ICESat-2 Open Ocean Dynamic Ocean Topography

Cryo2ICE Workshop

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Special thanks to: Patricia Vornberger, Tom Neumann, and Nathan Kurtz

1- Polar Science Center, APL University of Washington

2- University of Colorado

3- Goddard Space Flight Center

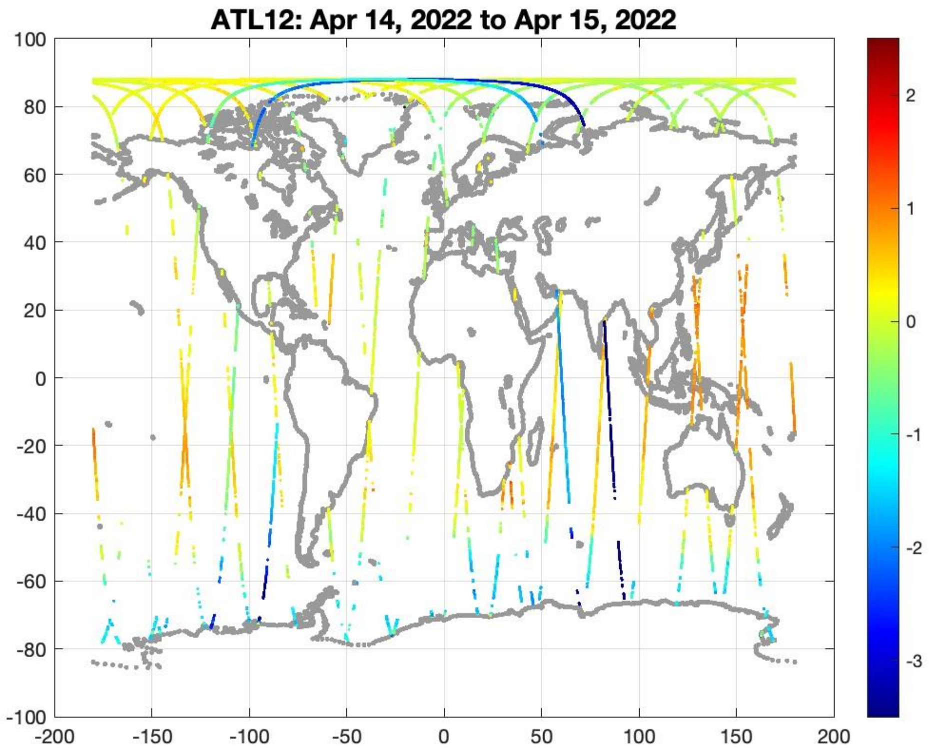
ICESat-2 ATL12 Along-track Sea Surface Heights (SSH)

ATL12 sea surface heights in files of 4-orbits over the world ocean >10-m deep. Include:

a) Ocean segment averages, the distribution, and first four moments of SSH for 6 beams plus the averages of pertinent geophysical variables and corrections such as SSB. Ocean segments are 0.5 to 7-km long to reduce uncertainty over wave covered surfaces.

b) 10-m bin averages of DOT=SSH-geoid within ocean segments. In addition to higher resolution, 10-m bin statistics provide sea state bias, harmonic fits and wave statistics. Release 7 will add first photon bias and DOT in sea ice.

