

Cooperative Institute for Satellite Earth System Studies

Advances in Radar Altimetry for Observing Sea State and Sea Level

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Acknowledgements

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Project/Proposal title: "Towards an Improved Reconciliation of High- and Low-Resolution Ocean Altimeter Measurements Under Changing Surface Wave Structure Conditions", and by the NOAA Product Development, Readiness, and Application (PDRA)/Jason Program.

It was also supported by NOAA grant NA19NES4320002 and NOAA grant NA24NESX432C0001 (Cooperative Institute for Satellite Earth System Studies - CISESS) at the University of Maryland/ESSIC.

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Introduction

Introduction

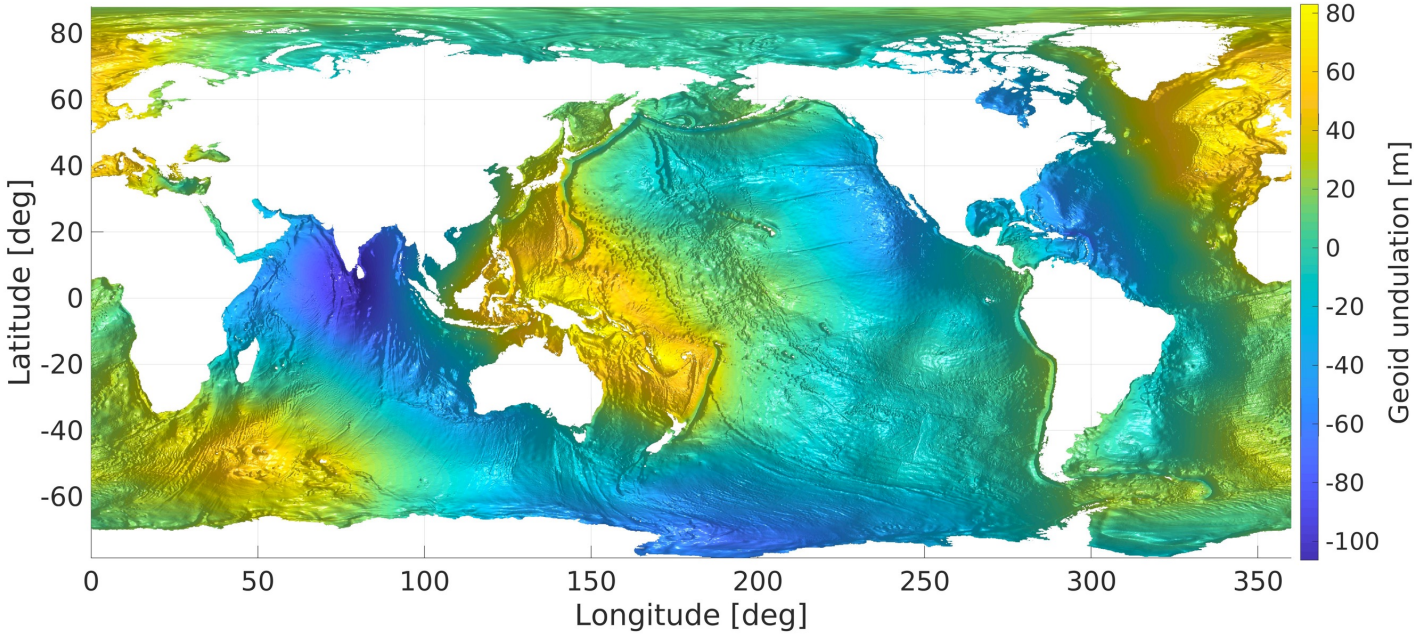
Originally developed to improve gravity field and ocean surface height measurements, spaceborne radar altimetry has become a core observing system for the marine environment.

Today, it provides critical observations of:

- sea level change
- wave generation and propagation
- wave Interactions with winds and currents

These observations directly support:

- understanding mesoscale features such as hurricanes, eddies, etc.
- improving wave climate models,
- enhancing weather and wave forecasting,
- assessing the impacts of waves on coastal and offshore environments



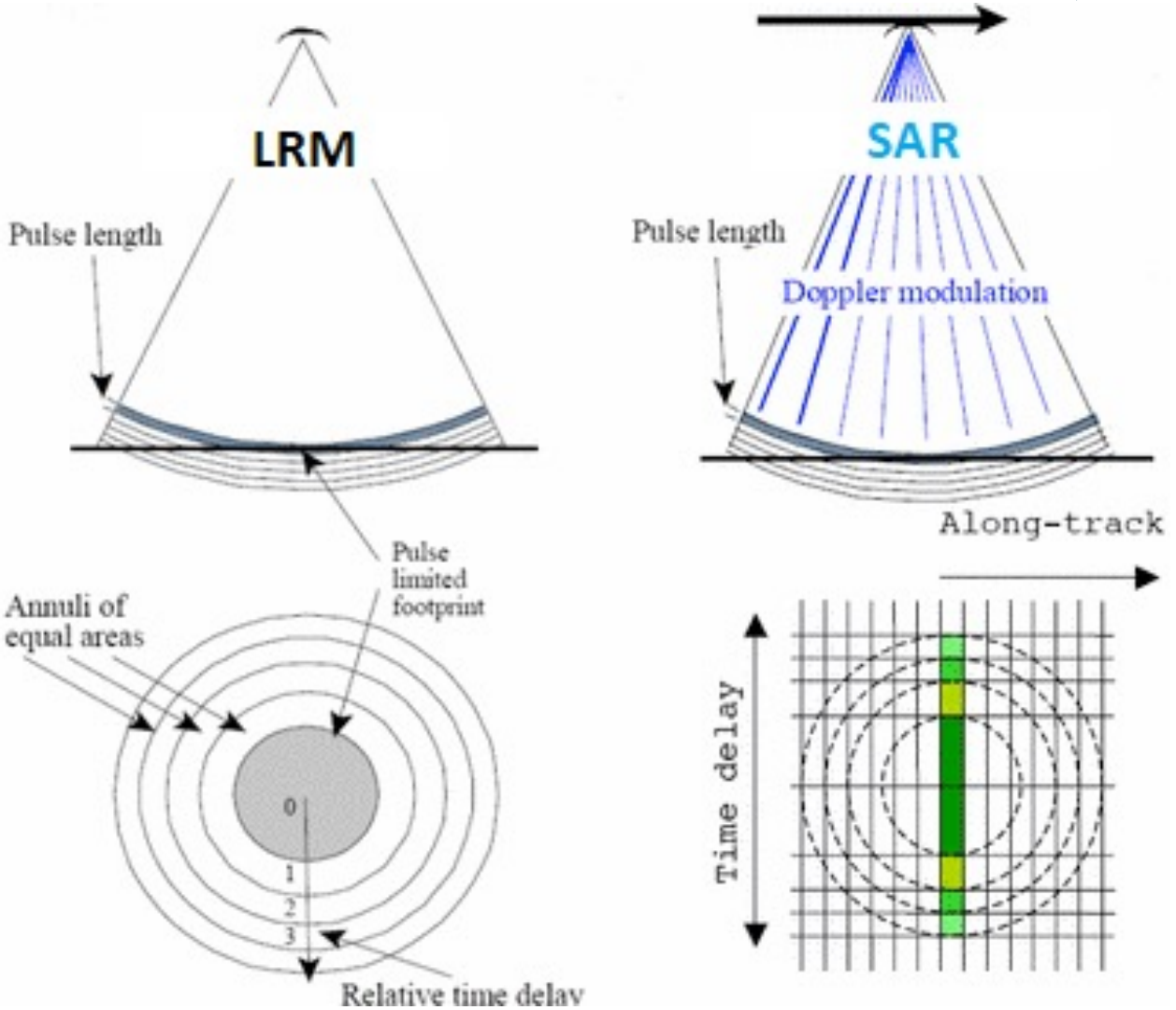
EIGEN-6C4 Geoid undulations(source: Geoid Spherical Harmonics derived by Christoph Förste et. al, 2005 [available at ICGEM] using satellite altimetry, satellite gravimetry [Goce, Grace, Lageos] and terrestrial methods [ground-, airborne-, and ship-gravimetry])

Introduction

Since 2010 two* observation modes are used

1. Low resolution mode (LRM)
    1. Detects power within range intervals
    2. Spatial resolution of 3 km to 5 km
2. Synthetic aperture radar (SAR) mode
    1. Detects power within range and azimuth cells
    2. Spatial resolution of ~300 m along-track and 3 km to 5 km across-track
    3. SAR sea level and significant wave height retrievals more precise compared to LMR

* three with wide-swath altimetry (not considered here)

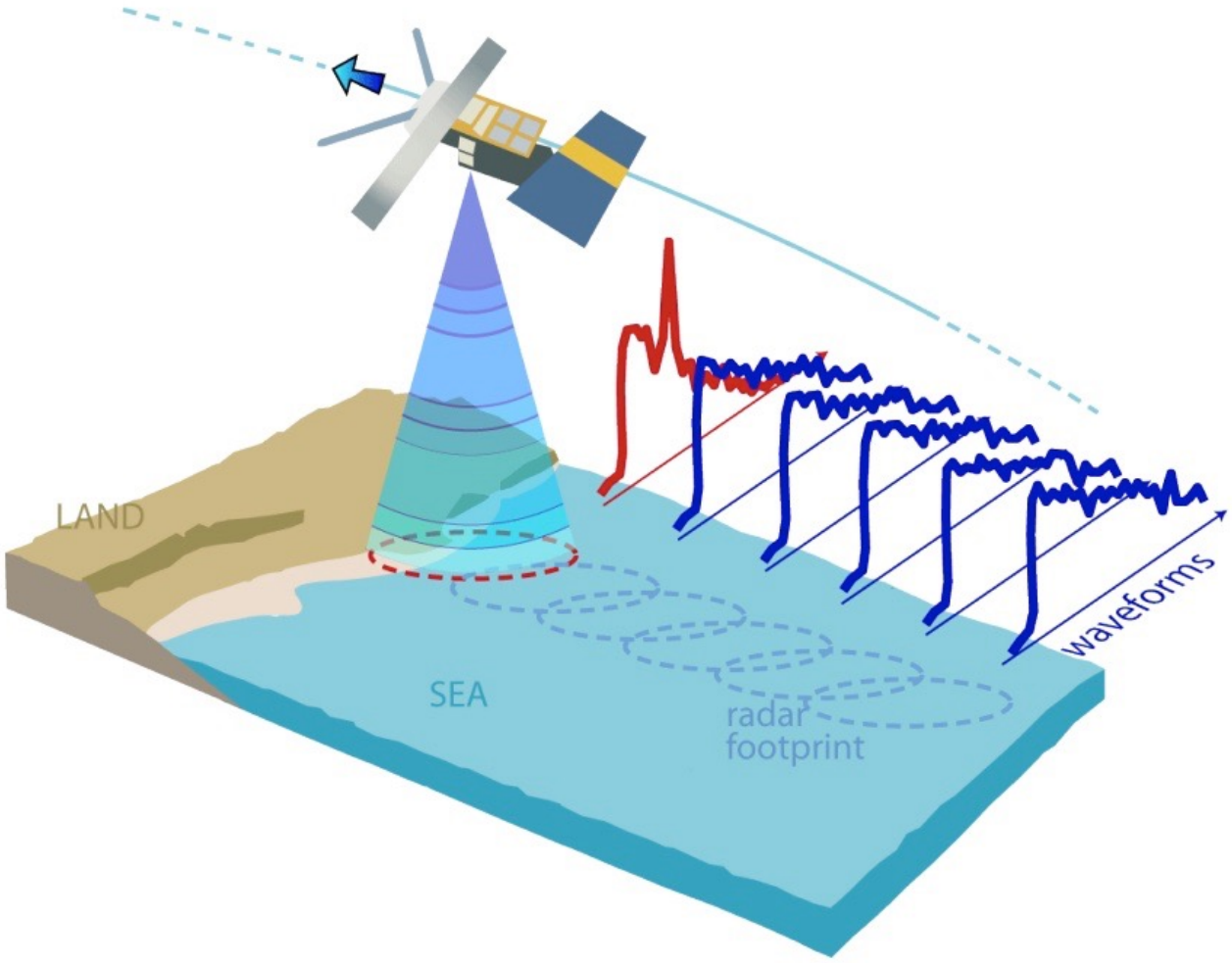


Conventional Altimetry and SAR Altimetry concept (source: Radar Altimetry Tutorial)

Introduction

- **Level 0:** Raw data, not available.
- **Level 1A:** Complex echoes plus data required to generate Level 1B data.
- **Level 1B:** Waveforms and stacks referenced to Earth coordinates ready for retracking.
- **Level 2:** Along-track geophysical parameters (e.g., sea level, SWH, wind speed) with all corrections applied.
- **Level 3:** Along-track data merged and cross-calibrated across missions for bias consistency.
- **Level 4:** Gridded or mapped fields derived from Level-3 data via interpolation and assimilation.

Input data level used in my work
Intermediate data level of my work
Output data level of my work



Visualization of Conventional Altimetry Level 1B (source: Radar Altimetry Tutorial)

Open Ocean Surfaces

Open Ocean – Operational Algorithm

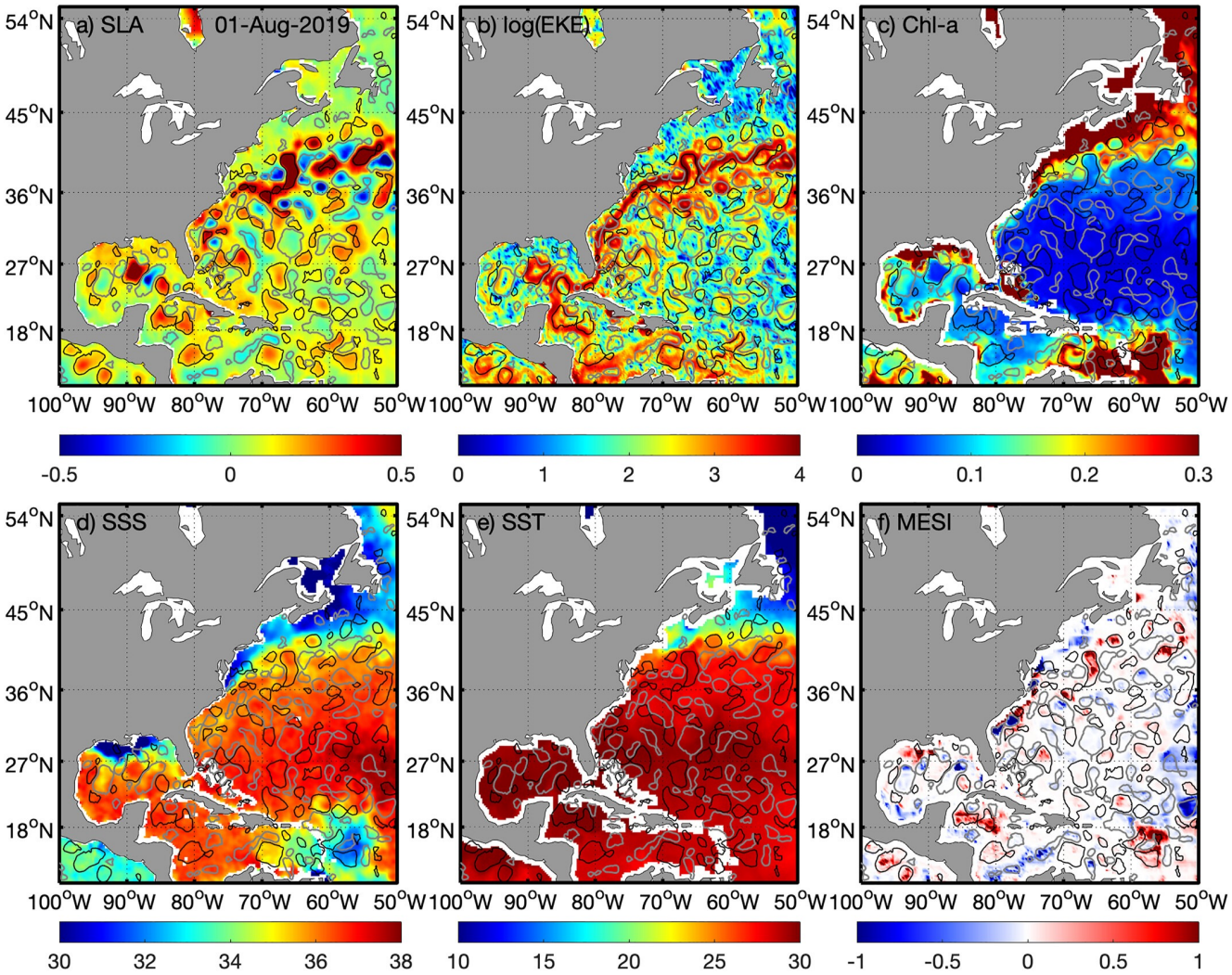
<u>Sea Level Anomaly is commonly used for:</u>

Ocean circulation and mesoscale dynamics

- Identification and tracking of:
  - Mesoscale eddies
  - Fronts and large-scale currents
- Estimation of geostrophic surface currents from SSH gradients

Operational and forecasting applications

- Constraining ocean and coupled forecast models
- Model validation and data assimilation
- Providing large-scale context for regional and coastal forecasts



Eddy detection using a multiparameter approach including SLA. Available at NOAA CoastWatch.
Source: Roman-Stork, H. L., Byrne, D. A., & Leuliette, E. W. (2023). MESI: A Multiparameter Eddy Significance Index. *Earth and Space Science*, 10, e2022EA002583. https://doi.org/10.1029/2022EA002583, Figure 5.

