Mean Sea Surface modeling advances using SWOT : the CNES CLS solution

Charayron Rémy, Schaeffer Philippe, Ballarotta Maxime, Pujol Marie-Isabelle (CLS)

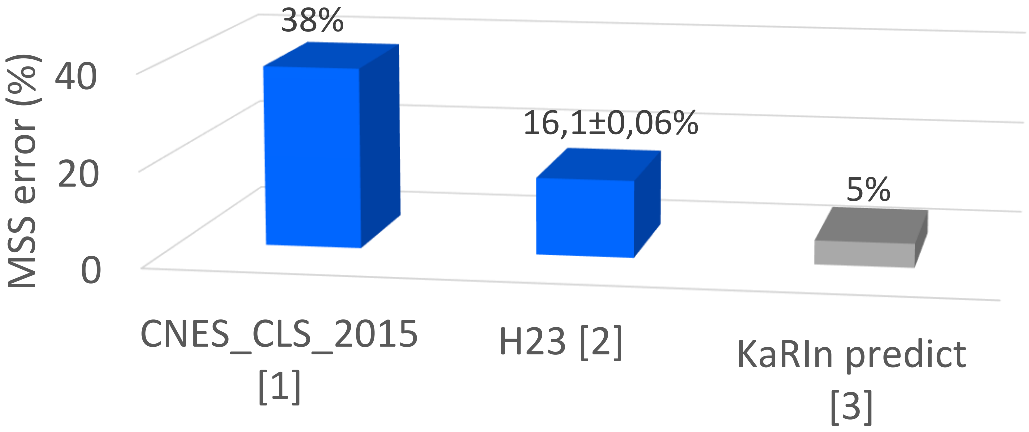
Delepoulle Antoine (DATLAS)

Dibarboure Gerald (CNES)

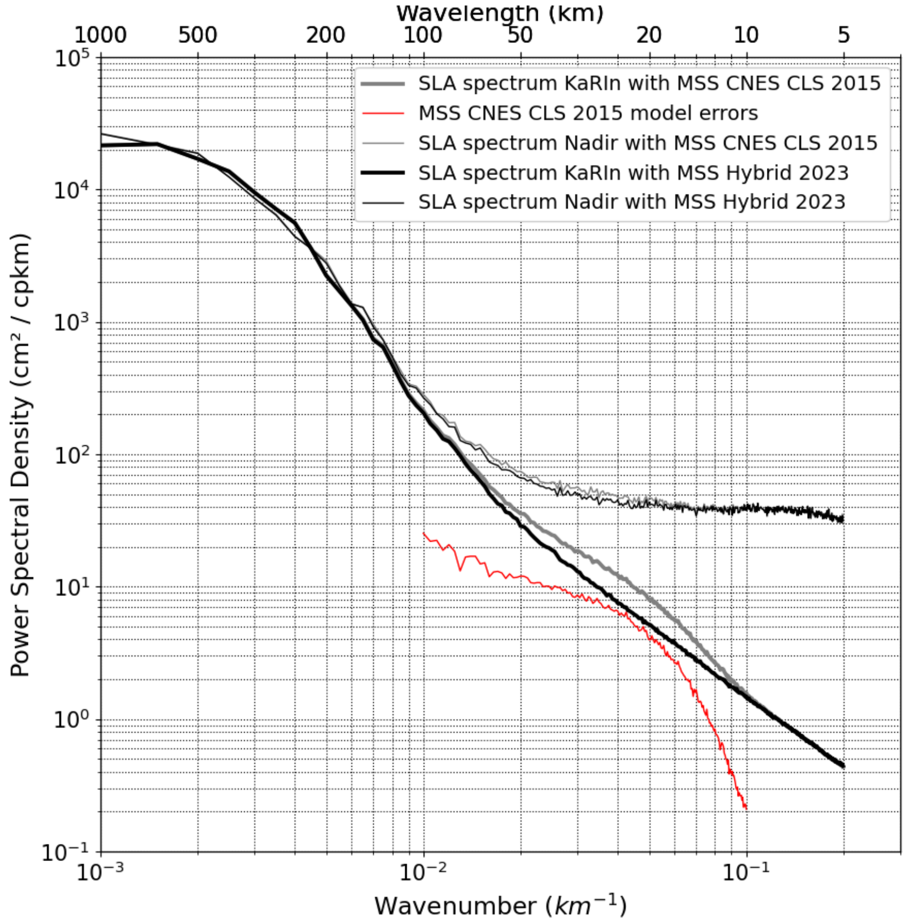
OSTST 2026

CLS cnes datlas

The SWOT KaRIn data promise



Mean MSS error PSD in % of the mean true SSHA PSD on the [15km ; 100km] wavelengths interval for several MSS models including a hypothetical future model built thanks to SWOT-KaRIn data.