Ocean segment average DOT from four 4-orbit ATL12 files, April 14-15, 2022



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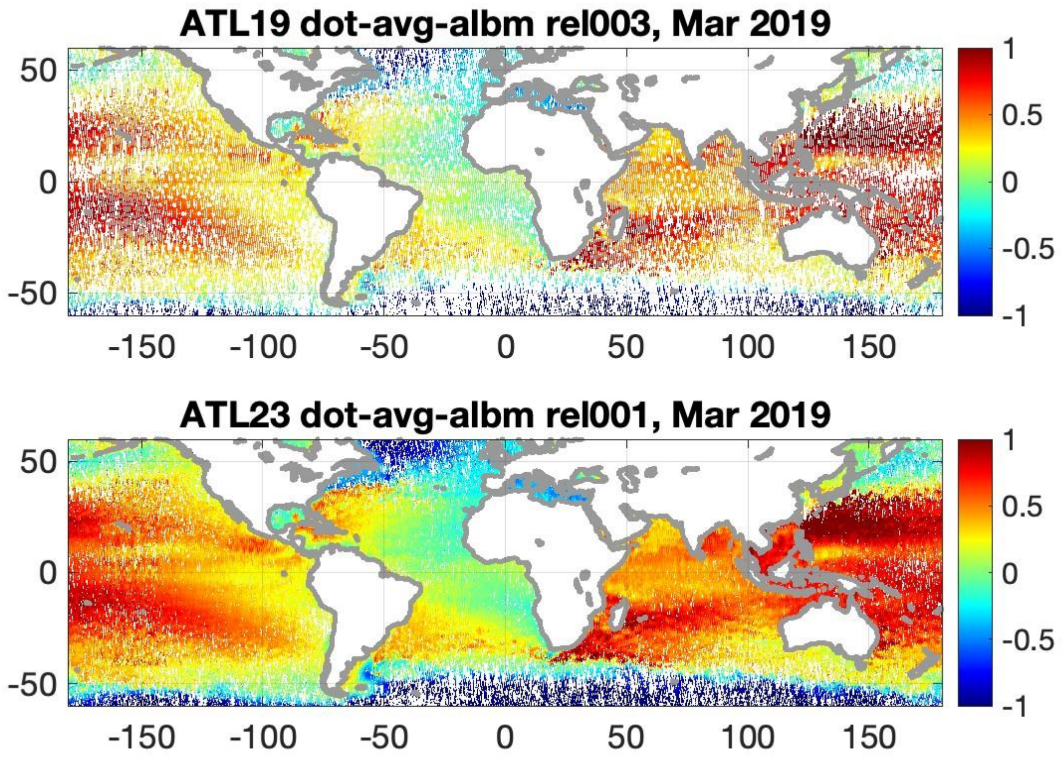
ICESat-2 ATL19 and ATL23 Gridded Dynamic Ocean Topography (DOT)

ATL19 are monthly grid-averages of ATL12 DOT plus related variables.

a) In ¼° Mid-Latitude Grid and 25-km polar stereographic N. & S. Polar Grids
b) Include individual beam averages (checks inter-beam bias), all-beam averages, cell-centered averages, and in Rel 4, minimum uncertainty centered averages.

ATL23 (new Rel. 1) are 3-month grid-averages of ATL12 DOT plus related variables. Similar to ATL19 but extending over 3 months to cover the ~91 day repeat of ICESat-2 and fill more grid cells.

DOT over the Mid-Latitude Grid from (top) ATL19 for March 2019 and (bottom) ATL23 for average over, Feb-March-April 2019



Importance of ICESat-2 ATL12 10-m Averages

10-m bin averages of DOT=SSH-geoid are critical to understanding the DOT statistics of longer (e.g., 7 km) ocean segments. In addition to providing higher resolution, 10-m bin heights are used:

1) To compute the horizontal length scale and height variance (significant wave height, SWH) needed to determining the uncertainty of the ocean segment average heights.
2) To compute harmonics that can be used to remove the wave signature.
3) Provide photon rate and first photon bias used with ATL07 in Release 7 to yield DOT in sea ice.
4) And most important to this presentation, 10-m photon rate, r, and DOT variations, η', are used to directly compute the ocean segment electromagnetic sea state bias equal to:

$$SSB = \frac{\sum_{j=1}^{K} r_j' \eta_j'}{\sum_{j=1}^{K} r_j}$$

J. Morison, Dickinson, Hancock, Roberts, Robbins, 7/29/2023

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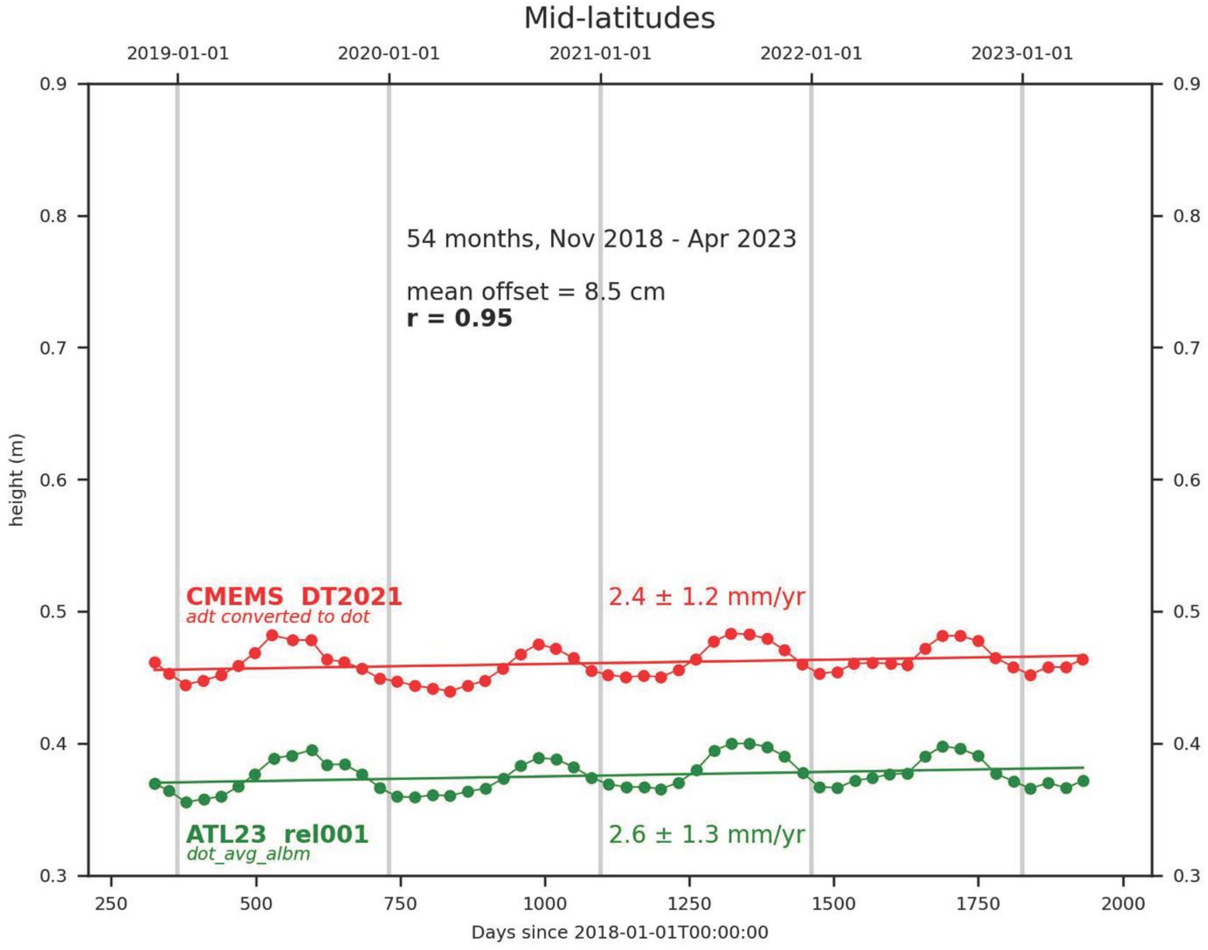
Comparisons with Mid-latitude AVISO Radar Altimetry

The GSFC group* has compared ICESat-2 mid-latitude ATL23 DOT (*dot_avg_albm*) gridded averages from Nov. 2018 to Apr 2023 with DOT computed from gridded AVISO CMEMS absolute DOT data in overlapping latitude-longitude bins. These show:

- Nearly identical seasonal fluctuation with max DOT in late late Aug and min in Jan-Mar
- Nearly identical trends ~ 2.5 mm/yr
- CMEMS-ICESat-2 bias = 8.5 cm.