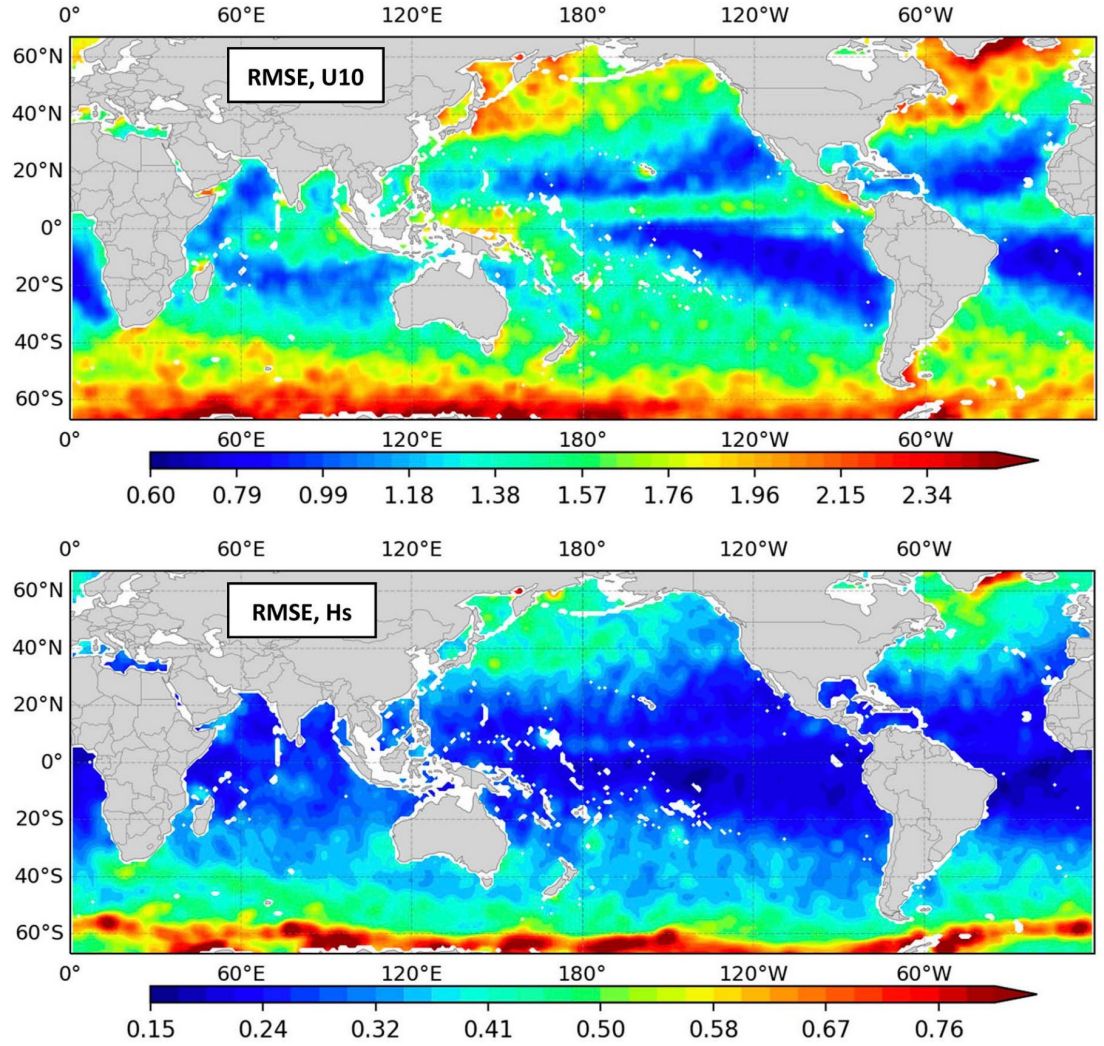
Open Ocean – Operational Algorithm

Significant Wave Height is used for:

- Standard descriptor of sea-state severity and wave energy
- Operational wave forecasting and marine safety applications
- Wave climate analysis and extreme event statistics
- First-order indicator of wave-driven coastal and offshore impacts

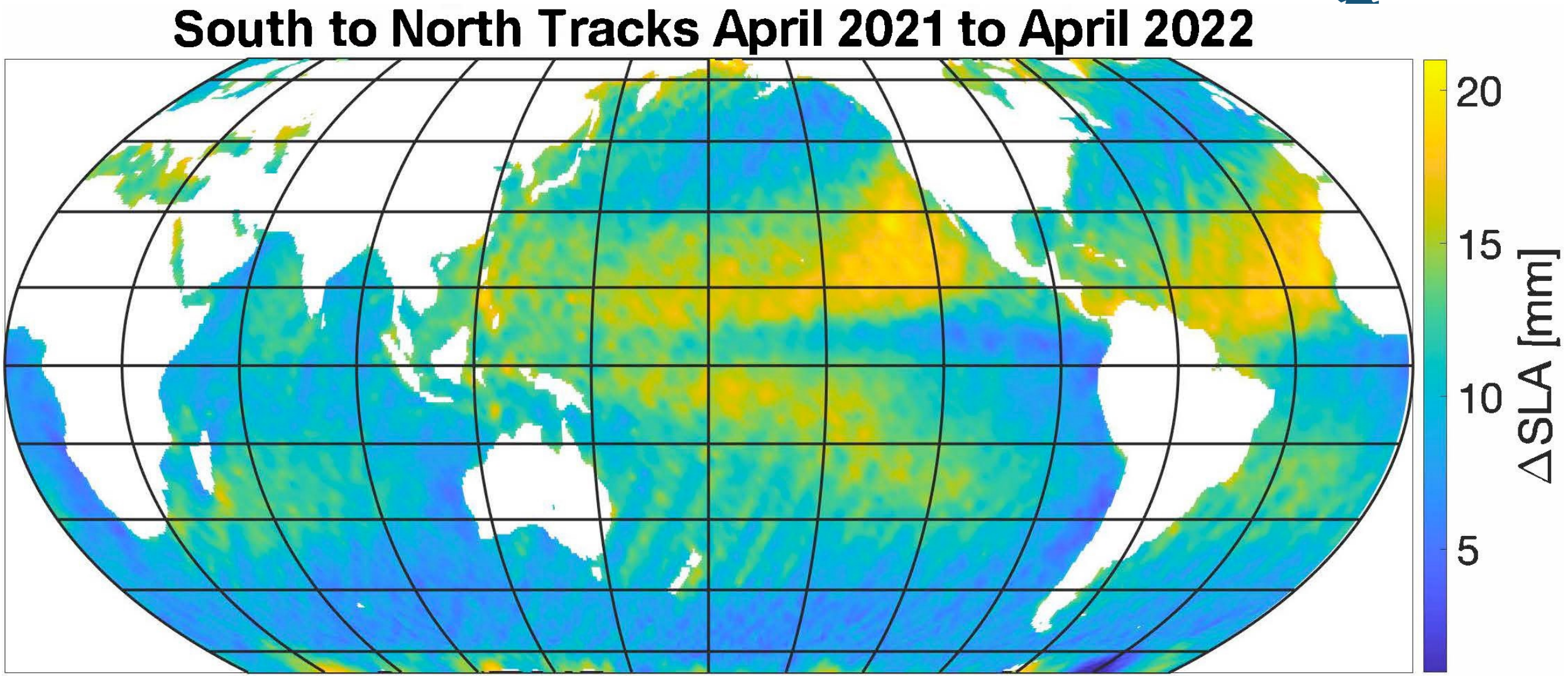
Wind Speed 10 m above Sea Level is used for:

- Forcing for wave generation and air-sea exchange
- Core input for atmospheric, wave, and coupled forecast models
- Identification of storm intensity and wind-driven hazards



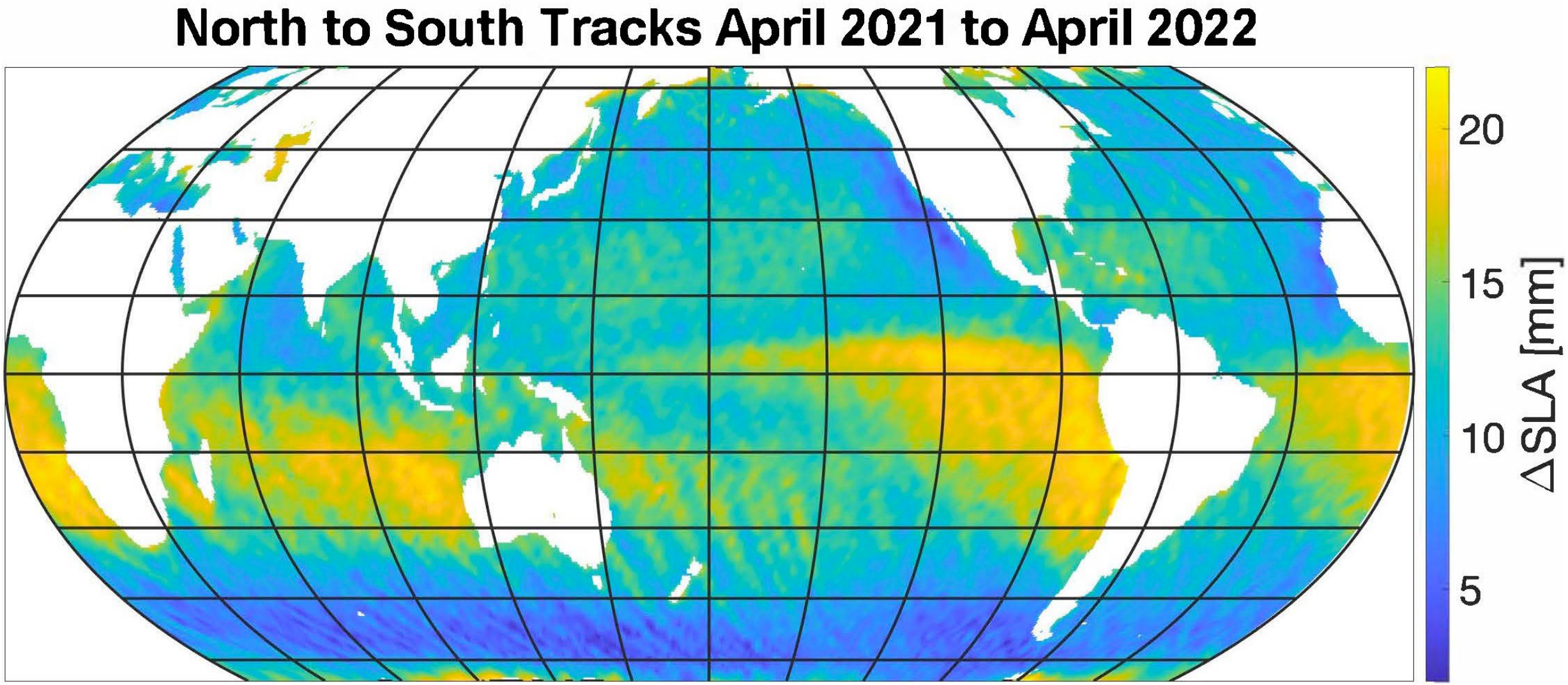
Spatial validation of the NOAA Global Ensemble Forecast System, version 12 GEFSv12 first 24h wave reforecast using altimeter data. Source: Campos, R. M., and Coauthors, 2024: Development and Validation of NOAA's 20-Year Global Wave Ensemble Reforecast. *Wea. Forecasting*, **39**, 1651–1672, https://doi.org/10.1175/WAF-D-24-0043.1.

Open Ocean – Operational Algorithm



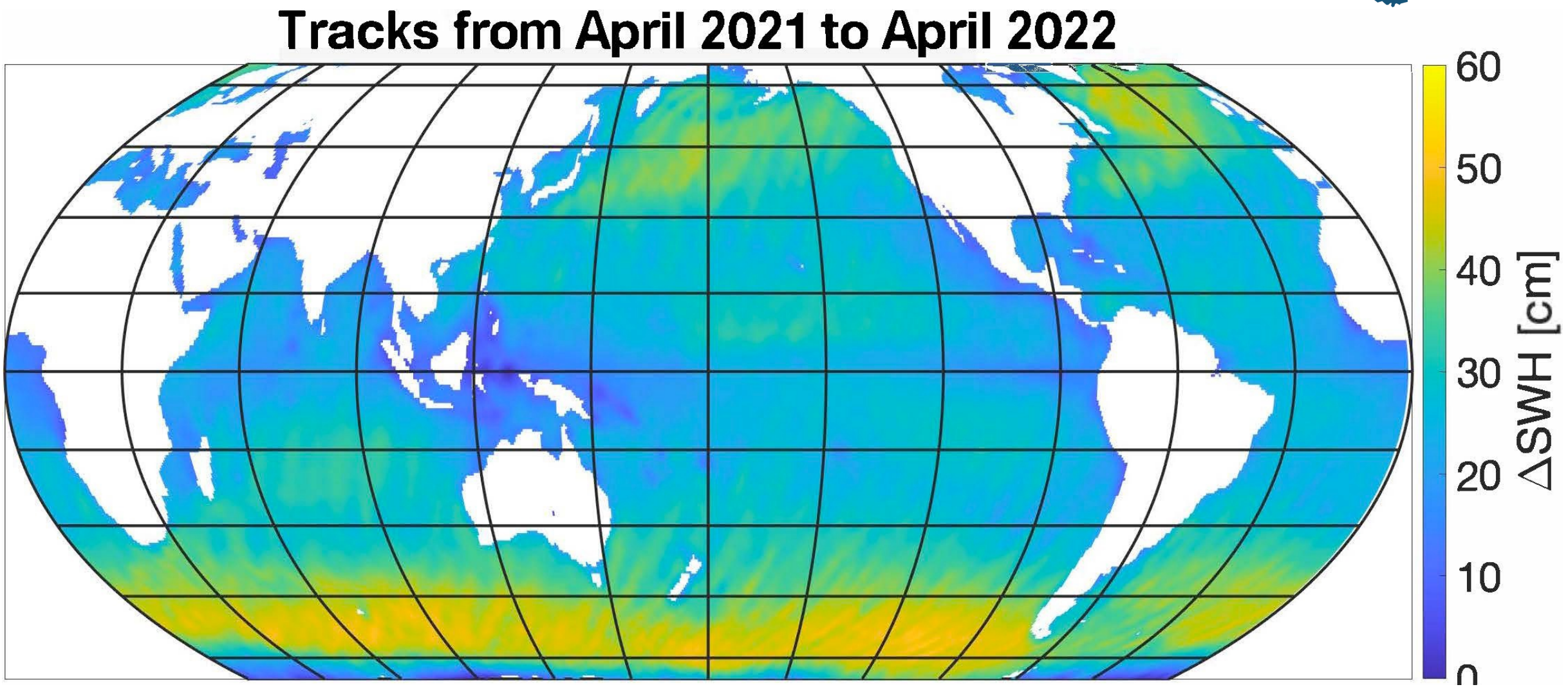
Sea level anomaly inconsistencies between Sentinel-6MF LRM and SAR altimetry for satellite tracks from south to north

Open Ocean – Operational Algorithm



Sea level anomaly inconsistencies between Sentinel-6MF LRM and SAR altimetry for satellite tracks from north to south

Open Ocean – Operational Algorithm



Significant wave height inconsistencies between Sentinel-6MF LRM and SAR altimetry

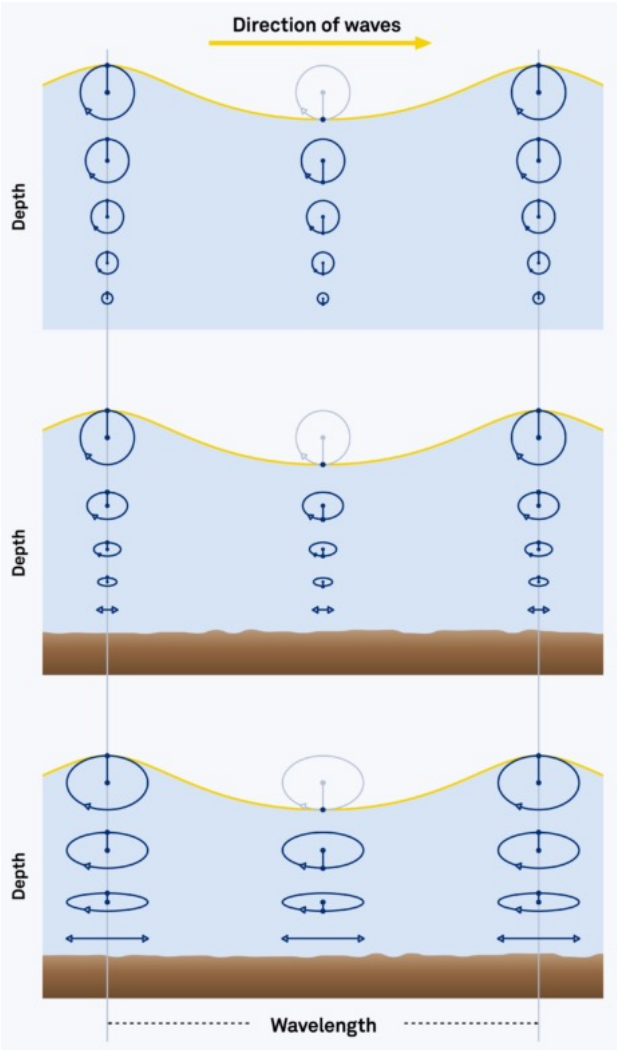
Open Ocean – Novel Algorithm

New Parameter derivable!!!

Standard Deviation of Vertical Wave Velocities (σ_v):

Related to mean zero up-crossing period: $T_{02} = \frac{\pi}{2} \frac{SWH}{\sigma_v}$

- captures wave dynamics beyond height
- Sea states dominated by higher-frequency energy produce:
  - Increased vessel motion and slamming
  - Elevated fatigue and safety risk
- Long-period swell may be high in amplitude, yet dynamically smoother
- Enables a more realistic assessment of coastal and reef impacts
- Improves forecasts of breaking, turbulence, and air–sea exchange



Wave orbital velocities describe different paths as a function of the relative water depth
Source: https://www.nortekgroup.com/knowledge-center/wiki/new-to-waves

Open Ocean – Novel Algorithm

New Parameter derivable!!!