PSD of the KaRIn (thick solid line) and Nadir SSHA (thin solid line) based on the CNES/CLS2015 MSS (grey) and on the Hybrid 2023 model (black). MSS CNES_CLS_2015 estimated errors (red). From [1]

<u>Nadir-based MSSs present significant errors at short wavelengths :</u>

- Mainly omission errors
- Create artificial hump on KaRIn SSHA PSD at small mesoscale ($\lambda \in [10km\,;100km]$)

<u>SWOT-KaRIn data are expected to able MSS error reduction :</u>

- SWOT-KaRIn unprecedented precision and 2-dimensional observations
- More than 30 cycles in science phase should lead to MSS error < ~5% of SSHA variance [2]

→ presentation of the CNES_CLS_2025 solution

[1] Pujol et al, 2016 https://doi.org/10.1029/2017JC013503
[2] Laloue et al, 2024. https://doi.org/10.1029/2024EA003836
[3] Dibarboure et Pujol, 2019. https://doi.org/10.1016/j.asr.2019.06.018

MSS CNES_CLS_2025 computation methodology

$$\boldsymbol{CNES\_CLS\_2025 = Hybrid23 \;+\; InnovComb}$$

New MSS model

MSS draft **to capture large-scale content** from H23 [1]

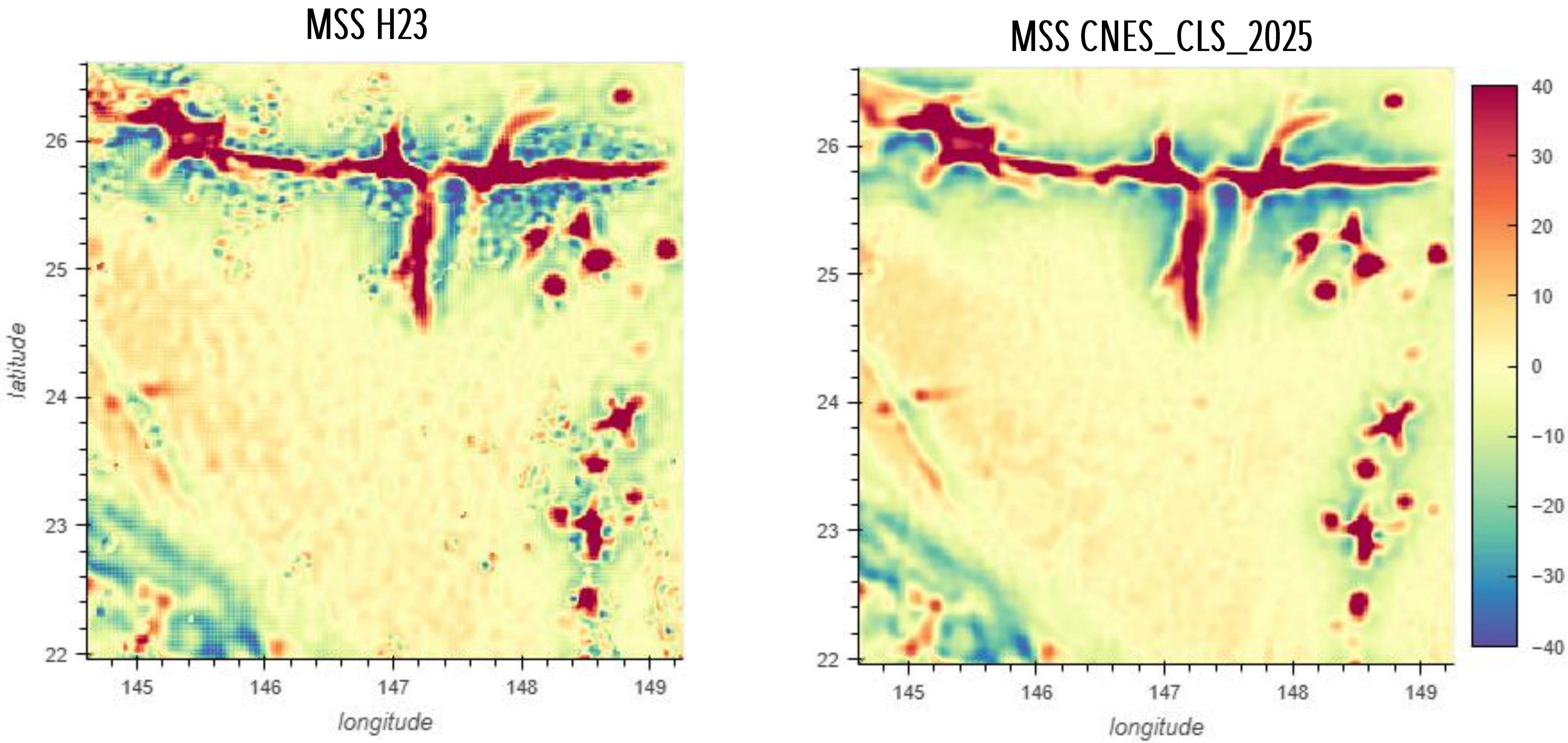
Combine **KaRIn-based* and nadir-based**** MSS innovation solutions **to improve scales from 10 to 100km**

- *KaRIn SSHA 2km measurements over 31 cycles of science phase; include MSS compression correction
- ** Nadir 1Hz measurement from AltiKa and Cryosat-2 (geodetic phases) used in KaRIn diamonds; include MSS compression correction and using MIOST mapping [2]

[1] Laloue et al, 2024. https://doi.org/10.1029/2024EA003836
[2] Ubelmann et al, 2021. https://doi.org/10.1029/2020JC016560