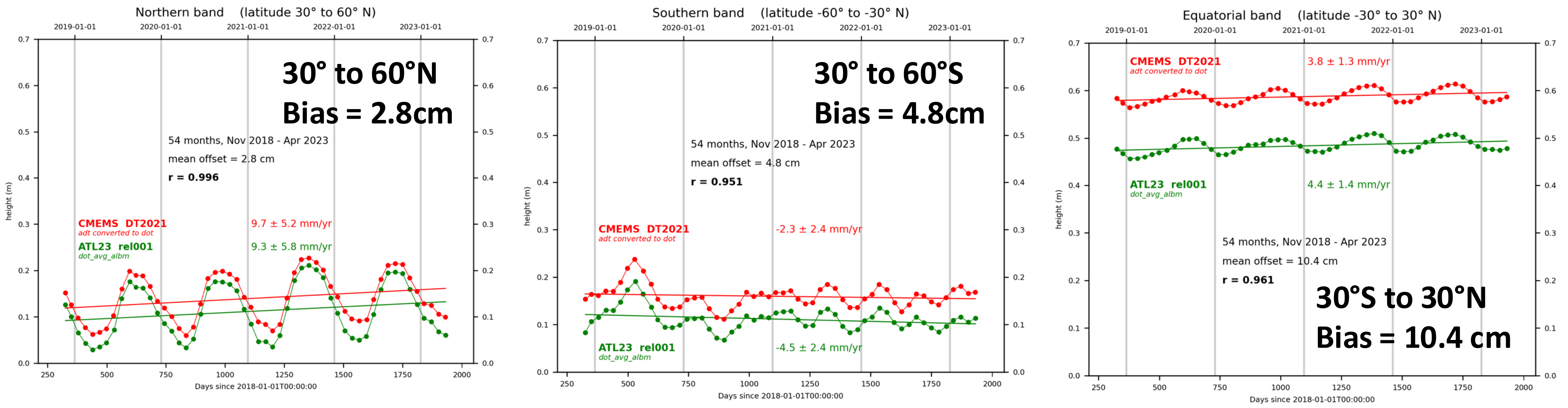


60°S to 60°N
Bias = 8.5 cm

* Vornberger, Robbins, and Hancock

Comparisons with Mid-latitude AVISO Radar Altimetry

However, the bias varies by latitude band, suggesting the bias is not fundamentally instrumental



The seasonal cycles in the latitude bands are in phase but the amplitude is largest in the northern band, next largest in the tropical band, and much smaller in the southern band. This implies:

- An average cycle is dominated by the Northern Hemisphere.
- Anomalies about the average seasonal cycle will show opposite phases in Northern and Southern Hemispheres

Comparisons with Mid-latitude AVISO Radar Altimetry

Putnam has carried out a crossover comparison of mid-latitude ATL12 ICESat-2 with radar altimeters (RA) Jason 3 over 2020 and Sentinel 6 over 2022 (See Putnam et al. presentation).

Without SSB correction, the sea level anomaly from the radar altimeters and from ICESat-2 at crossovers give average RA-ICESat-2 bias = 0.82 cm in 2020 and 2.71 cm in 2022 suggesting **the RA and ICESat-2 instruments give nearly the same surface heights.**

However, when the respective SSB corrections are applied, the corrected average RA-ICESat-2 bias = 7.64 cm in 2020 and 9.09 cm in 2022. These are similar to the mid-latitude average bias of ~8.5 cm of CMEMS - ICESat-2 and indicates that **the SSB corrections for the RA are larger than the SSB corrections for ICESsat-2**.