Mean line-of-sight velocity (u_x):

- Main component related with wind-speed along-track component
- Improves interpretation of surface conditions relevant to navigation and operations
- Provides context for air–sea momentum exchange and surface mixing
- Supports assessment of near-surface habitat conditions, larval transport, and reef exposure

WND	10-m wind speed
HS	Significant wave height
FP	Peak frequency
T01	Mean wave period (Tm0, 1)
T02	Mean wave period (Tm0, 2)
DIR	Mean wave direction
DP	Peak wave direction
SPR	Mean directional spread
PHS	Partitioned wave heights
PTP	Partitioned peak period
PDIR	Partitioned mean direction

Wave variables of field outputs generated for the 20-yr GEFSv12 wave reforecast.
Parameters retrievable by radar altimetry are highlighted in red (LRM) and orange (SAR).
Source: Campos, R. M., and Coauthors, 2024: Development and Validation of NOAA's 20-Year Global Wave Ensemble Reforecast. *Wea. Forecasting*, 39, 1651–1672, https://doi.org/10.1175/WAF-D-24-0043.1.

Open Ocean - Results

Results presented here are generated with TERP-SAR

- Published and can be downloaded from MathWorks File exchange
- Idea: Create your own level-2 product!
- Contains a variation of geophysical parameter retrieval algorithms

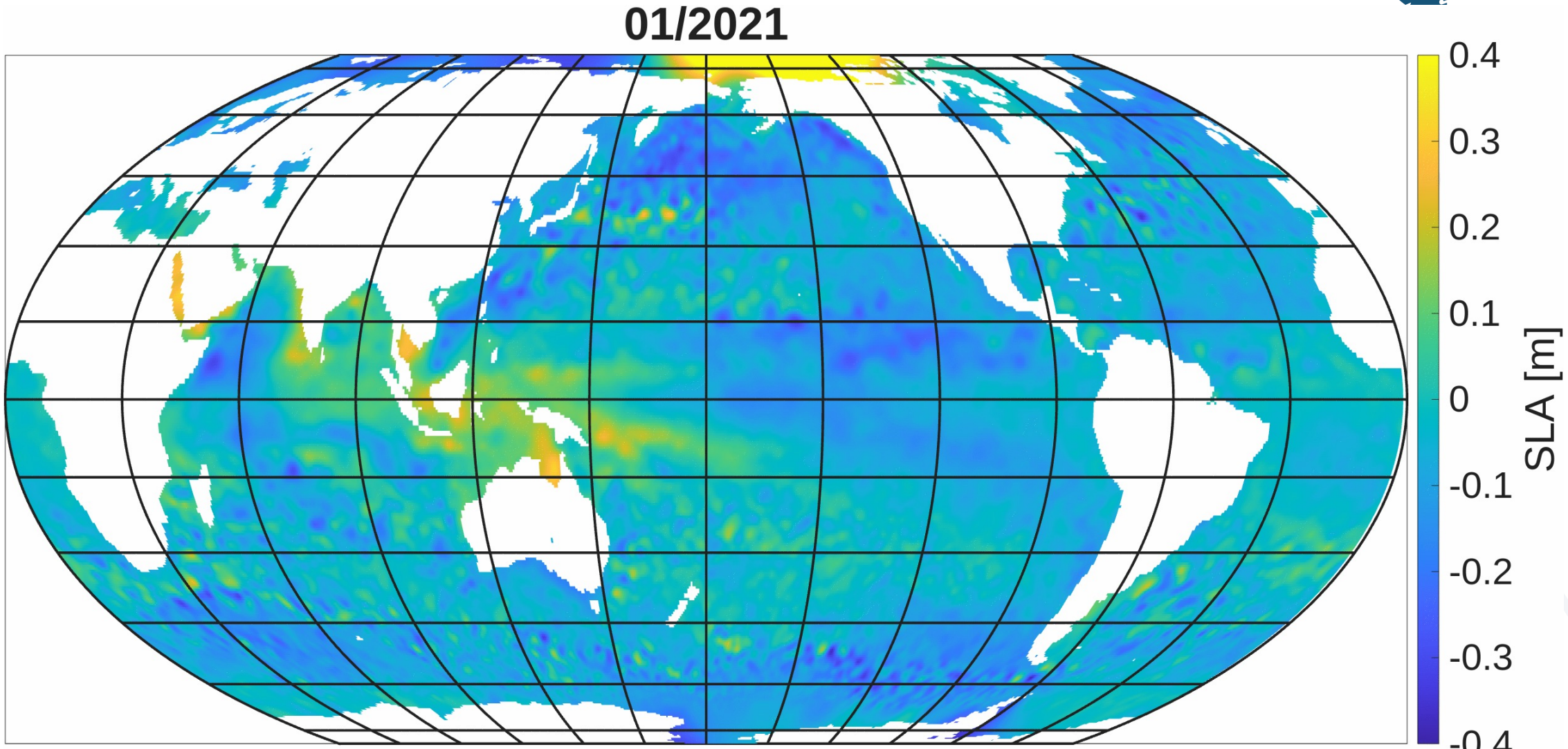
Novel algorithm

- Wind speed 10 m above sea level
- Improved Sea level anomaly
- Improved Significant Wave Height
- STD of observational vertical wave motion σ_v
- Mean line-of-sight velocity u_x

Operational algorithm

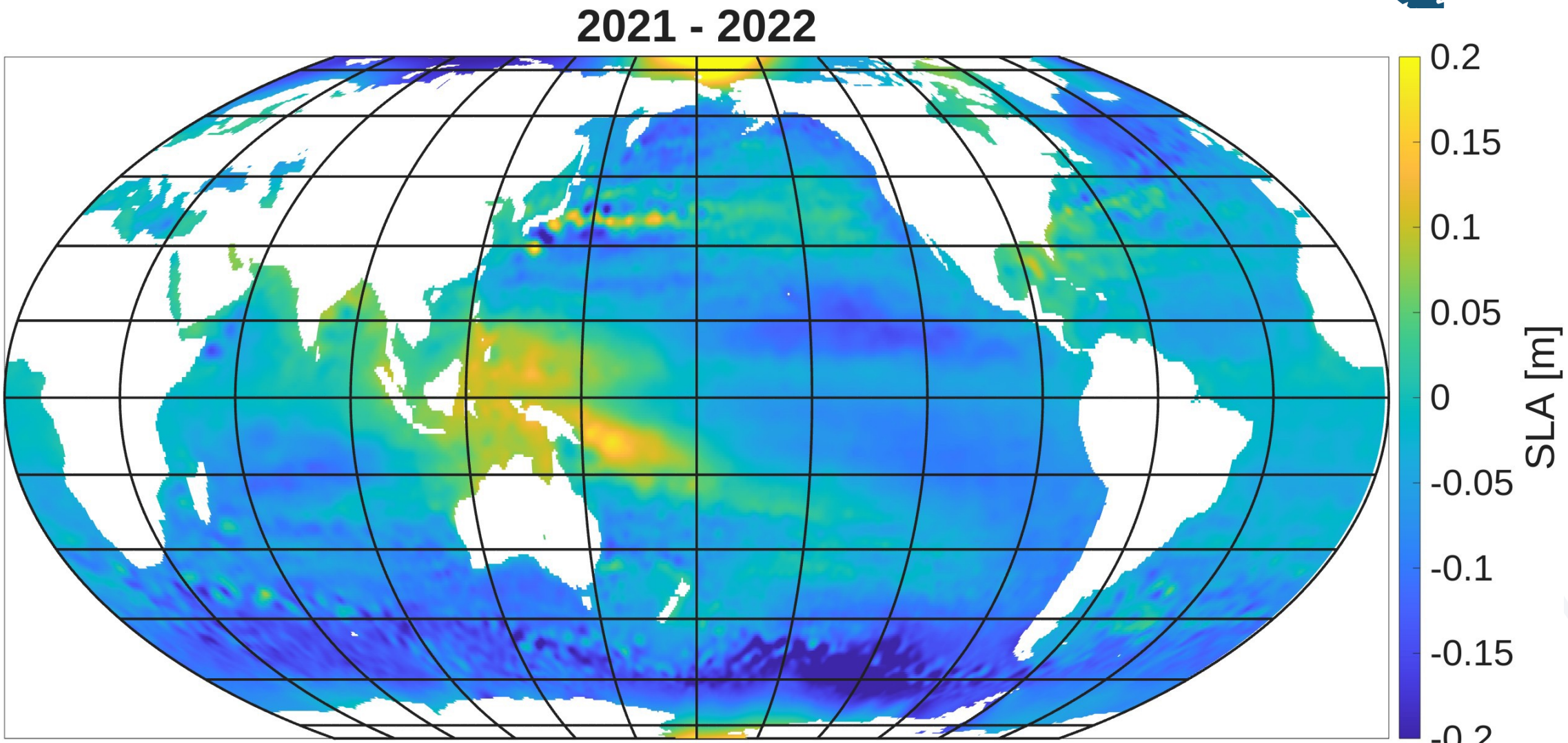
- Wind speed 10 m above sea level
- Sea level anomaly
- Significant Wave Height

Open Ocean - Results



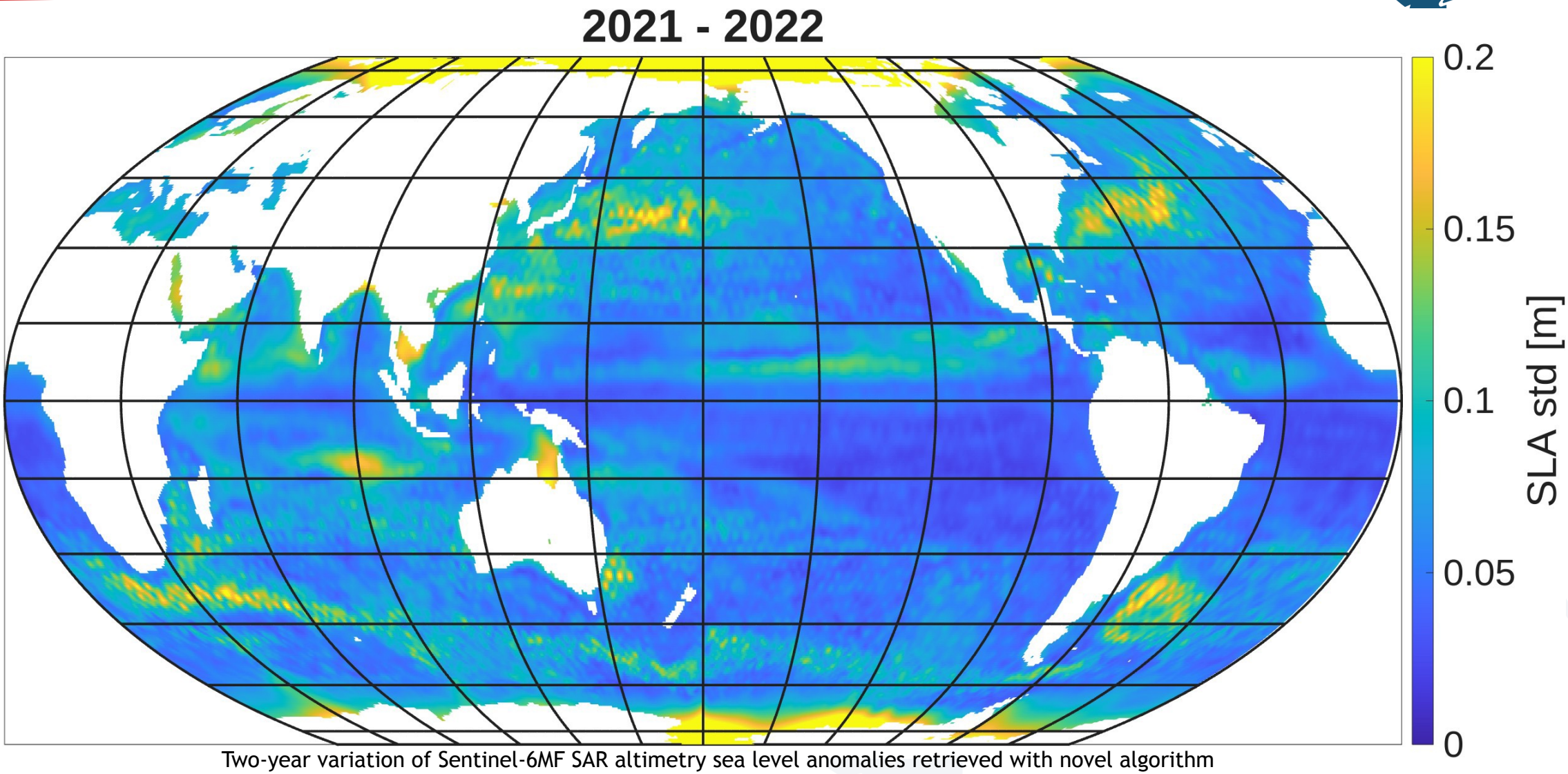
Monthly averaged Sentinel-6MF SAR altimetry sea level anomalies retrieved with novel algorithm

Open Ocean - Results



Two-year averaged Sentinel-6MF SAR altimetry sea level anomalies retrieved with novel algorithm

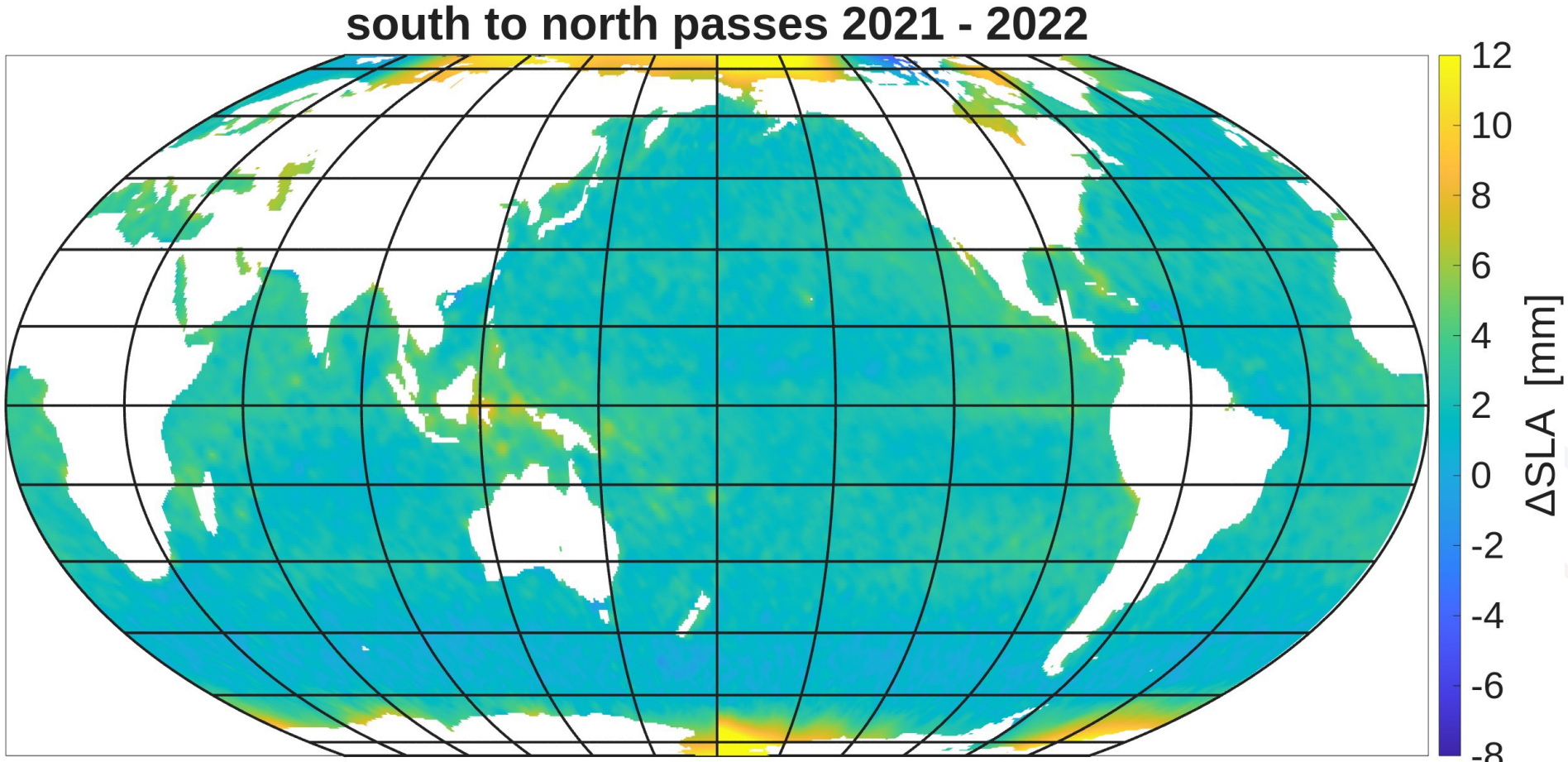
Open Ocean - Results



Two-year variation of Sentinel-6MF SAR altimetry sea level anomalies retrieved with novel algorithm

Open Ocean - Results

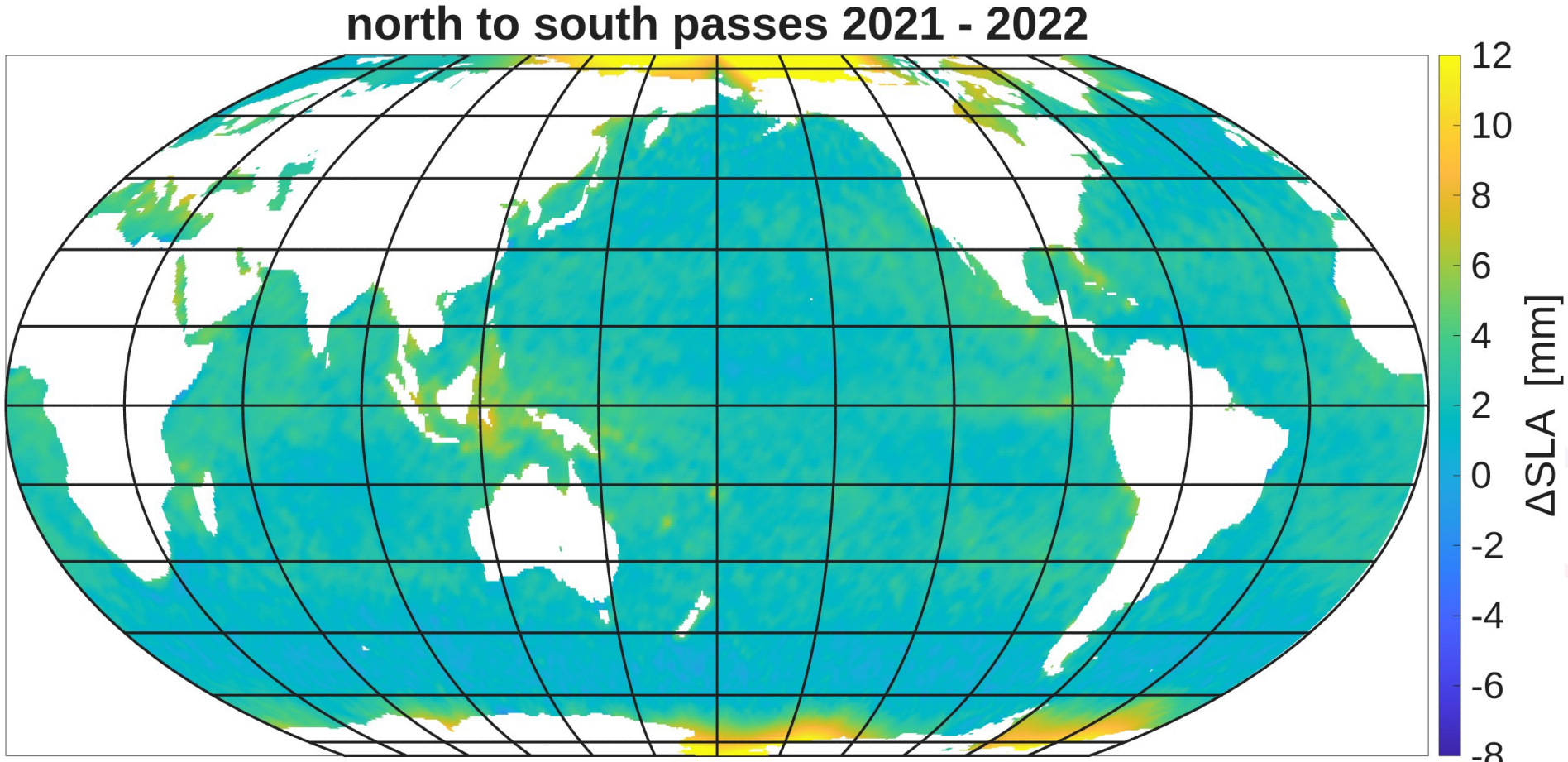
Novel SAR altimetry algorithm provides consistent sea level anomalies!