MSS CNES_CLS_2025 qualitative validation

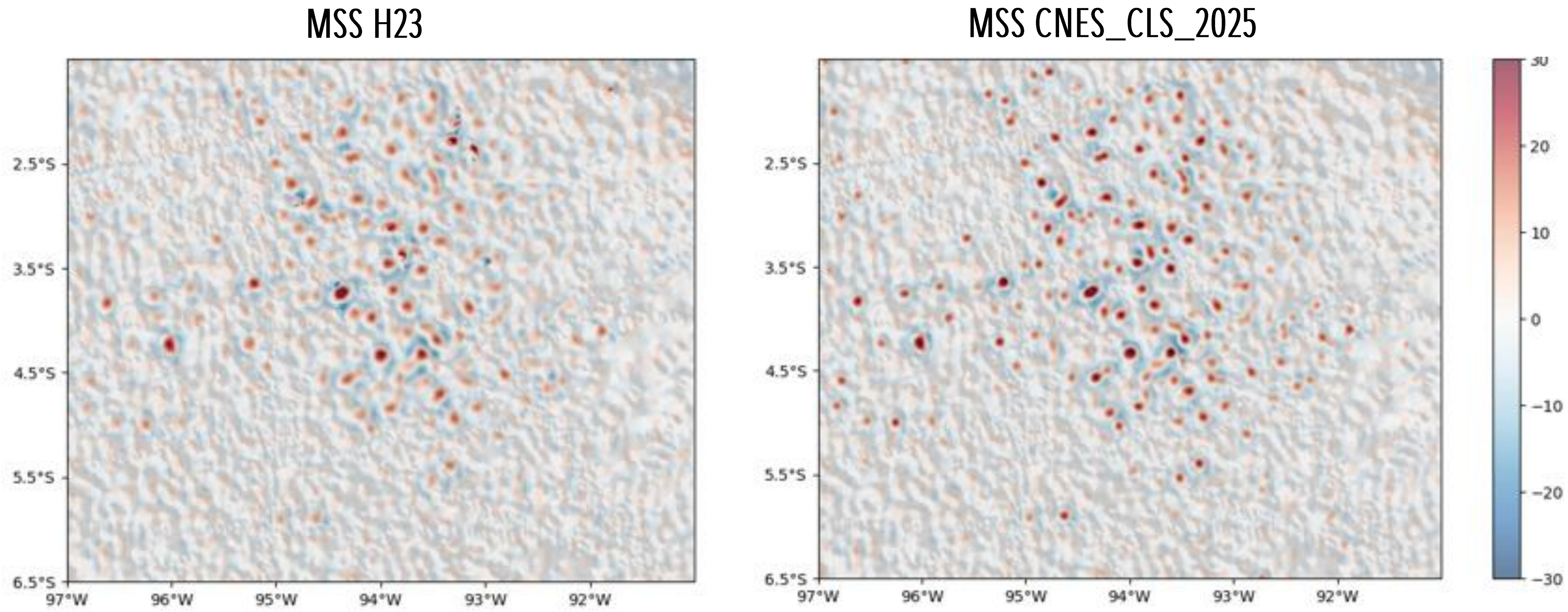
MSS CNES_CLS_25 removes hybridization and lineation artefacts visible in H23



Visualisation of the short WL (< 20km) of the MSSs (units: mm)

MSS CNES_CLS_2025 qualitative validation

Seamounts improved in quantity and intensity in MSS CNES_CLS_2025.



Visualisation of the short wavelengths (<20km) of the MSS (units: mm)

MSS CNES_CLS_2025 : impact on SSHA variance

CNES_CLS_2025 contributes to significantly reduce the SSHA variance:

- Mainly visible along geodetic structures
- Small spots of SSHA variance increase : signature of commission errors (e.g. internal tides); usualy << 1% SSHA variance
- Same results for KaRIn & nadir measurements

Var(SSHA(CNES_CLS_25)) – Var(SSHA(H23)) (cm²)

