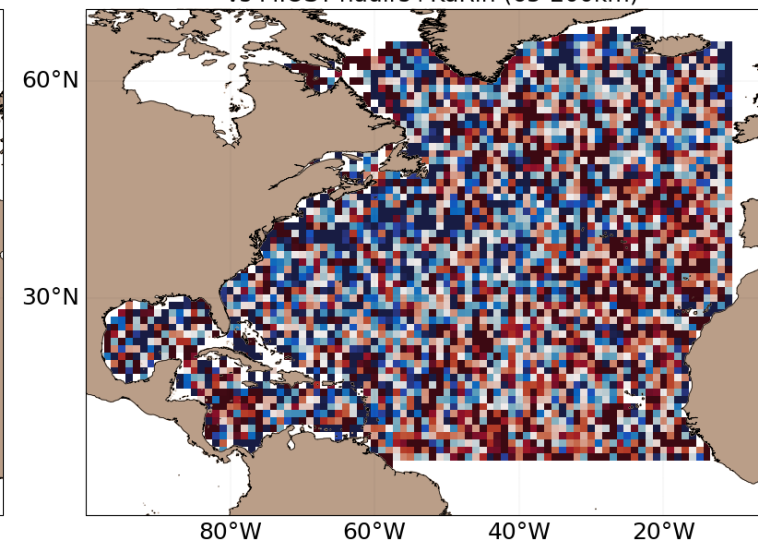
FOR SPATIAL SCALE < 500km

Δ RMSE 4Dvarnet-nadirs+KaRin vs MIOST-nadirs+KaRin (65-500km)

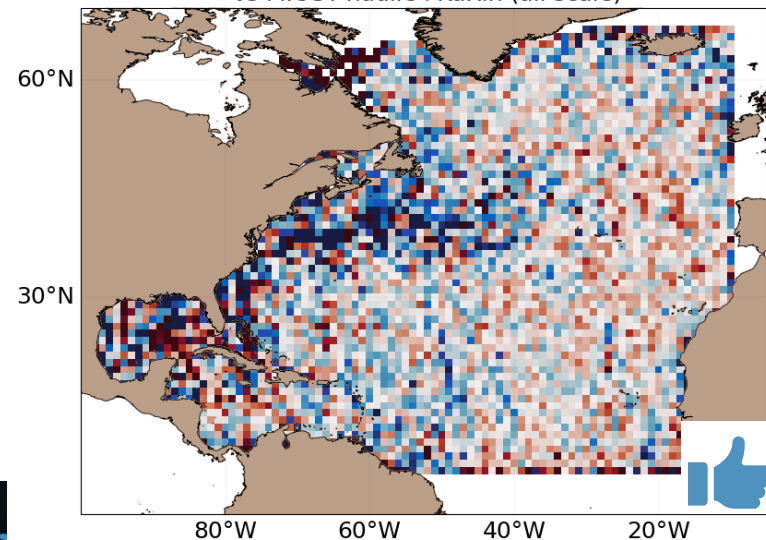


FOR SPATIAL SCALE < 200km

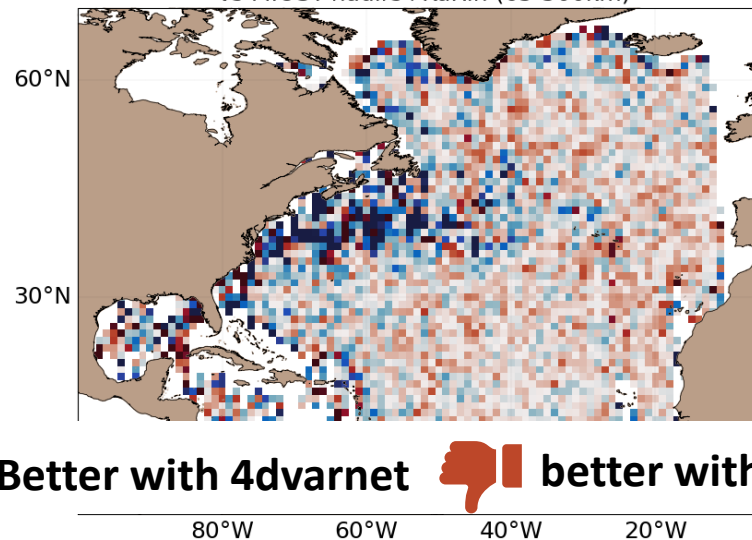
Δ RMSE 4Dvarnet-nadirs+KaRin vs MIOST-nadirs+KaRin (65-200km)



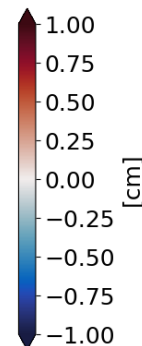
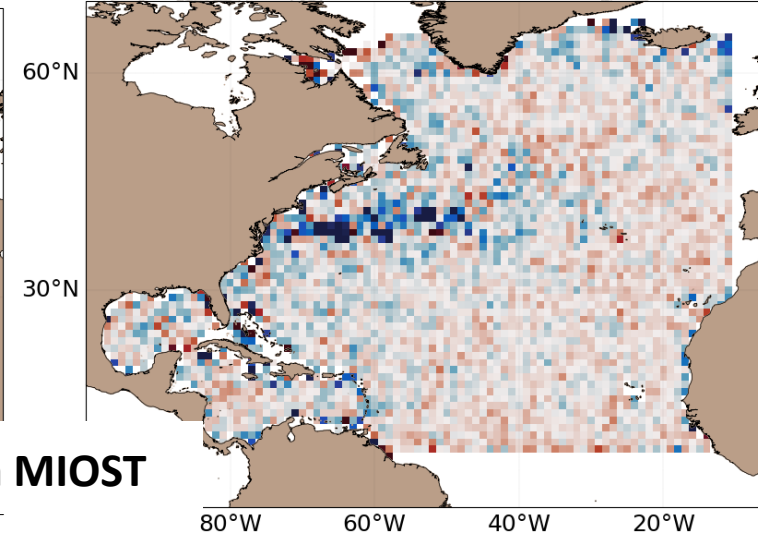
Δ RMSE 4Dvarnet-nadirs+KaRin vs MIOST-nadirs+KaRin (all scale)



Δ RMSE 4Dvarnet-nadirs+KaRin vs MIOST-nadirs+KaRin (65-500km)



Δ RMSE 4Dvarnet-nadirs+KaRin vs MIOST-nadirs+KaRin (65-200km)



Better with 4dvarnet



better with MIOST