Mean sea level anomaly differences between LRM and SAR over the years 2021 and 2022 for south to north passes.

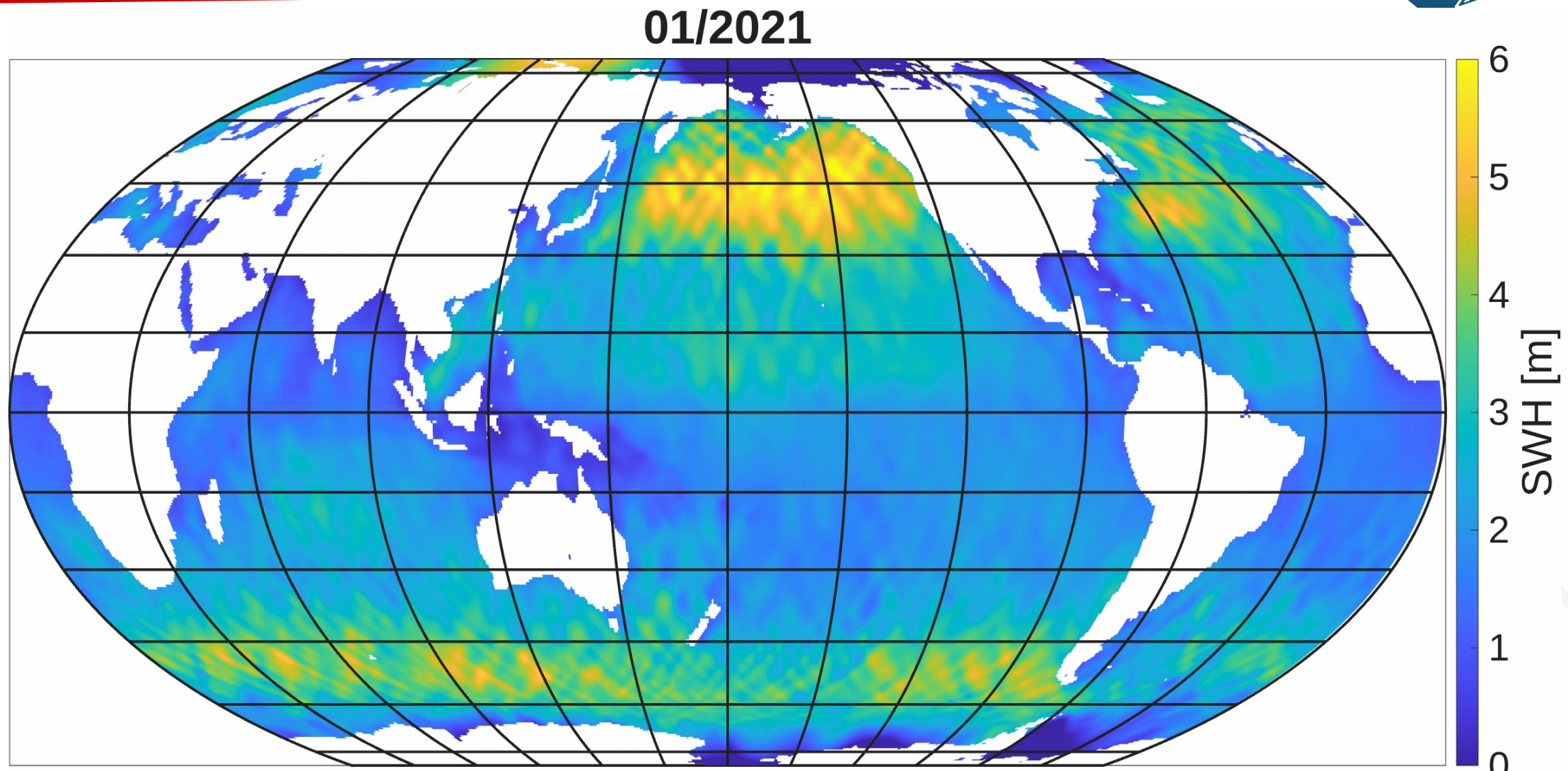
Open Ocean - Results

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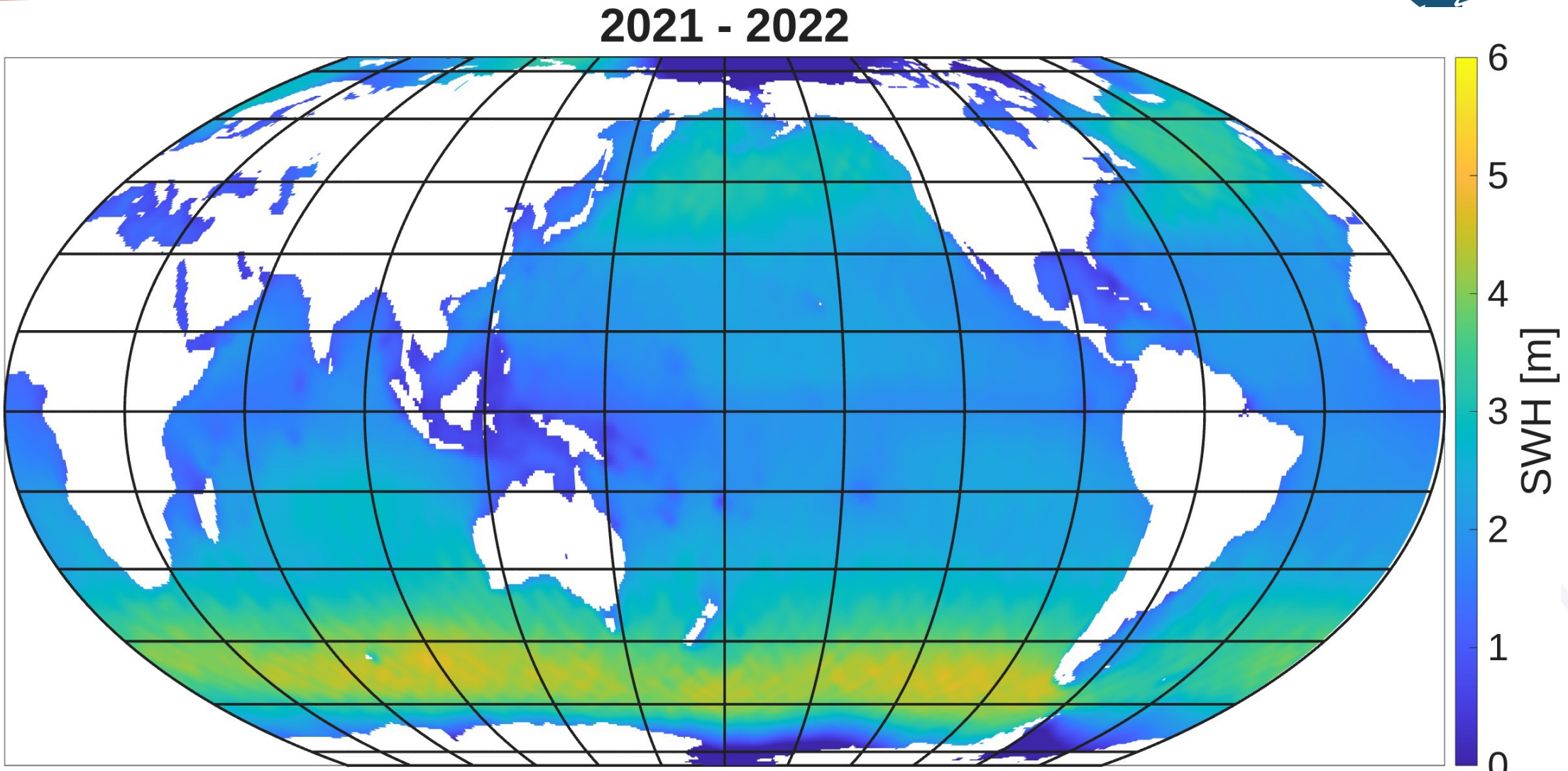
Mean sea level anomaly differences between LRM and SAR over the years 2021 and 2022 for north to south passes.

Open Ocean - Results



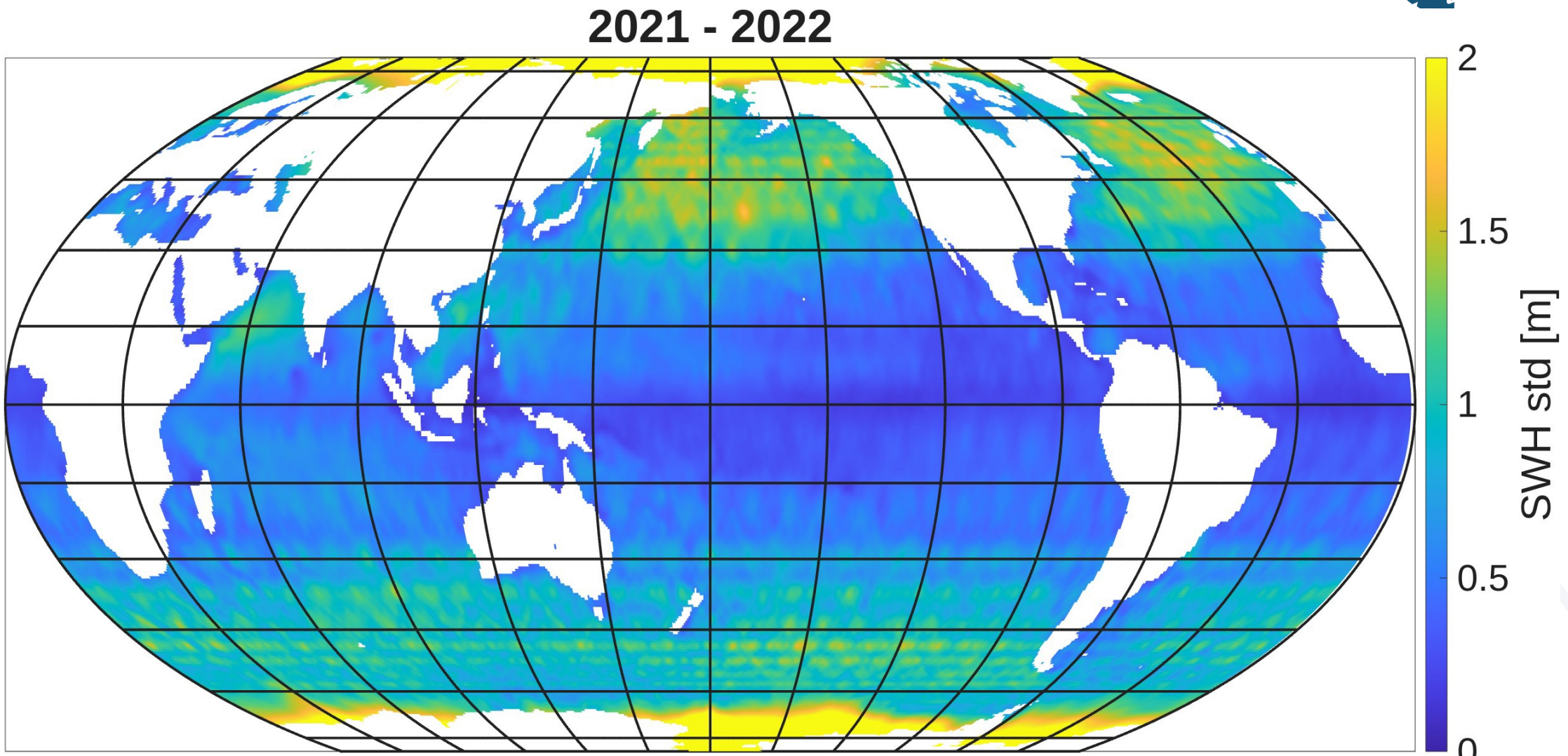
Monthly averaged Sentinel-6MF SAR altimetry significant wave heights retrieved with novel algorithm

Open Ocean - Results



Two-year averaged Sentinel-6MF SAR altimetry significant wave heights retrieved with novel algorithm

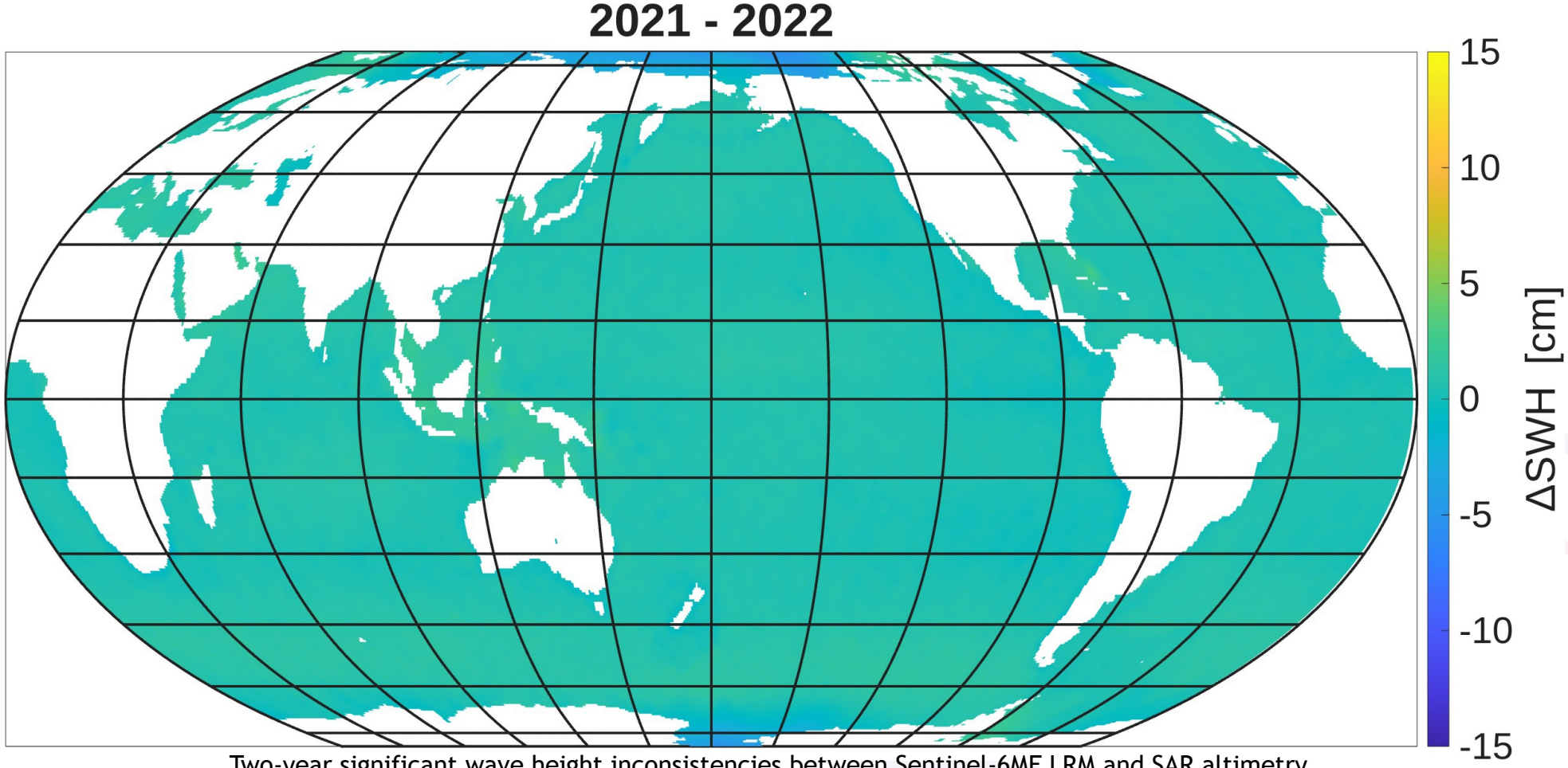
Open Ocean - Results



Two-year variation of Sentinel-6MF SAR altimetry significant wave heights retrieved with novel algorithm