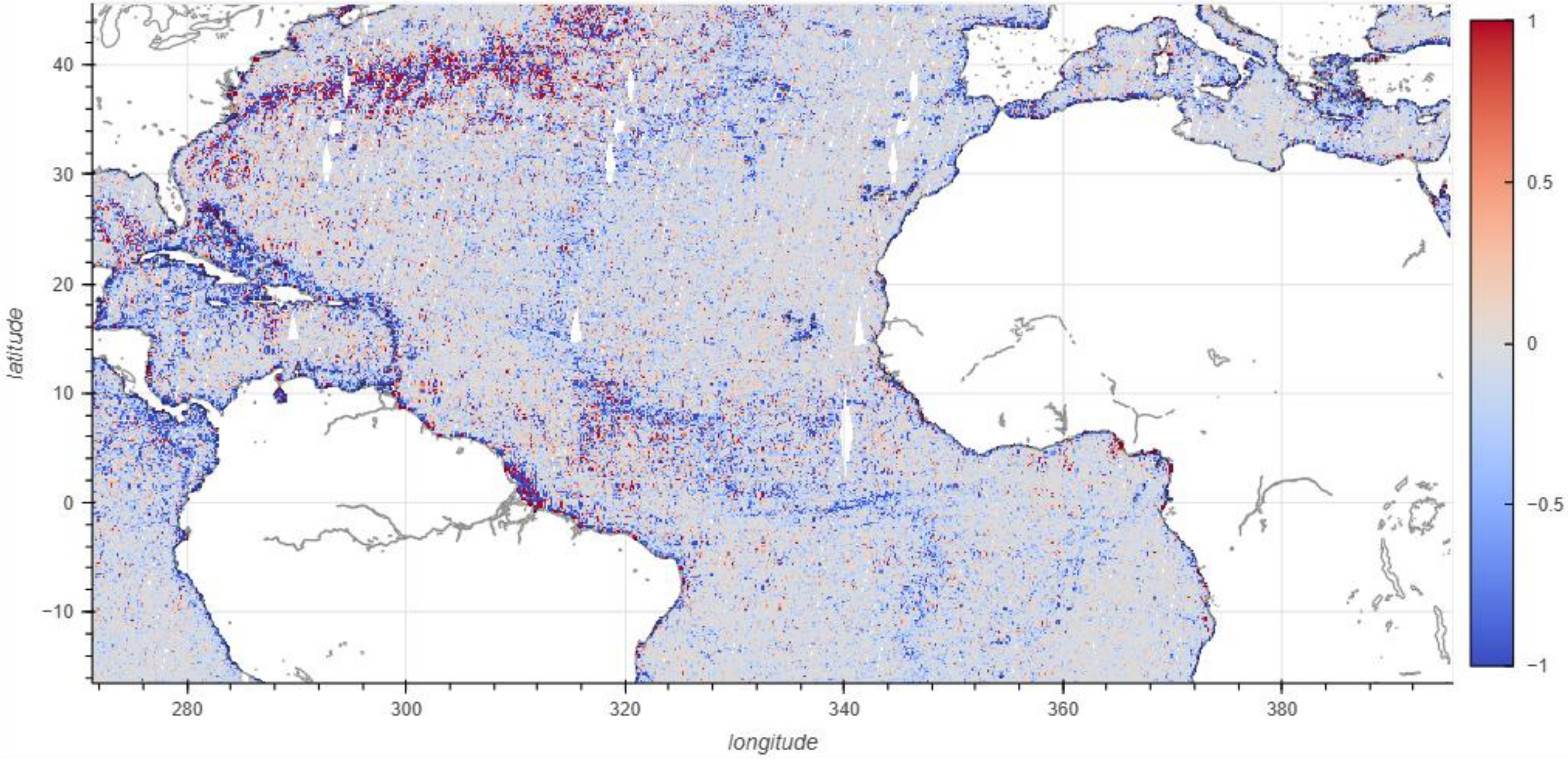


Fig: KaRIn SSHA variance reduction (cm²) when using MSS CNES_CLS_2025 rather than H23

MSS CNES_CLS_2025 error quantification at short WL

MSS errors at short wavelengths estimated using methodology previously defined in [2] & [3] using independat KaRIn data during the science phase

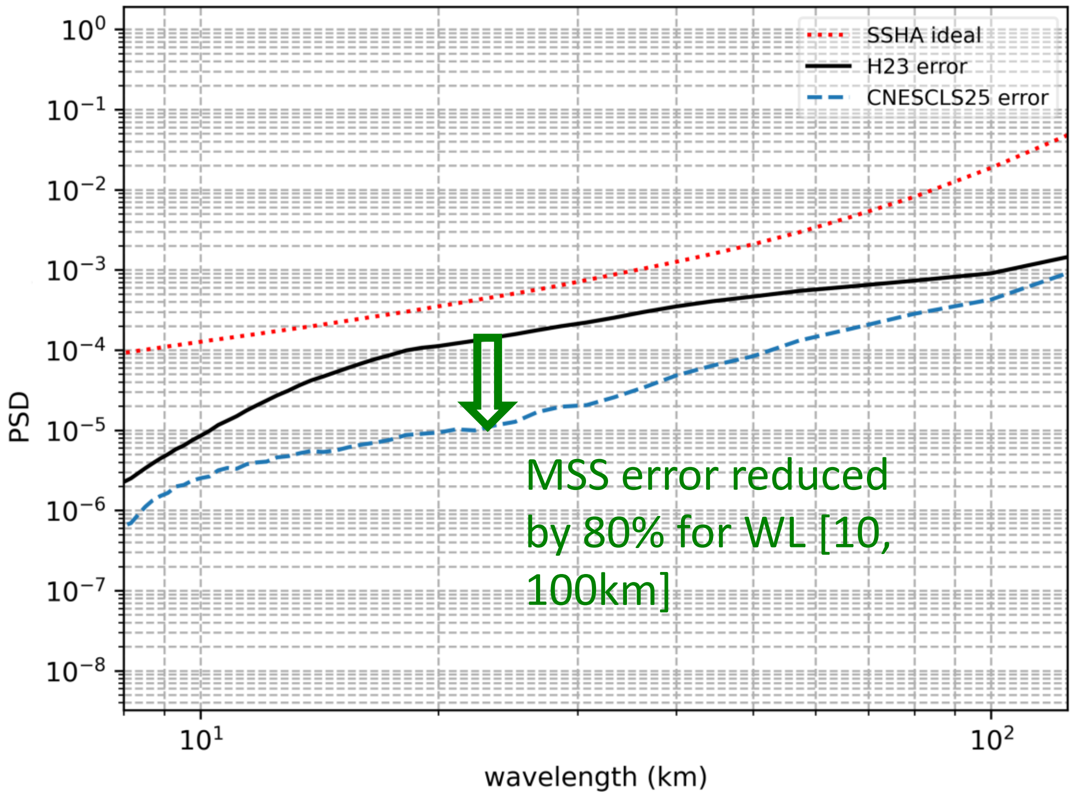
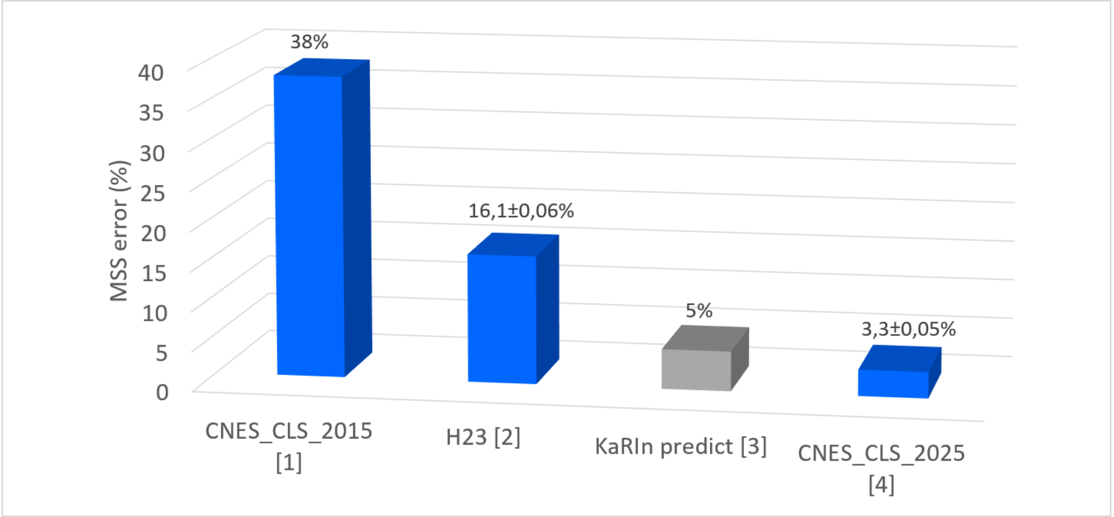