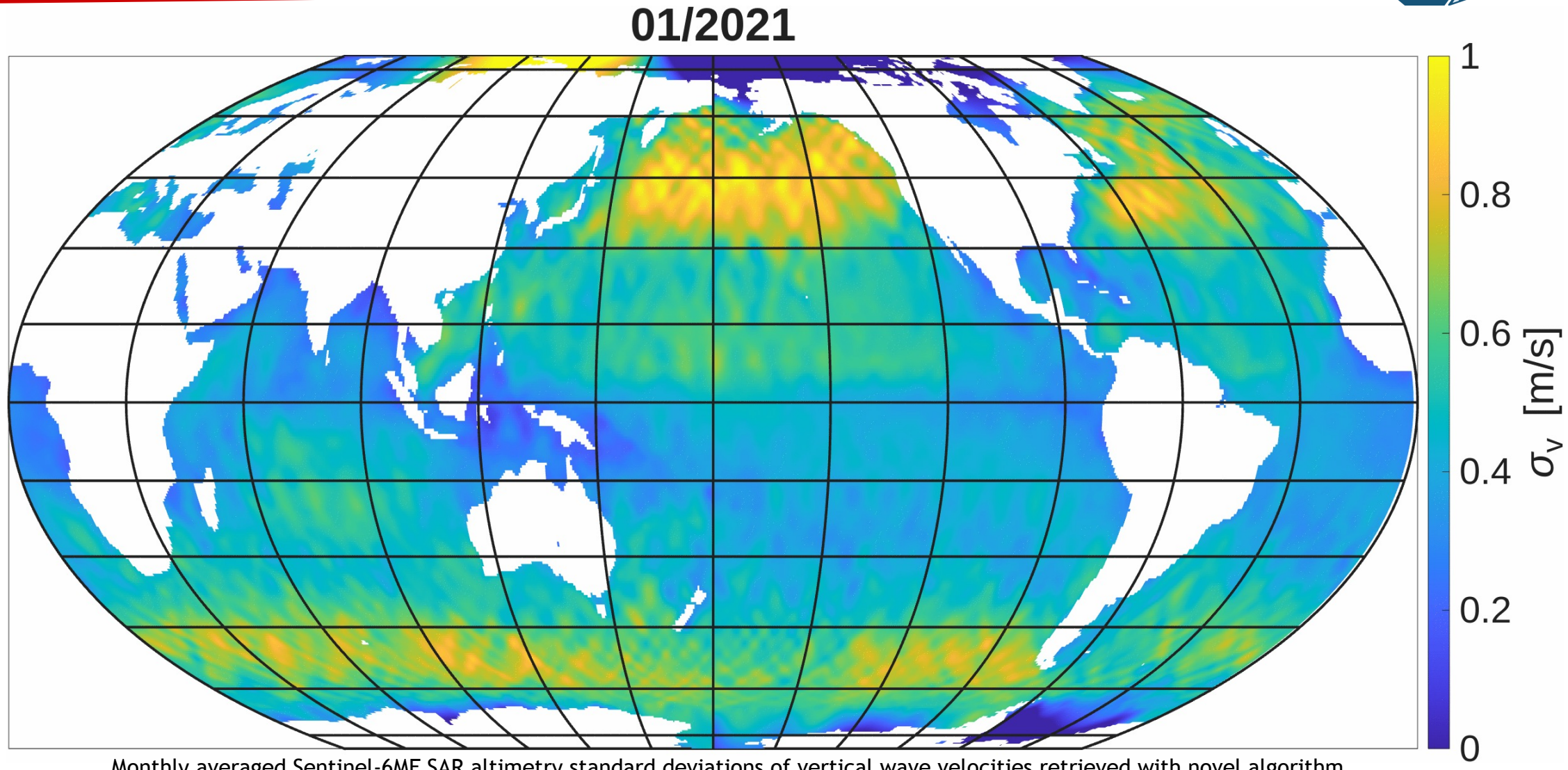
Open Ocean - Results

Novel SAR altimetry algorithm provides consistent sea level anomalies!



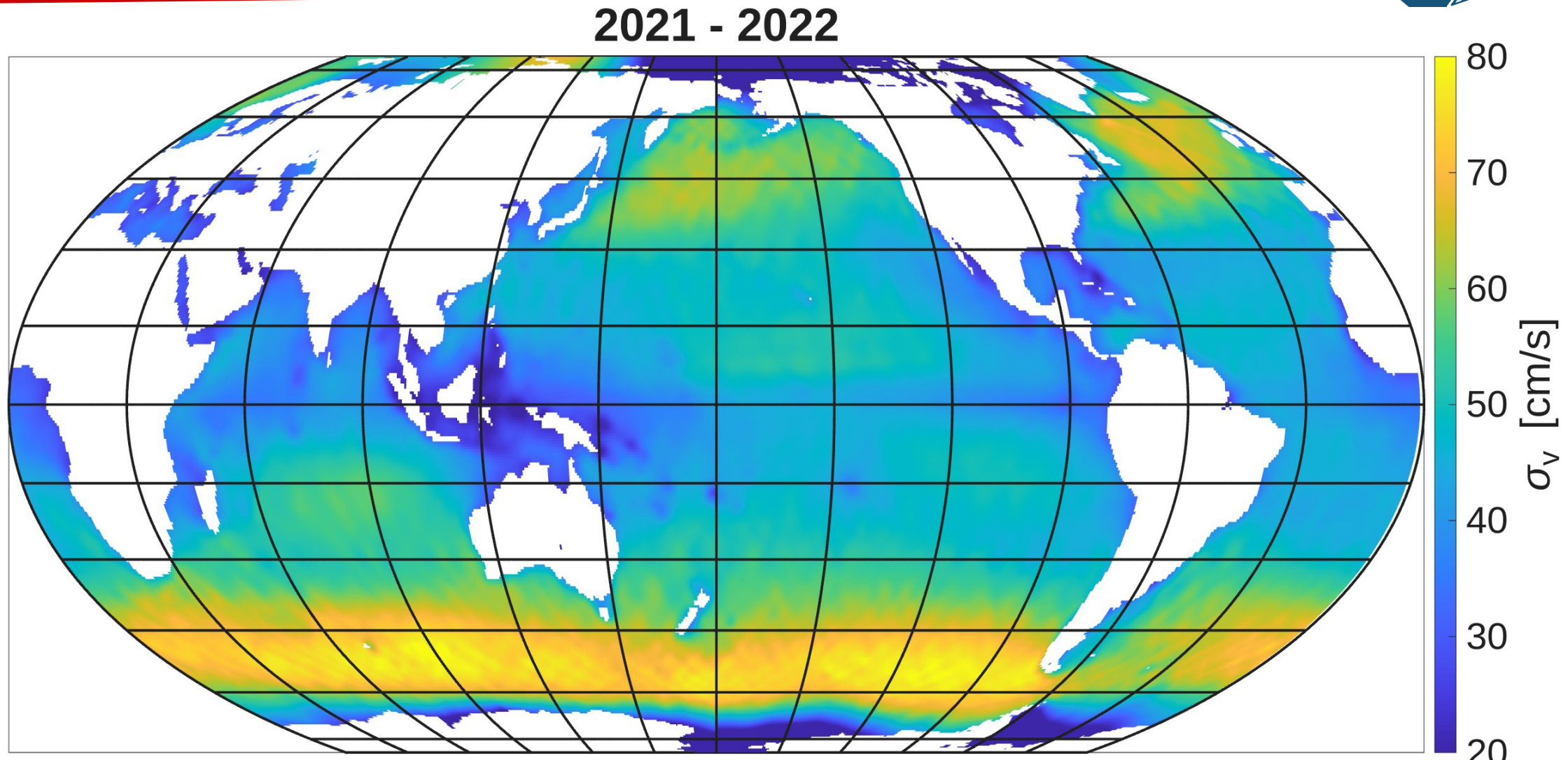
Two-year significant wave height inconsistencies between Sentinel-6MF LRM and SAR altimetry

Open Ocean - Results



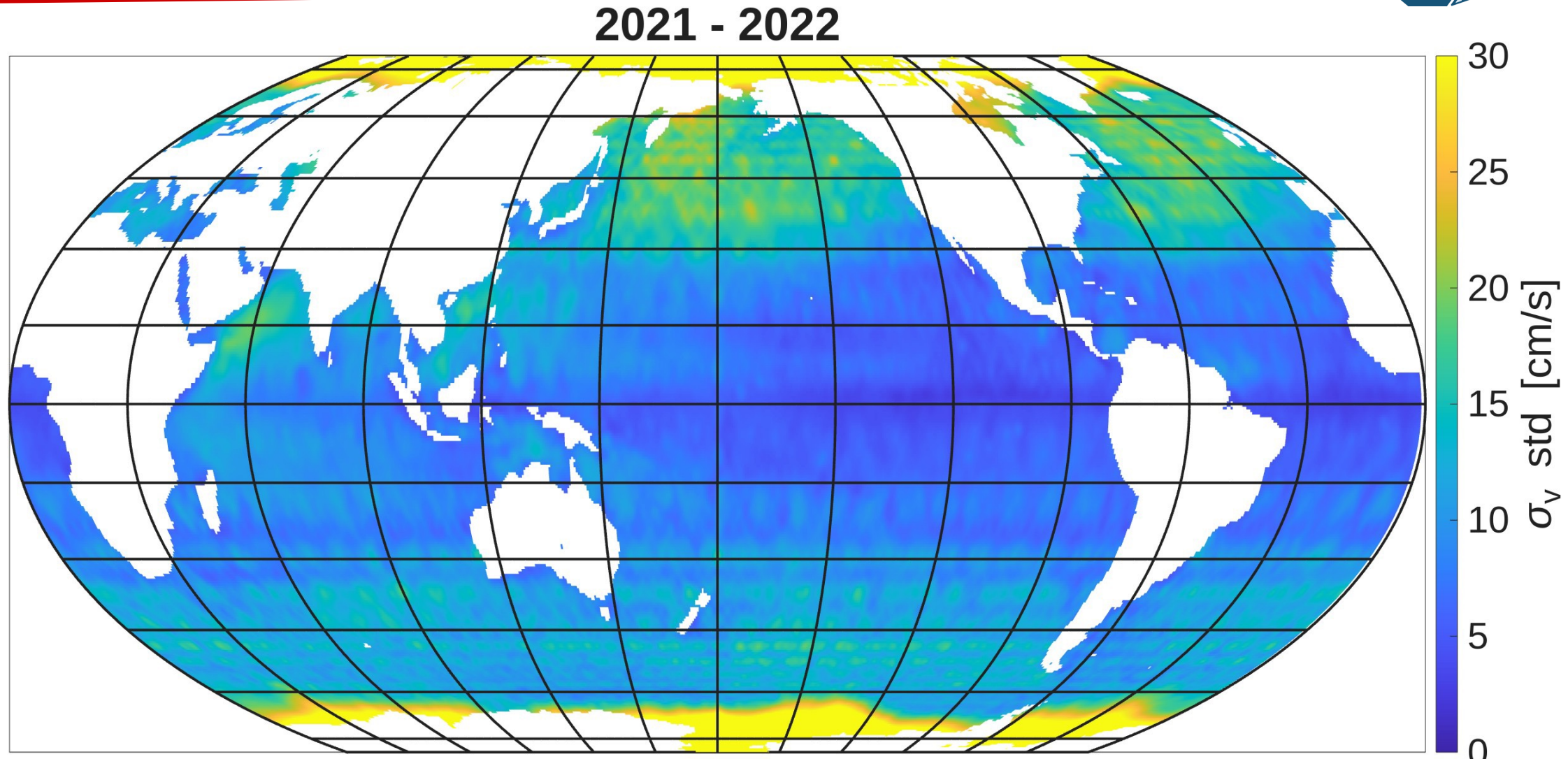
Monthly averaged Sentinel-6MF SAR altimetry standard deviations of vertical wave velocities retrieved with novel algorithm

Open Ocean - Results



Two-year averaged Sentinel-6MF SAR standard deviations of vertical wave velocities retrieved with novel algorithm

Open Ocean - Results

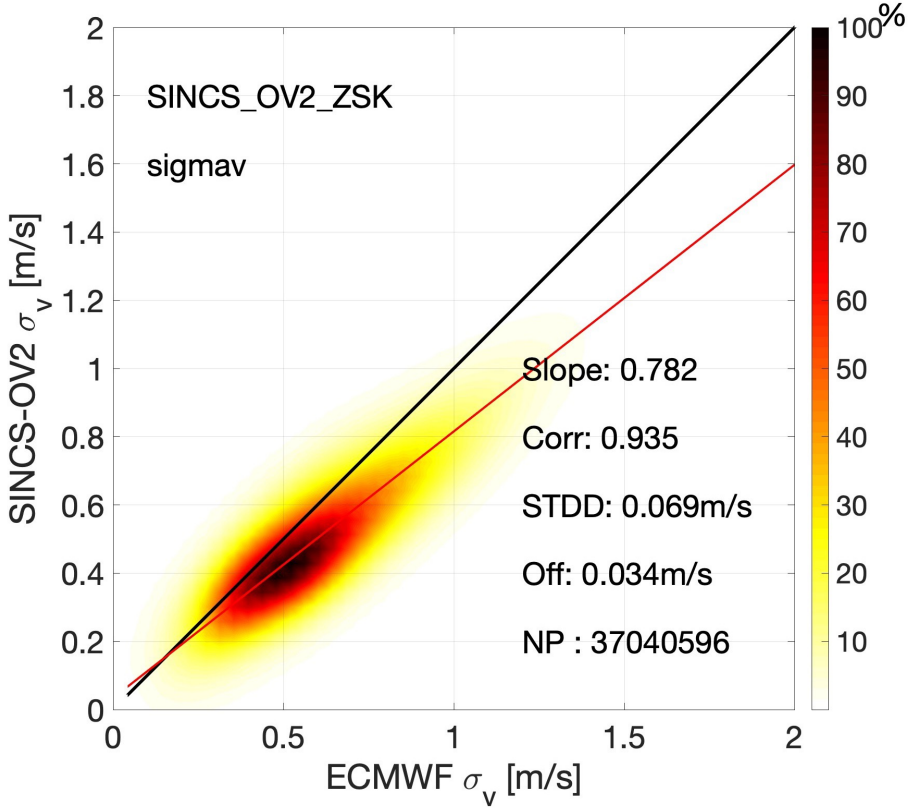


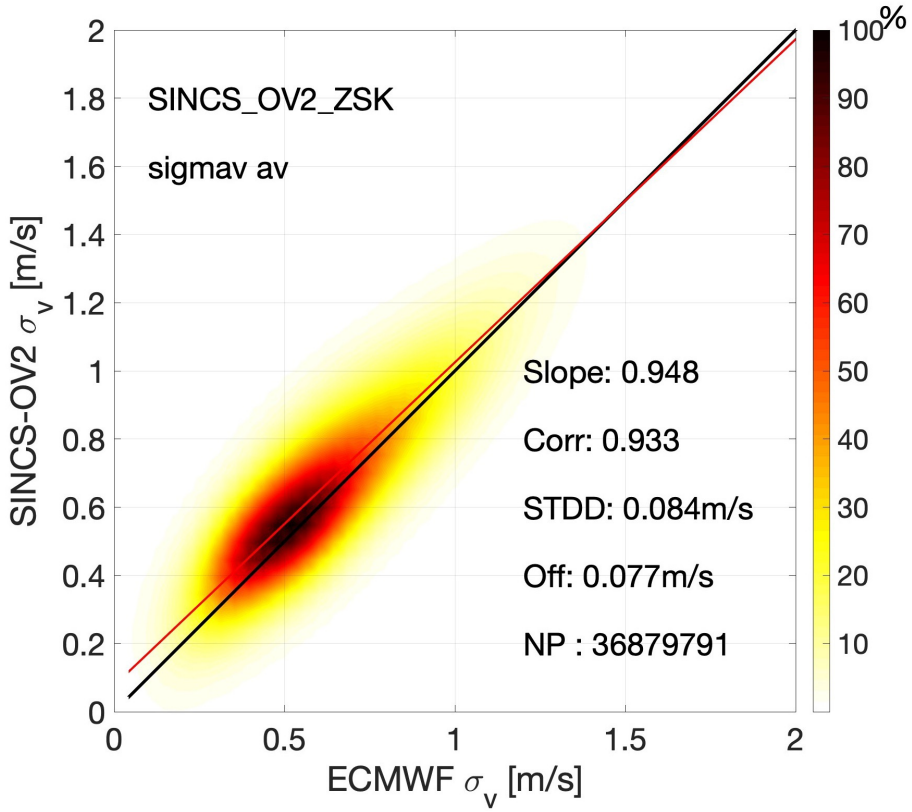
Two-year variation of Sentinel-6MF SAR standard deviations of vertical wave velocities retrieved with novel algorithm

Open Ocean - Results

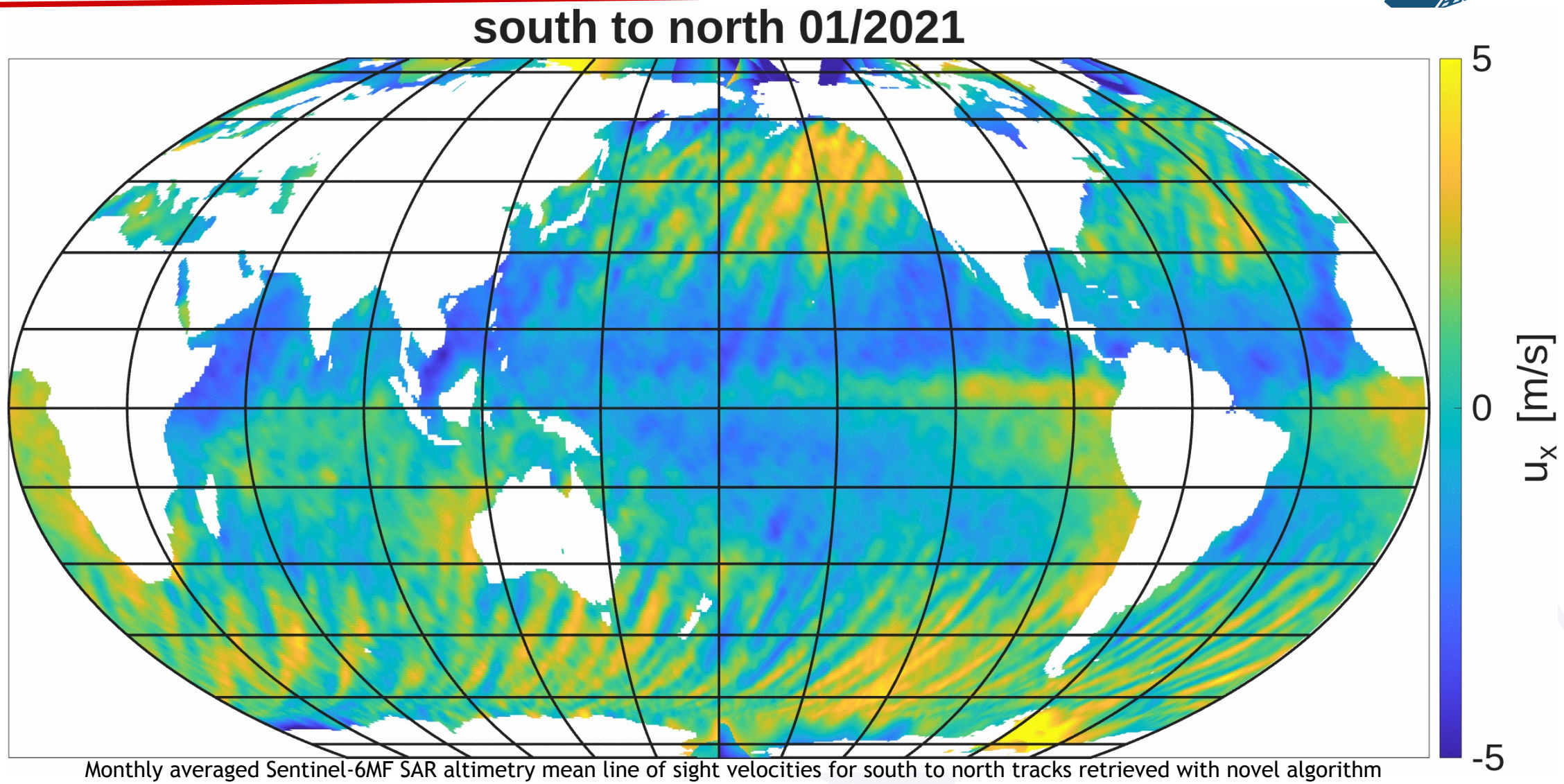
Left: Observable standard deviations of vertical wave motion

Right: Vertical wave motions corrected for vertical motion/slope correlations



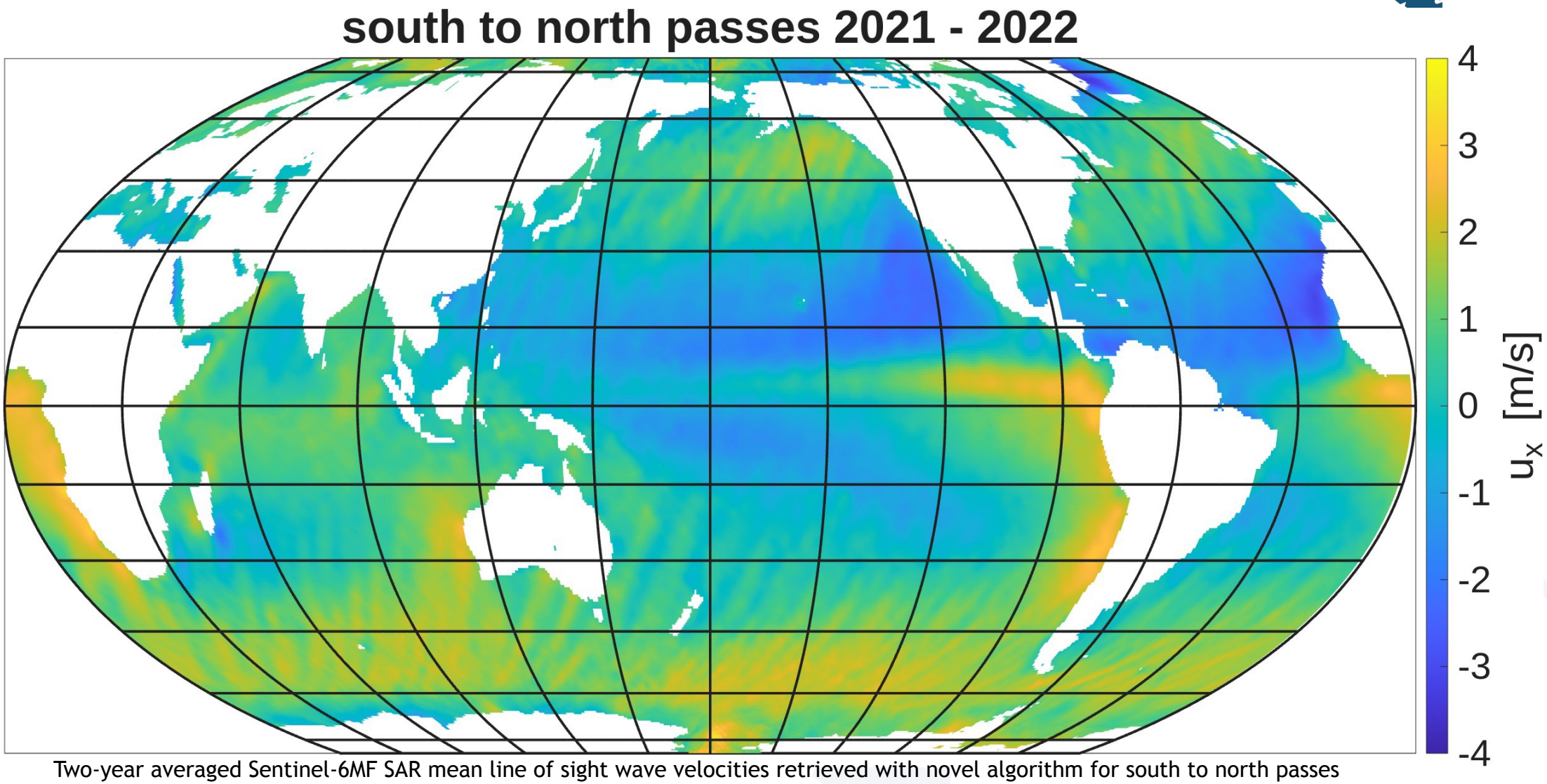


Open Ocean - Results



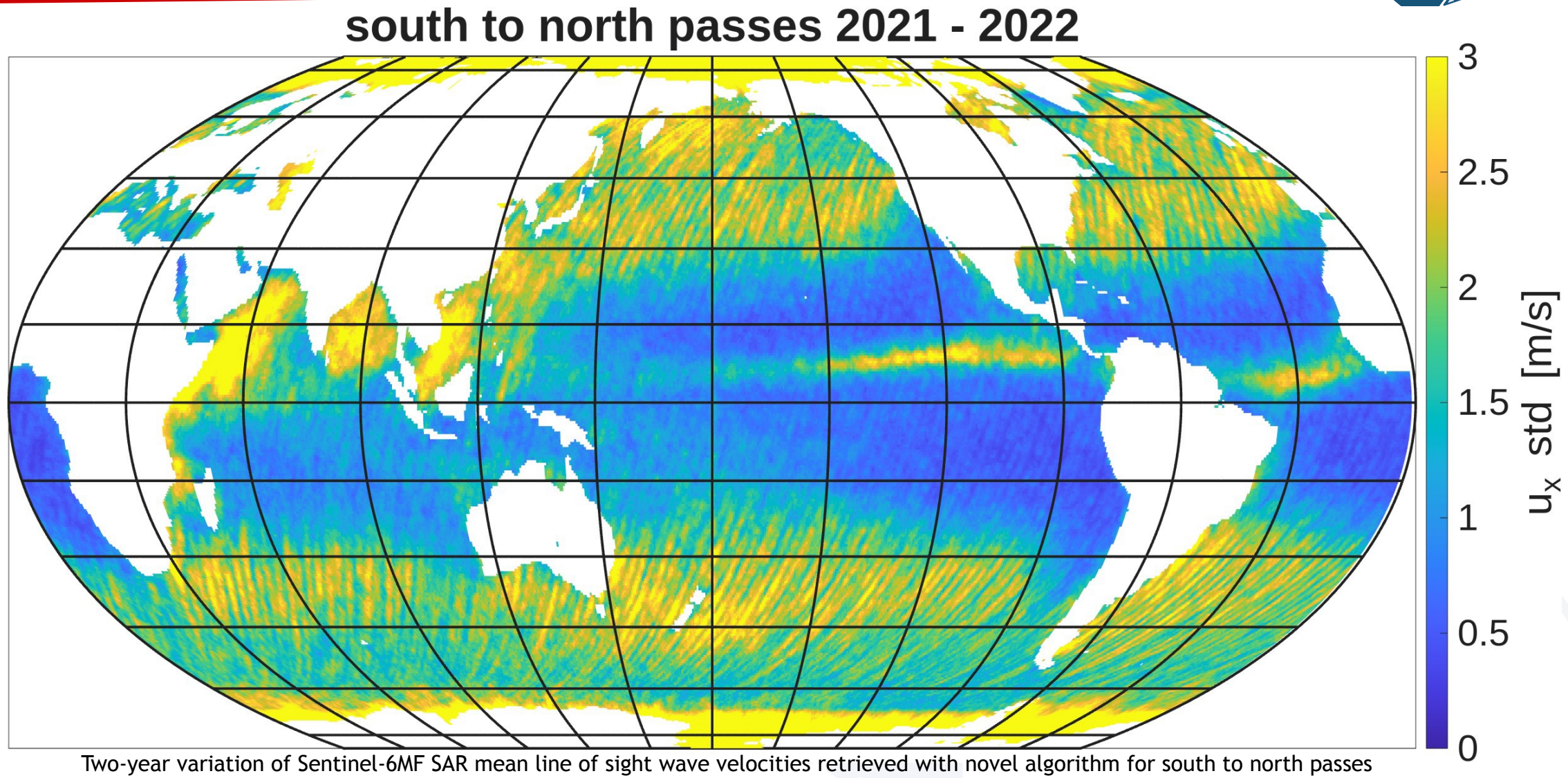
Monthly averaged Sentinel-6MF SAR altimetry mean line of sight velocities for south to north tracks retrieved with novel algorithm

Open Ocean - Results



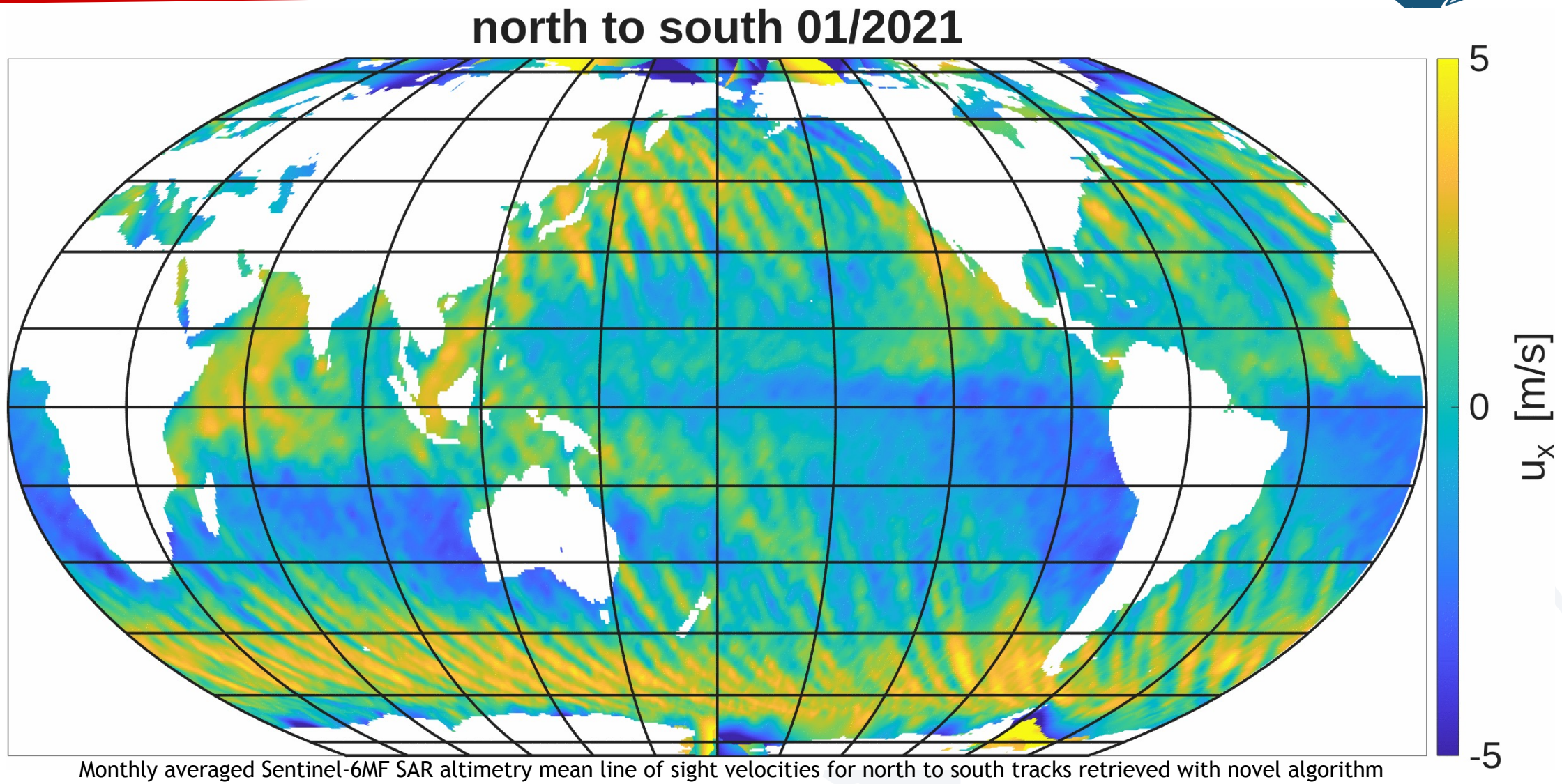
Two-year averaged Sentinel-6MF SAR mean line of sight wave velocities retrieved with novel algorithm for south to north passes

Open Ocean - Results



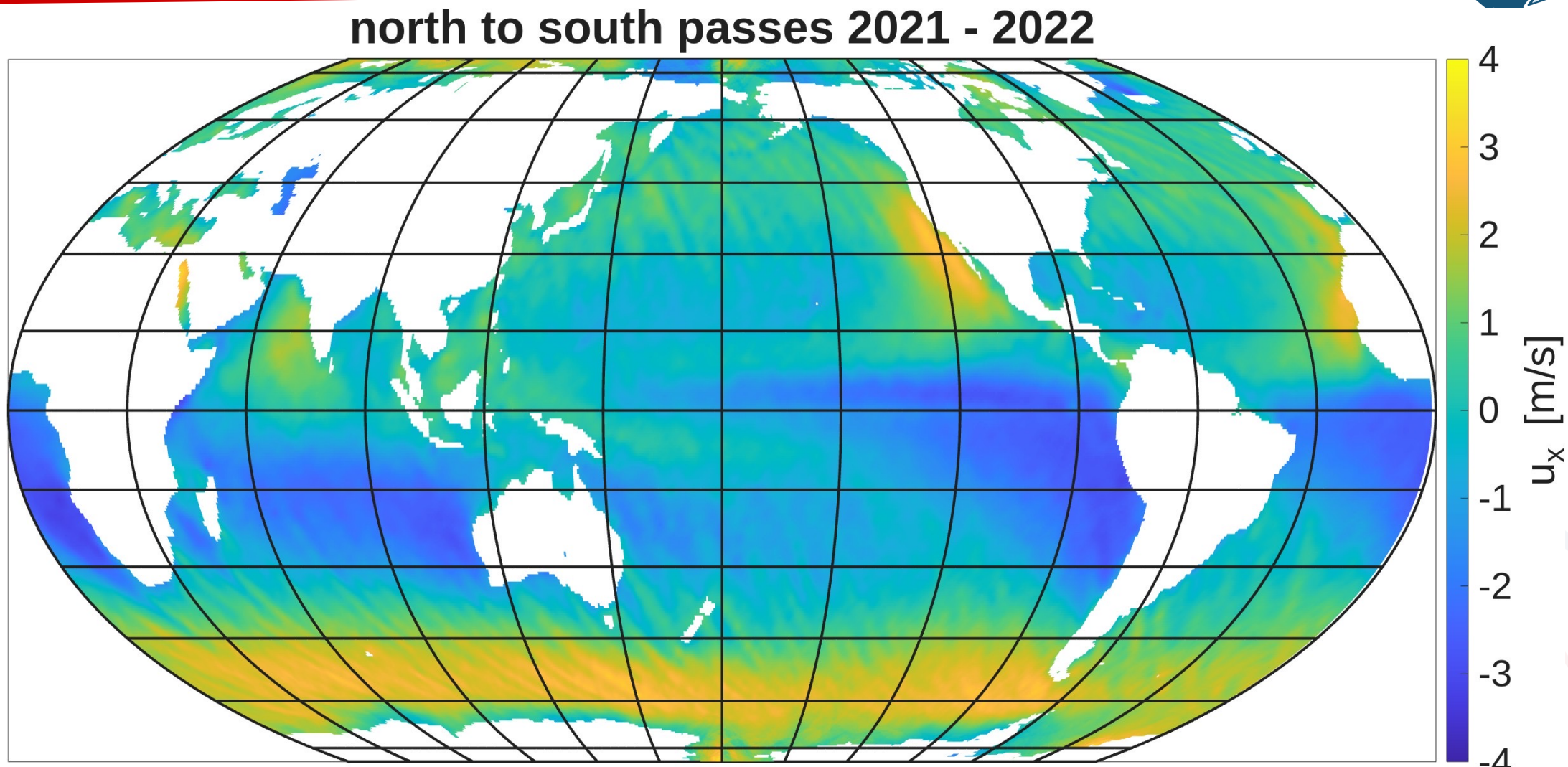
Two-year variation of Sentinel-6MF SAR mean line of sight wave velocities retrieved with novel algorithm for south to north passes