Fig: Mean MSS error PSD for different MSSs (black & blue) and SSHA without MSS error PSD (red).

- Significant reduction of the MSS error with CNES_CLS_2025 version : **error reduced by ~80% compared to H23 in the [10-100km] WL range**
- Maximal reduction at WL ~50-30km
- MSS CNES_CLS_2025 **mean error in the [10-100km] WL range is ~3,3% of the SSHA variance**

→**MSS is no more the main source of error for KaRIn at short WL**



Mean MSS error PSD in % of the mean ideal SSHA PSD on the [10km ; 100km] wavelengths interval.

[1] Pujol et al, 2016 https://doi.org/10.1029/2017JC013503
[2] Laloue et al, 2024. https://doi.org/10.1029/2024EA003836
[3] Dibarboure et Pujol, 2019. https://doi.org/10.1016/j.asr.2019.06.018
[4] Charayron et al, 2026 (preprint) (DOI: 10.24400/527896/a01-2024.011)

MSS CNES_CLS_2025 commission error estimation

Estimated in relative to the SSHA(H23), using 2 cycles of KaRIn science measurements

- 1 cycle independant of the MSS : SSHA variance reduction suposed to be unduced by MSS error reduction only
- 1 cycle used for MSS computation : SSHA variance reduction suposed to be unduced by MSS error reduction & MSS commission error