Open Ocean - Results



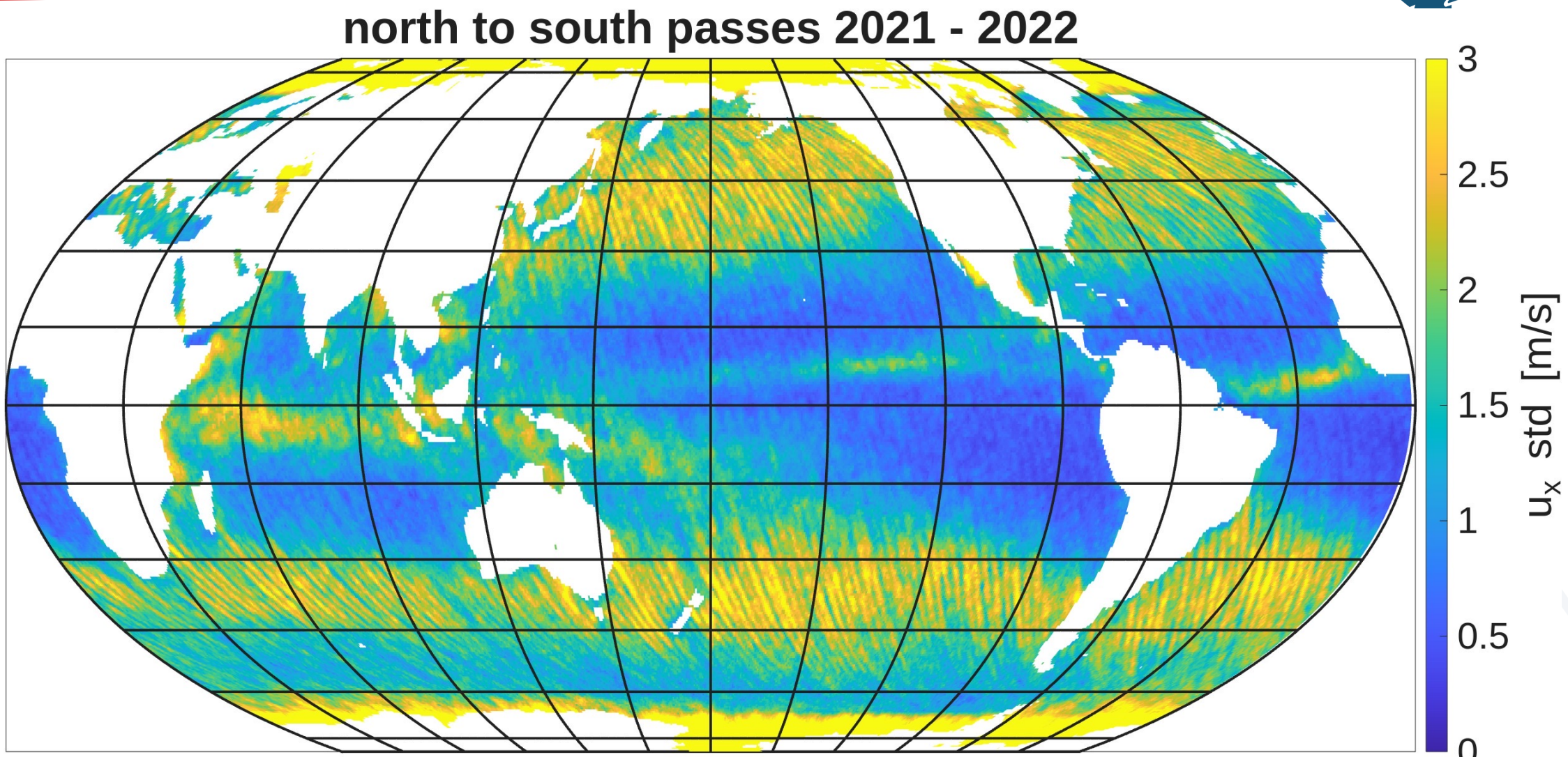
Monthly averaged Sentinel-6MF SAR altimetry mean line of sight velocities for north to south tracks retrieved with novel algorithm

Open Ocean - Results



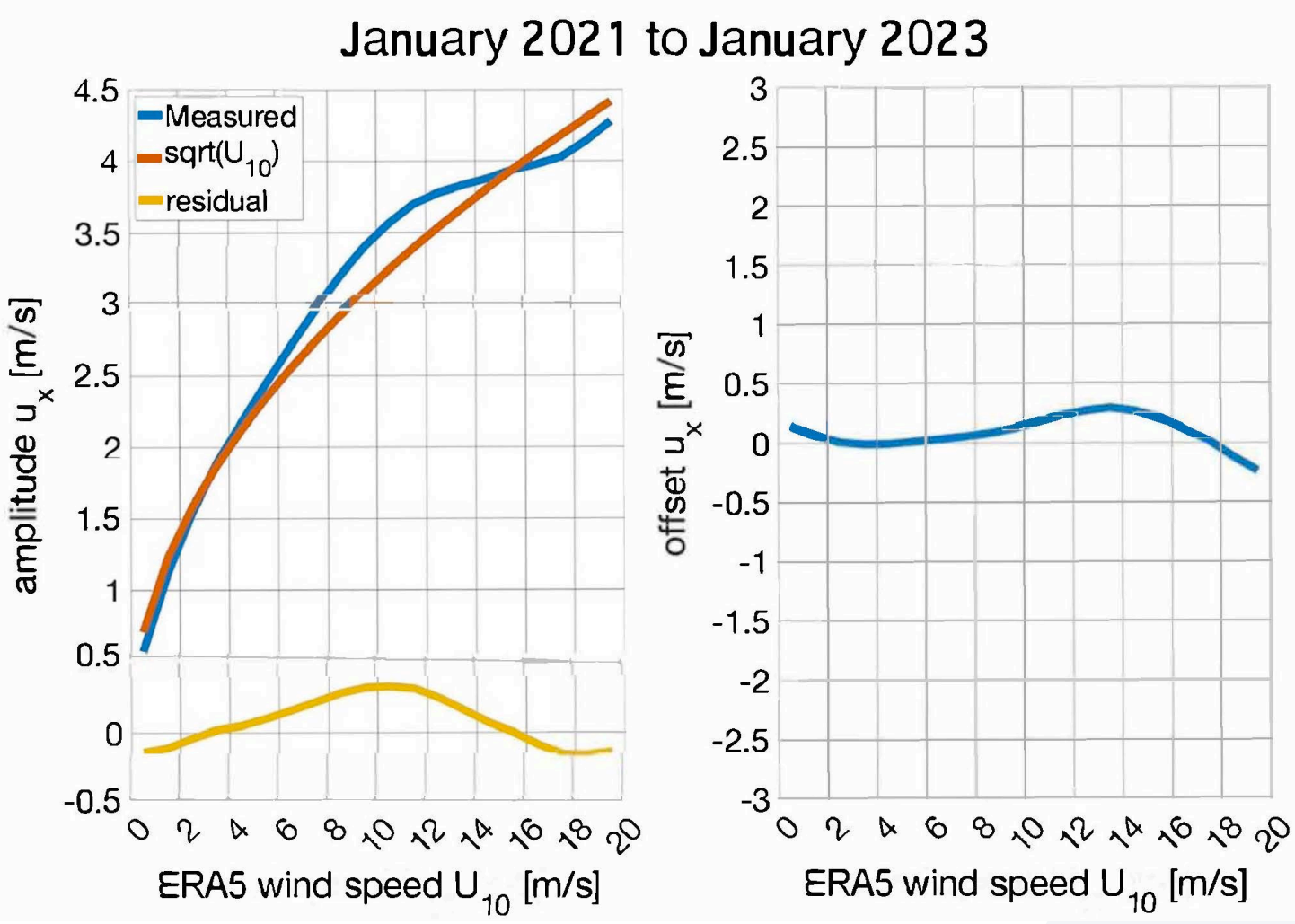
Two-year averaged Sentinel-6MF SAR mean line of sight wave velocities retrieved with novel algorithm for north to south passes

Open Ocean - Results



Two-year variation of Sentinel-6MF SAR mean line of sight wave velocities retrieved with novel algorithm for north to south passes

Open Ocean - Results



Fitting measured u_x with
$u_x = amplitude \cdot \cos(\theta_{sat} - \theta_{wind}) + offset$
for each ERA5 wind-speed from 0 m/s to 20 m/s

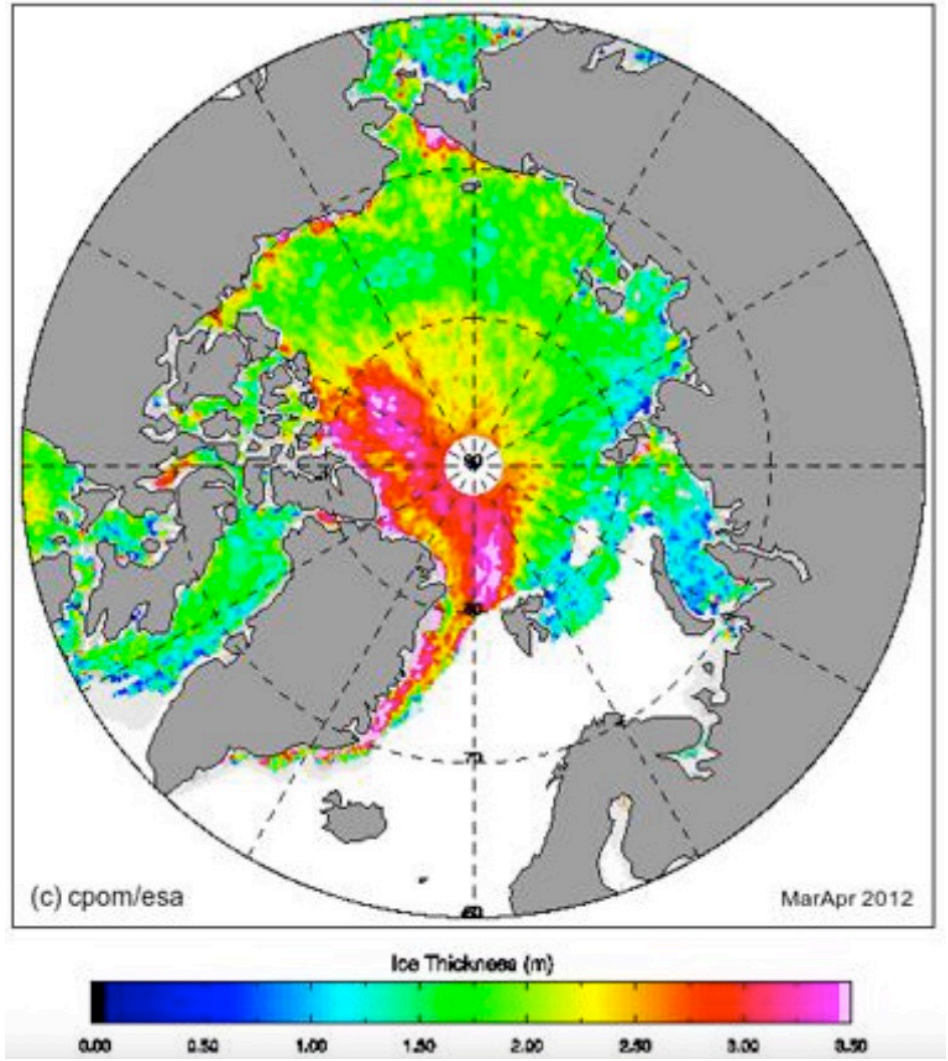
This revealed that:

- The amplitude follows approximately the square root of the wind-speed 10 m above sea level.
- The offset is (besides a bias already corrected) constant.

Snow-Covered Sea Ice

Sea Ice - Introduction

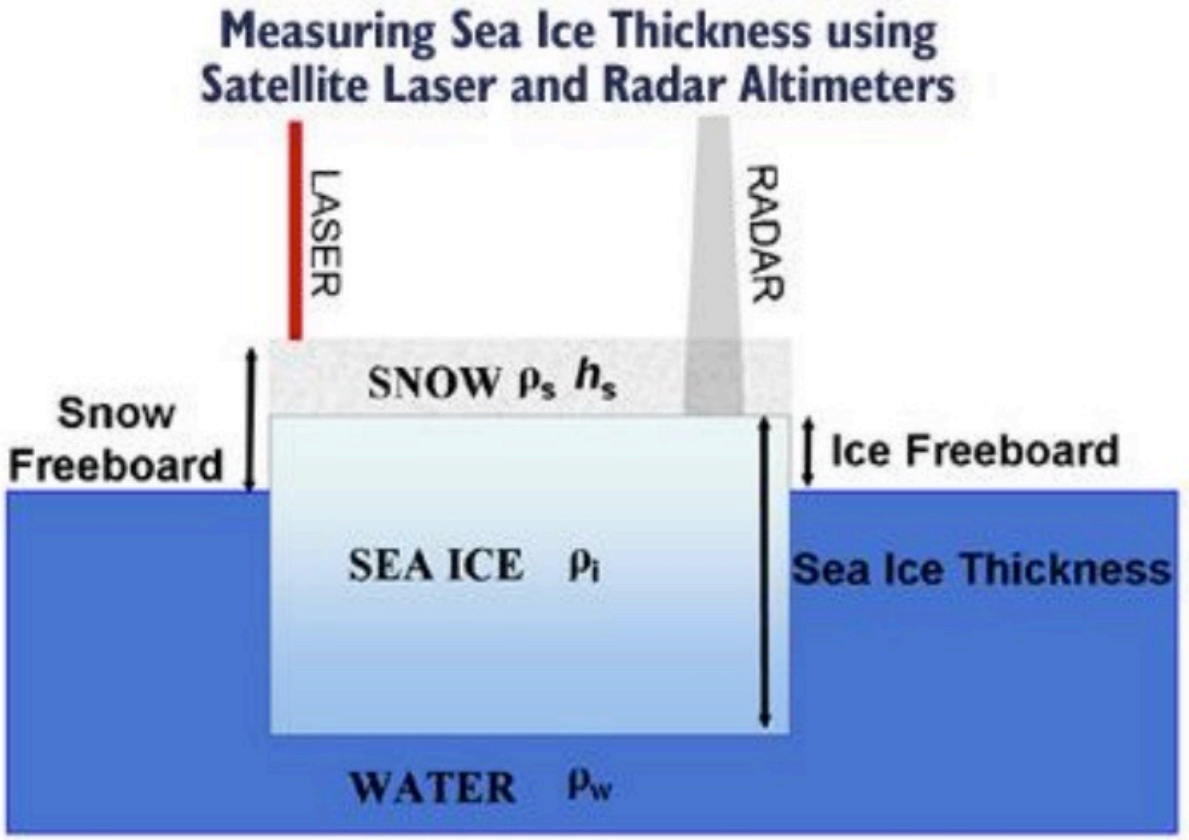
- Sea ice parameters of interest are usually
  - Radar freeboard (snow/ice interface)
  - Laser freeboard (air/snow interface)
  - Lead positions (distinguishable from melting ponds)
- Those parameters can then be used to determine the thickness of sea-ice
- Secondary parameters of interest
  - Snow/ice interface roughness
  - Air/snow and snow/ice backscattering



Sea Ice Thickness over Arctic
Source: Radar Altimetry Tutorial

Sea Ice - Introduction

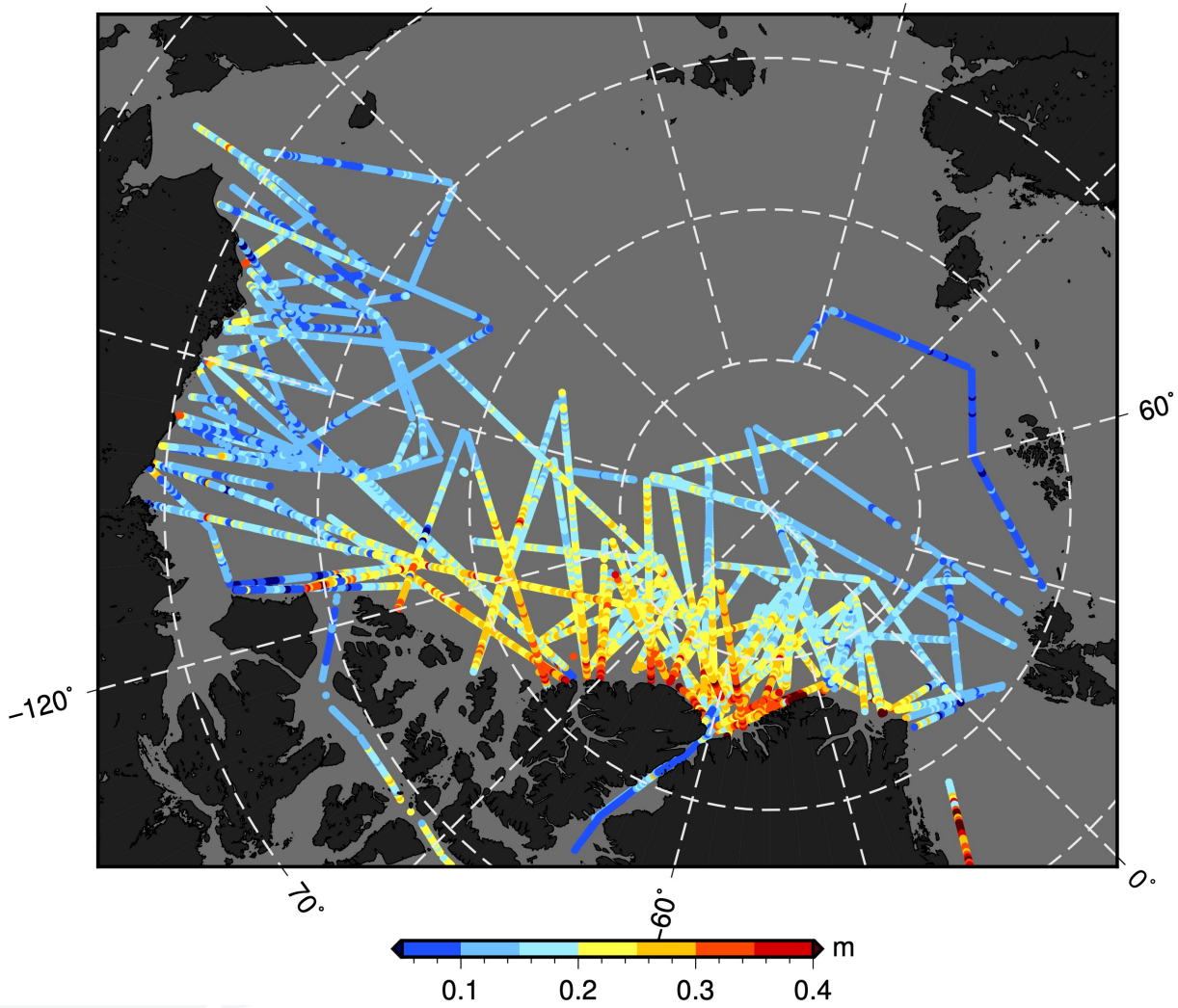
- The estimation of sea ice thickness requires the ice freeboard and the snow freeboard
- Freeboards are with respect to the sea level, which is determined by the elevation of close by leads
- Challenges
  - Off nadir leads let the sea level appear deeper
  - Melt ponds look like leads, leading to an overestimation of sea level.
  - Snow and ice freeboard are estimated by different instruments
- Let's see if a novel algorithm can help!