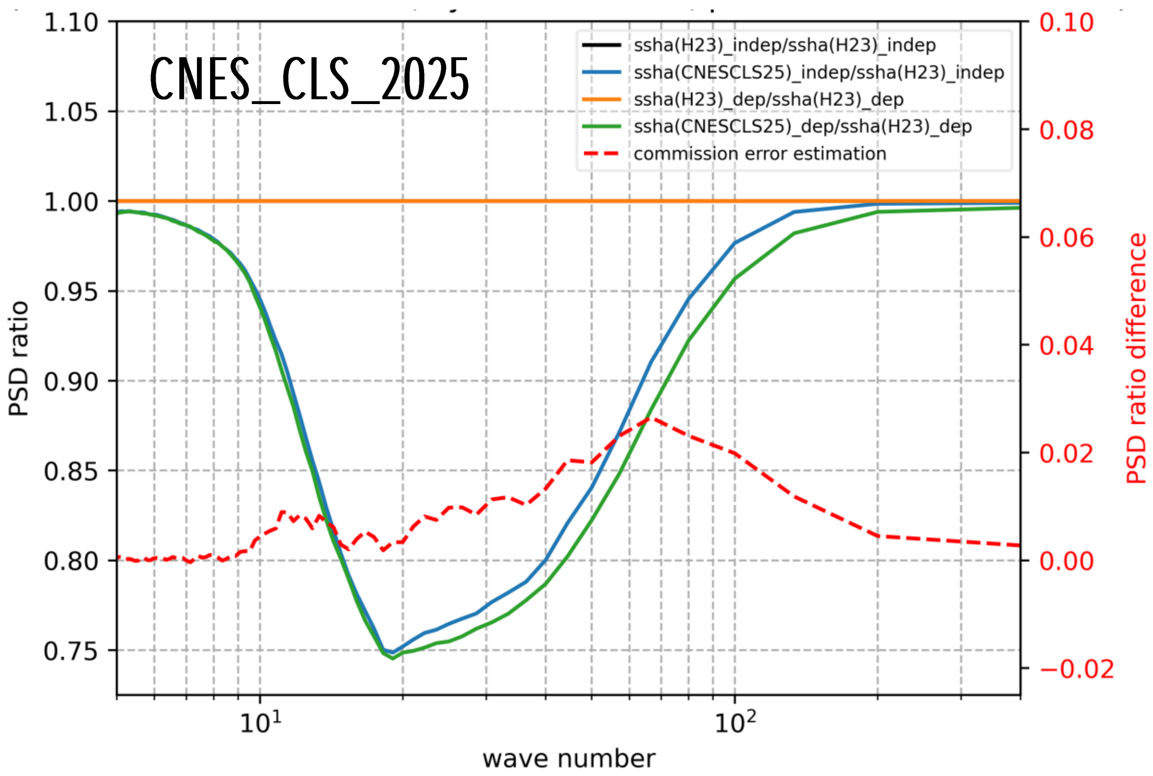


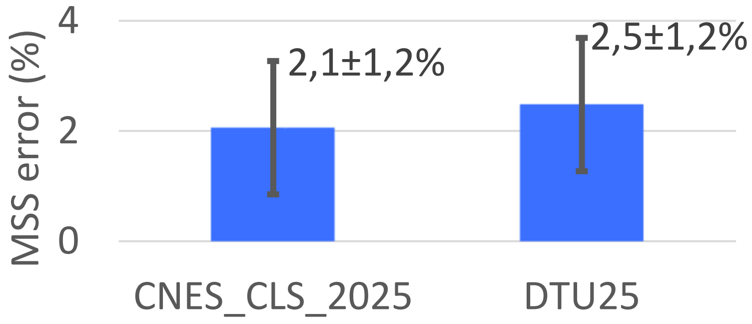
Fig: CNES_CLS_2025 commission error in % of the SSHA (red). SSHA PSD ratio when using MS CNES_CLS_2025 rather than H23 (blue & green)

- CNES_CLS_2025 commission error ≈ 2% of the SSHA(H23) on the 10 to 100km wavelength range (i.e. ≈ **60% of the MSS error**)
- Includes commission errors related to the ocean variability (mesoscales, tides, ….)

→ SSHA variance reduction remains a challenge for MSS computation

MSS CNES_CLS_2025 vs DTU25

MSS errors estimated using KaRIn CalVal phase (independant from both MSSs)



- Nearly similar mean errors for WL [100, 10 km]
- But high MSS errors estimation uncertainty due to the sparce spatial sampling of KaRIn CalVal
- Each MSS has its strength and weekness (KaRIn diamonds gestion, coastal areas, mesoscal variabiliity, specific arctefacts, …)

MSS CNES_CLS_25

DTU 25

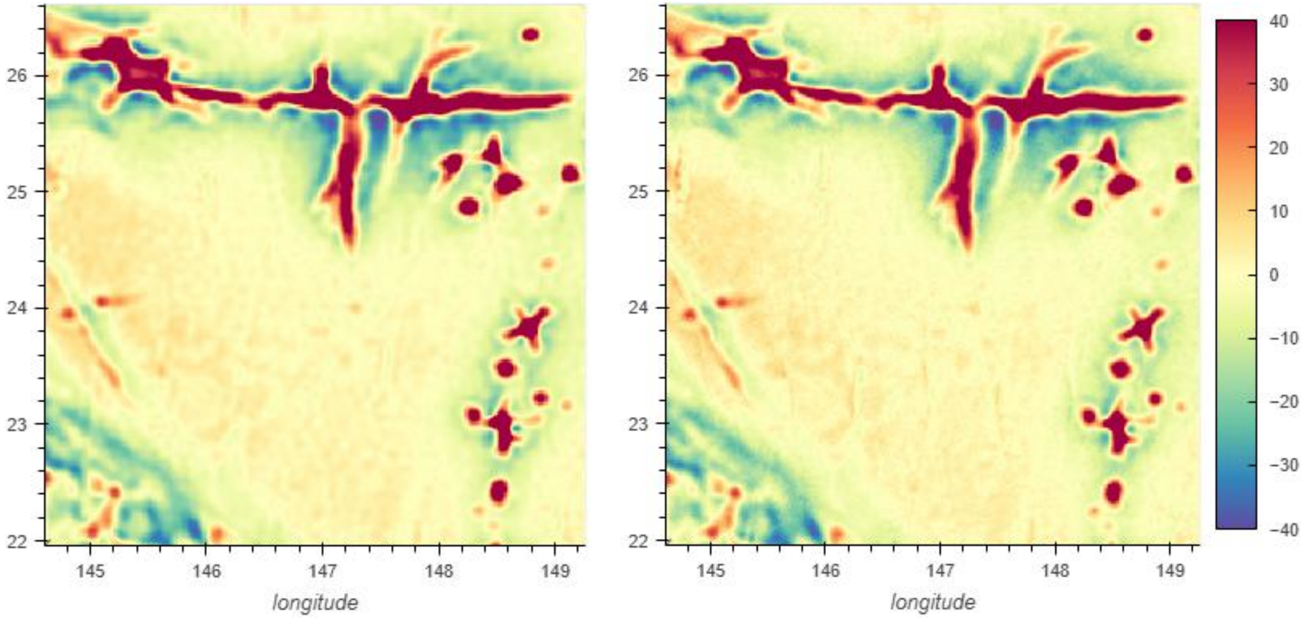


Fig: Short WL (< 20km) of the MSSs (units: mm)

Perspectives MSS CNES_CLS_2026

Improve geodetic structures restitution:

- Use KaRIn L3 250m to avoid MSS compression limitations
- Use KaRIn L3 v3 version for improved quality and longer time series
- Improve Nadir and KaRIn data selection for specific MSS application

Better manage ocean variability:

- Use alternative multimission gridded products for climate to mesoscale variability reduction : VarDyn [1] mapping including QG ocean dynamic ; 4DVarNet [2] mapping based on machine learning
- [tentative] use L3 KaRIn including residual tides reduction
- [tentative] Use multi-scale interpolation for a direct estimation of the MSS

Fill KaRIn diamonds:

- Use KaRIn L3 250m using measurement in the [6, 64km] band
- Optimize the combination of KaRIn and Nadir measurements

Improve MSS in polar area:

- [tentative] include KaRIn measurement in sea-ice leads areas

Take-home messages

- **New KaRIn-based MSSs errors significantly reduced compared to the last generation of nadir-based MSS:**
  - 80% error reduction at short WL; residual error ~3% of the SSHA variance; commission error induced by leakage of ocean variability explains ~60% of this error (MSS CNES_CLS_2025)

  → The MSS is no more the main source of error for KaRIn at short WL

- **CNES_CLS_25 ≈ DTU25 MSS in term of performances in open ocean (WL [10, 100km]).** Each one has its strengths and weaknesses

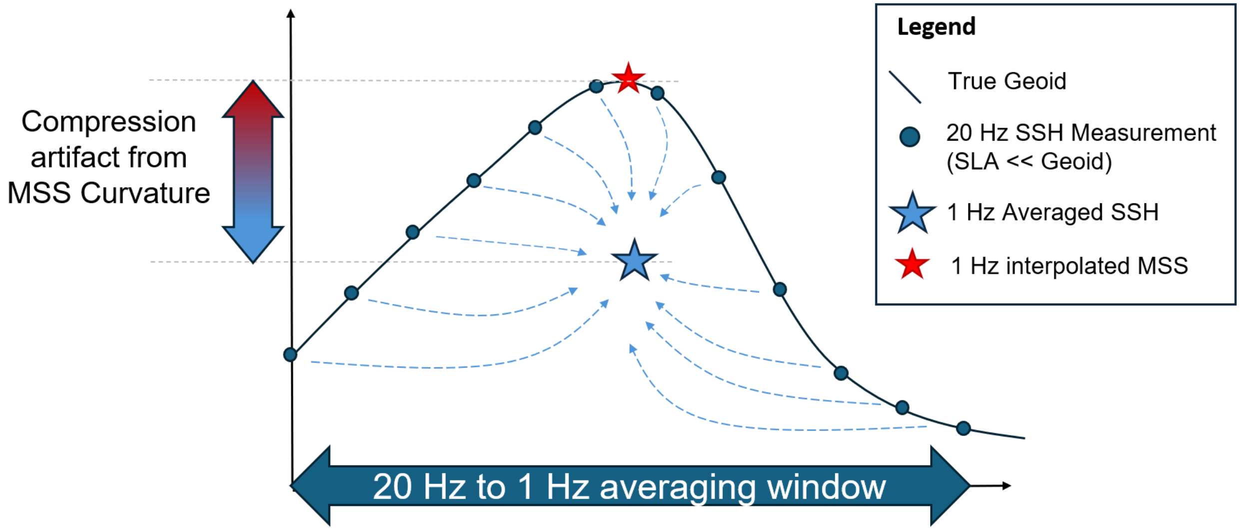
- **CNES_CLS_25 includes a compression correction in the processing allowing to retrieve the full MSS signal from KaRIn 2km & nadir 1Hz measurements:**
  - This MSS **must not be interpolated directly on 2km KaRIn or 1Hz nadir measurements, but must be « compressed »**
  - This MSS can be directly interpolated on KaRIn 250m & 20Hz measurements