Sea Ice Thickness Derivation; Source: Radar Altimetry Tutorial

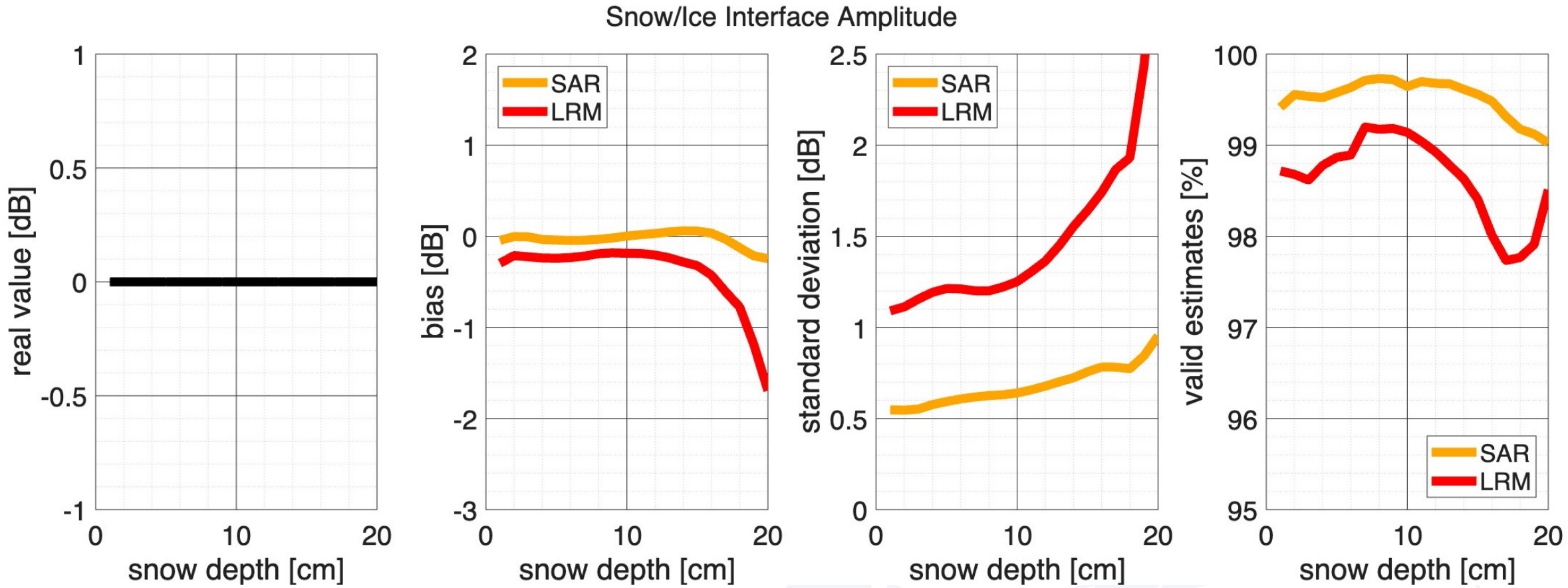
Sea Ice – Proof of Concept

- To test the potential of SAR altimetry, Monte Carlo Simulations were performed
- 20 snow depth realizations were defined ranging from 1 cm to 20 cm
- Ice roughness of snow amplitude depend on snow depth (assumption made here)
- Ice elevation, amplitude, Bi and Ci constant
- For each snow depth realization 10,000 exponential distributed SAR altimetry signals are simulated and processed by
  - LRM altimetry algorithm
    - No snow depth estimation possible
  - SAR altimetry algorithm
    - Snow depth estimation possible and tested

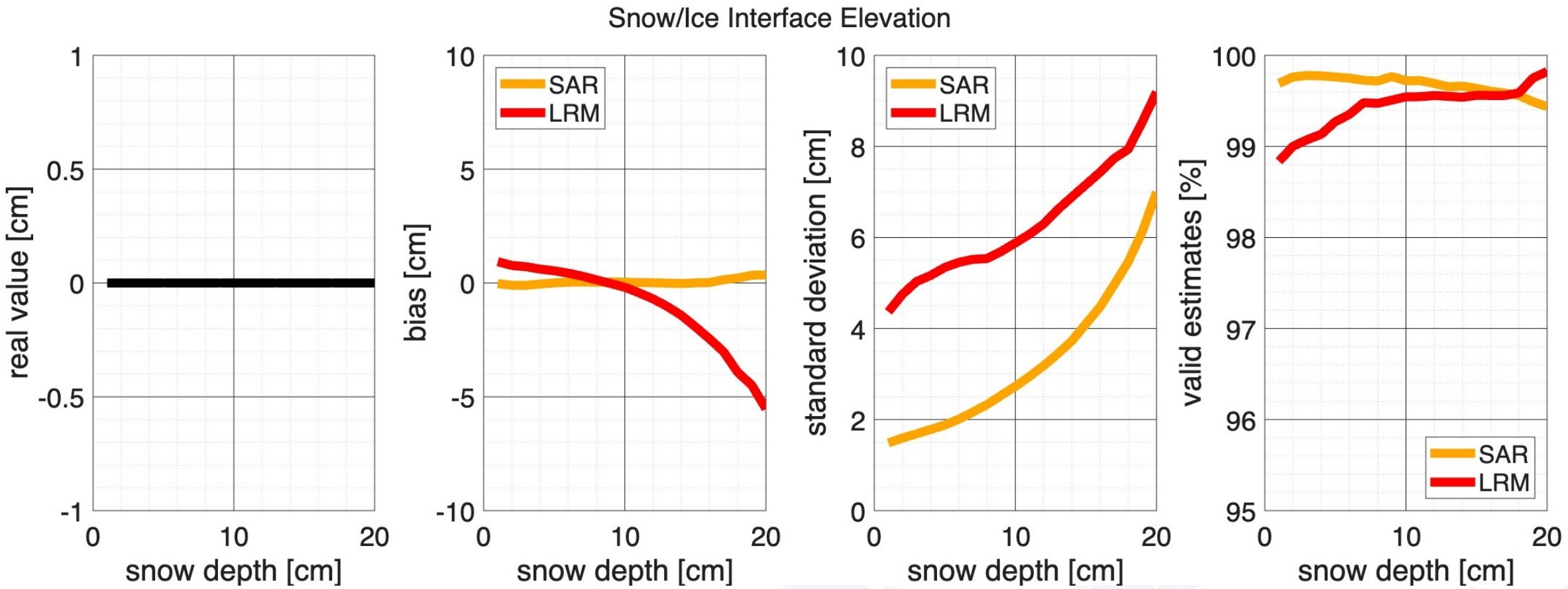


Mean sea ice surface roughness, σ_{elev}, for 10 km along-track segments for OIB Arctic flights between March and May, 2009-2018. Source: NOAA/NESDIS/STAR LSA

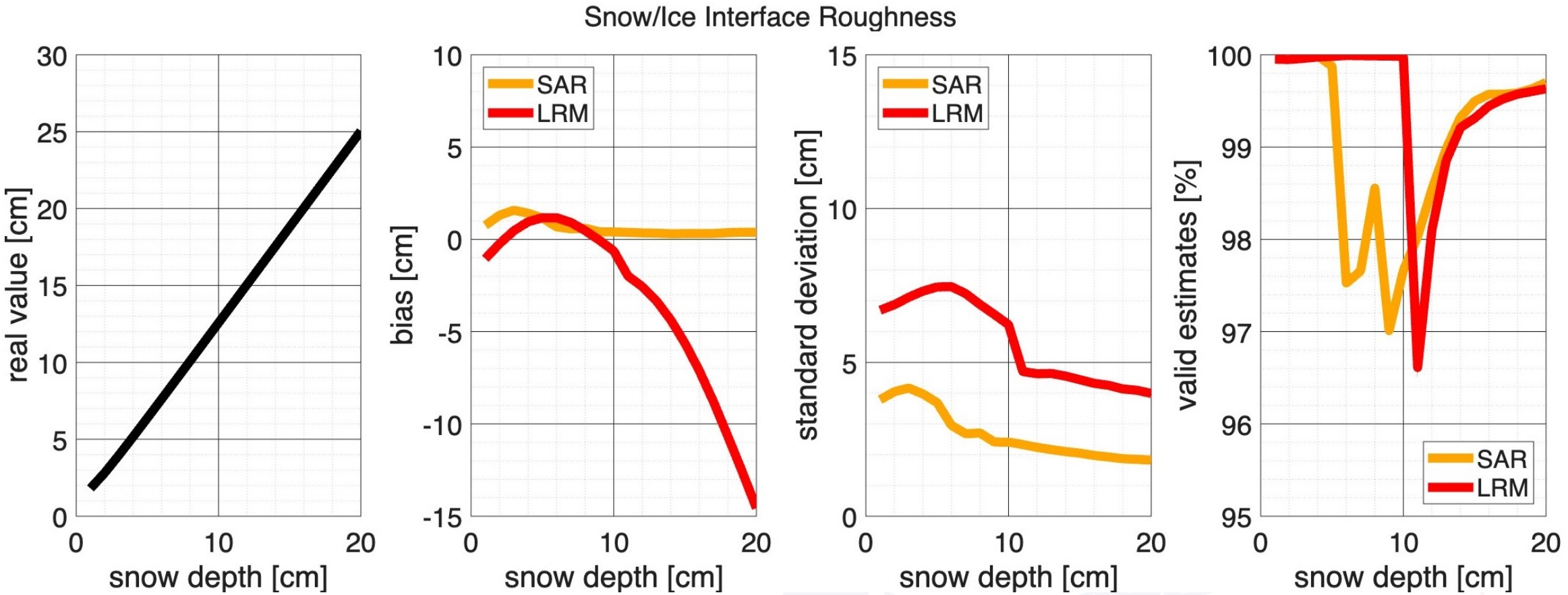
Sea Ice - Proof of Concept



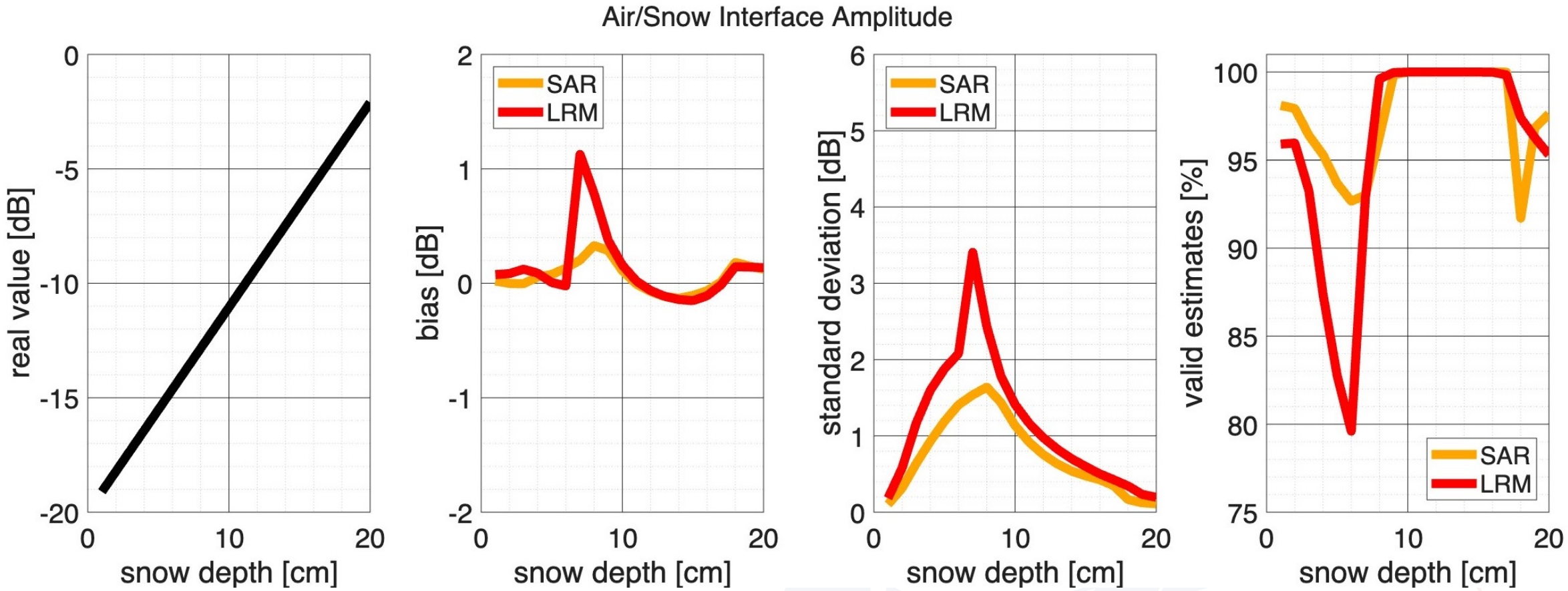
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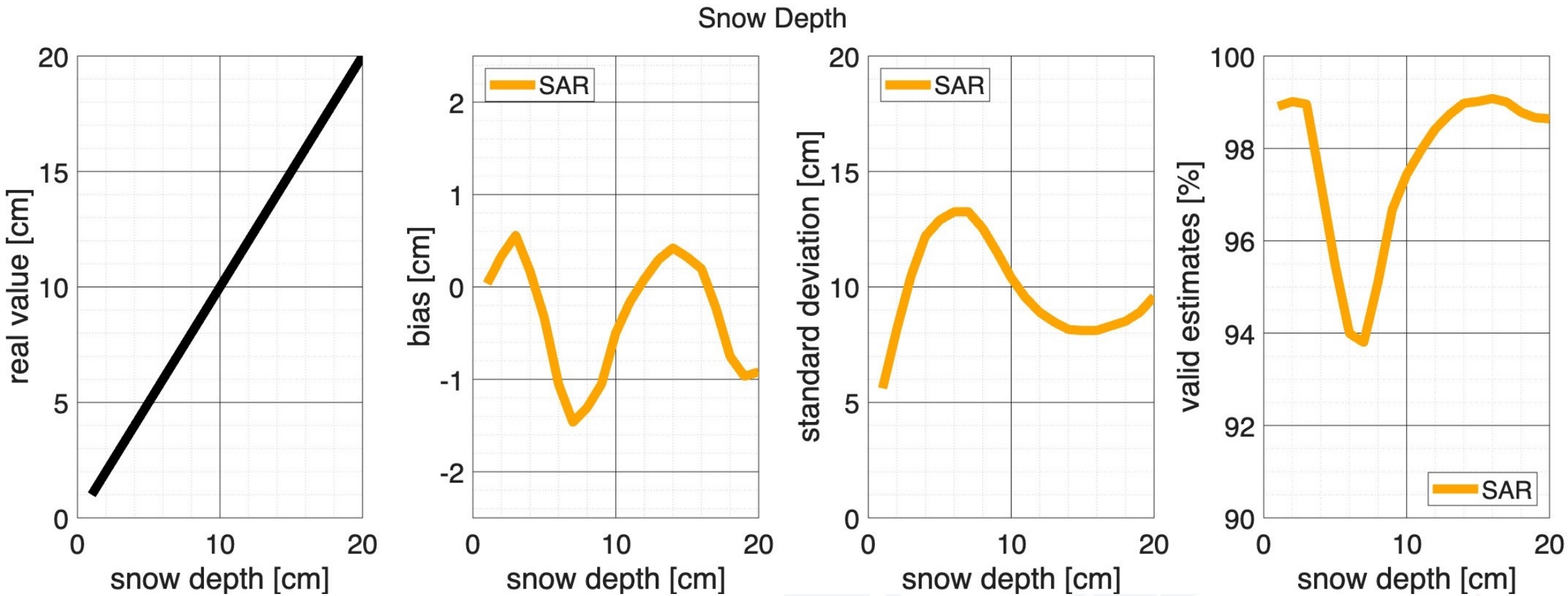
Sea Ice - Proof of Concept



Sea Ice - Proof of Concept



Sea Ice - Proof of Concept



Summary and Conclusion

SAR altimetry is capable to enhancing sea state observations:

- Standard deviations of vertical wave motion related with mean zero up-crossing wave periods
- Mean line-of-sight velocities related with wind speed and direction
- Current processing chain only up to Level-2

SAR altimetry should be capable of extending our understanding of snow-covered sea ice surface by

- Utilizing new geophysical parameter retrieval algorithms
- First results from Monte Carlo Simulations very promising
- However, still a lot of work to be done to make it combat ready

Thank you for your attention

You did it!