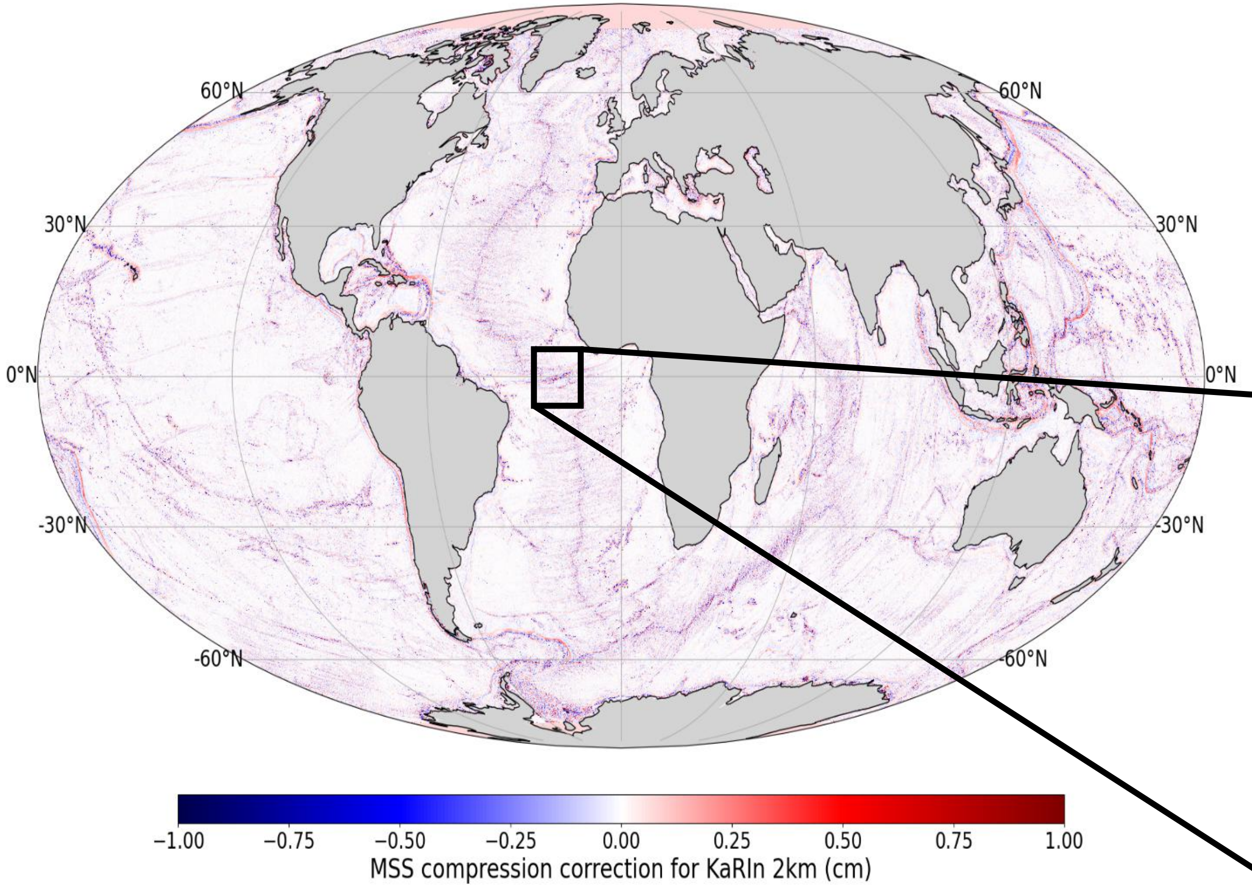
MSS compression error

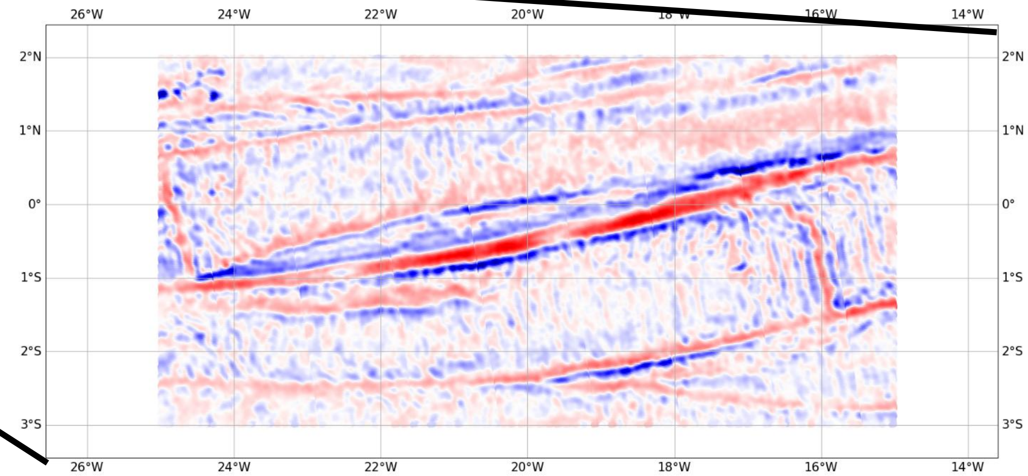
- Induced by the difference between compressed MSS and MSS at exact location
- Impact where MSS has curvature
- Up to 1,5 cm for KaRIn 2km; up to 4 cm for 1Hz nadir measurement

MSS compression error proxy computed for correction.

Fig: Illustration of discrepancy between 1 Hz SSH and MSS model due to the curvatures of geoid < 15 km (SWOT-era models)







Thank you!

MSS CNES_CLS_2025 access

https://doi.org/10.24400/527896/a01-2024.011

MSS CNES_CLS_2025 documentation:

Charayron R., Delepoulle A., Schaeffer P., Ballarotta M., Pujol MI., Dibarboure G., 2026. Introducing the CNES CLS 25 Mean Sea Surface, benchmarking an emerging generation of SWOT KaRIn based Models. Submitted in JGR-Ocean SWOT-Karin special issue.