The **ICESat-2 SSB correction is a direct computation** of EM bias (*Arnold et al.,* 1995; *Morison et al.,* 2022) from 10-m photon rate and DOT. In contrast:

The **RA SSB corrections** are a non-parametric fit versus SWH and wind speed of the uncorrected sea level anomaly averaged over a long period (e.g., 1 year) in SWH and wind speed bins (*Putnam et al*., 2023). This approach **assumes that DOT is naturally independent of SWH and wind speed**.

Arnold, D. V., W. K. Melville, R. H. Stewart, J. A. Kong, W. C. Keller, and E. Lamarre (1995), Measurements of electromagnetic bias at Ku and C bands, *J. Geophys. Res.*, *100*(C1), 969-980.

Putnam, A., Desai, S. D., & Nerem, R. S. (2023). Estimation of the Sea State Bias Using the Interpolation Method and Applications to Inter-Mission Calibration. *Marine Geodesy, 46*(6), 479-495

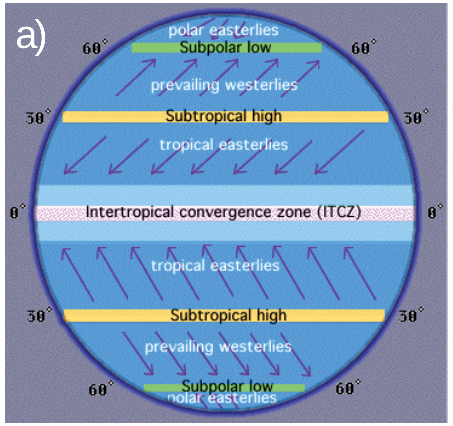
Comparisons with Mid-latitude AVISO Radar Altimetry

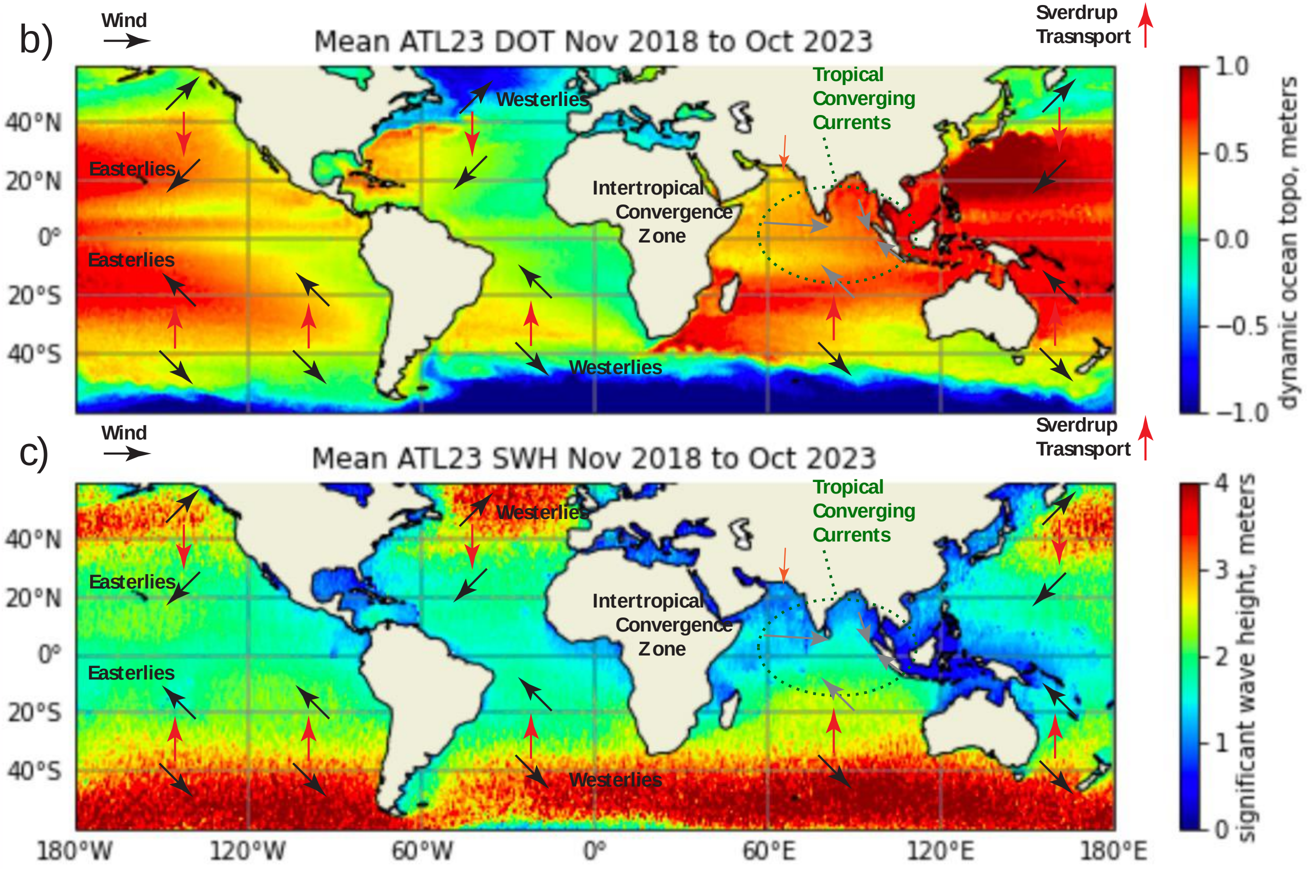
But is DOT naturally independent of SWH and wind speed? Given the qualitative correspondence of SWH, wind and wind stress, ICESat-2 SWH and DOT suggest not. For example:

ATL23, 5- years average DOT and SWH are inversely related seemingly associated with Sverdrup transport,

$$\dot{h} = \frac{-1}{\rho f} \nabla \times \tau,$$

from sub-tropical latitudes (±40°) of the Westerlies and Easterlies, where SWH is high, and DOT is low, toward the equator, where SWH is low, and DOT is high.



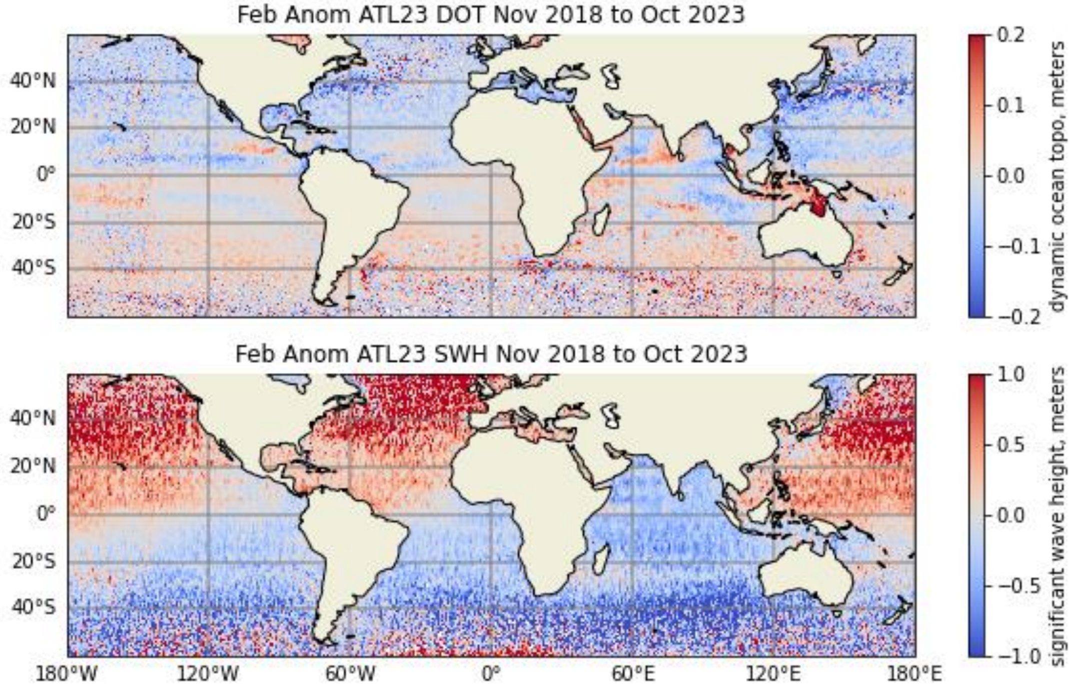


The equatorward transport is driven by the positive stress curl of the Westerlies & Easterlies in the N. Hem. and the negative stress curl of the Westerlies & Easterlies in the S. Hem.

Comparisons with Mid-latitude AVISO Radar Altimetry

More importantly, consider the seasonal cycles of DOT and SWH suggested by Feb and Aug ICESat-2 ATL23 averages:

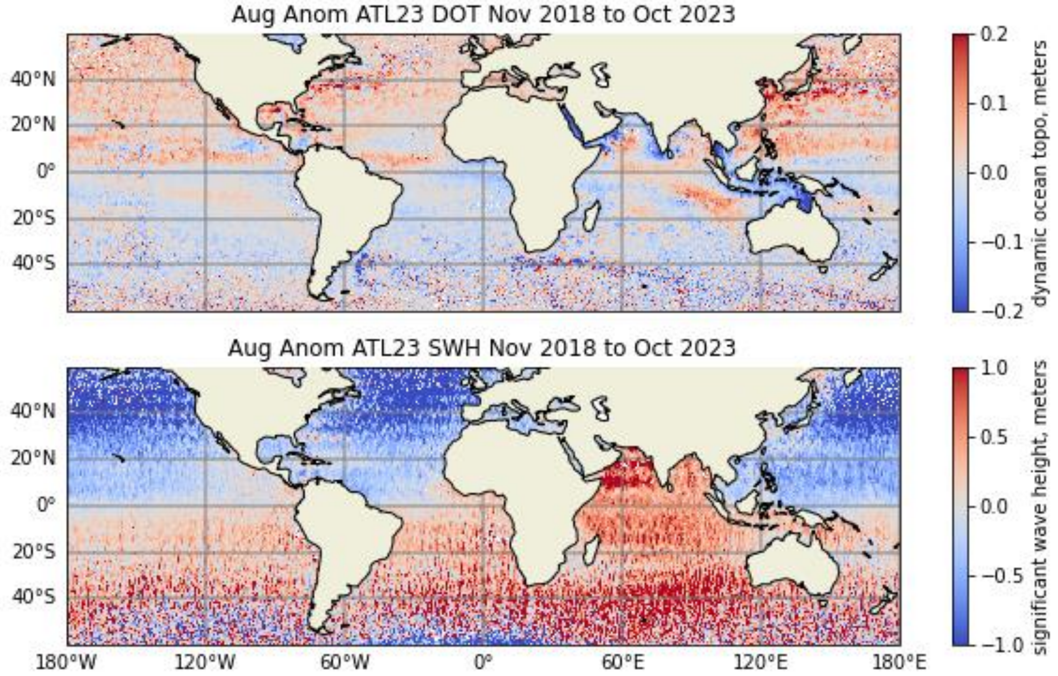
February



DOT

SWH

August



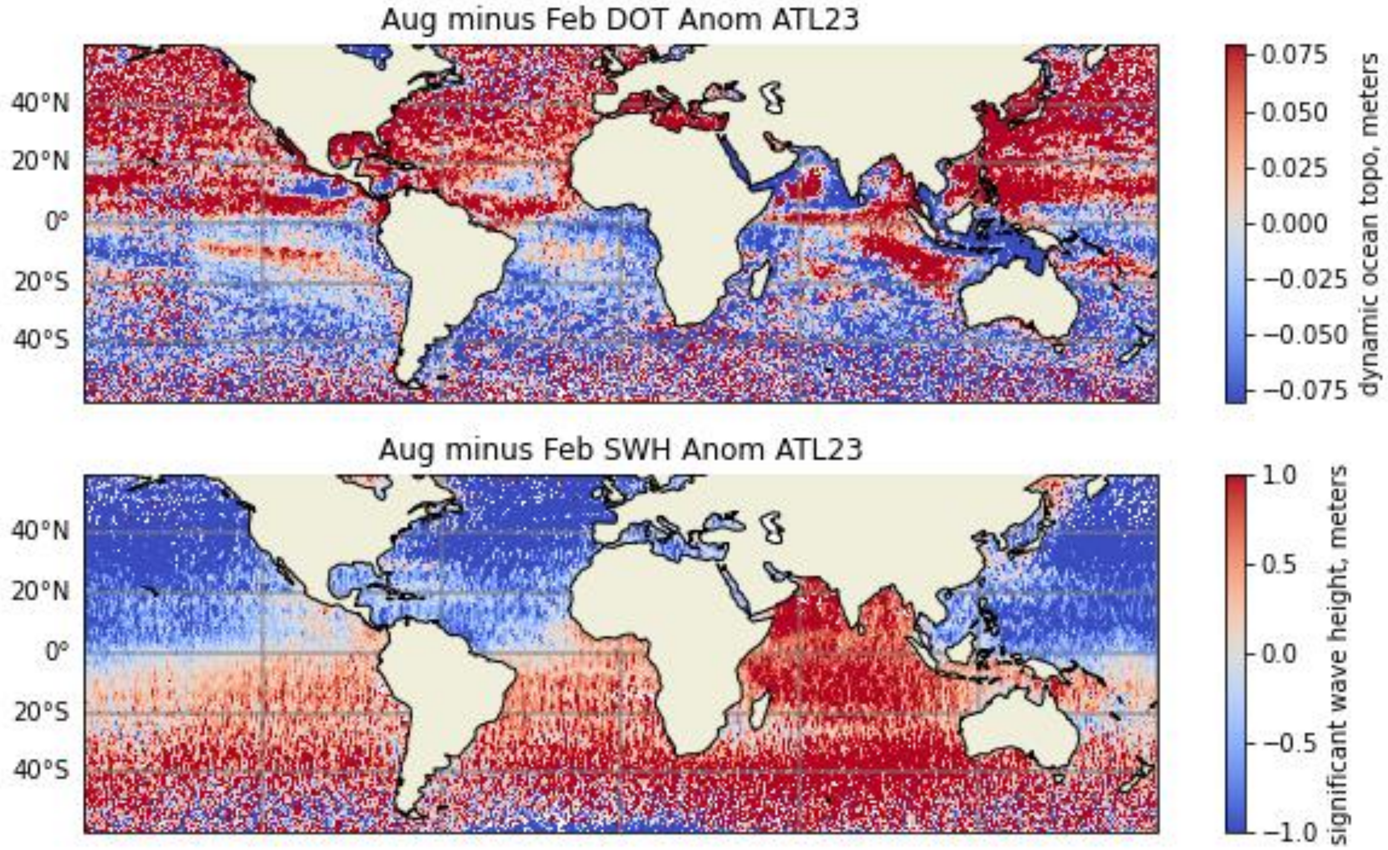
DOT is inversely related to SWH; in each hemisphere during winter when it's windy and SWH is high and DOT is low, and in summer SWH is low and DOT is high.

Comparisons with Mid-latitude AVISO Radar Altimetry

More importantly, consider the seasonal cycles of DOT and SWH suggested by Differences of Aug and Feb ICESat-2 ATL23 averages:

Aug - Feb DOT

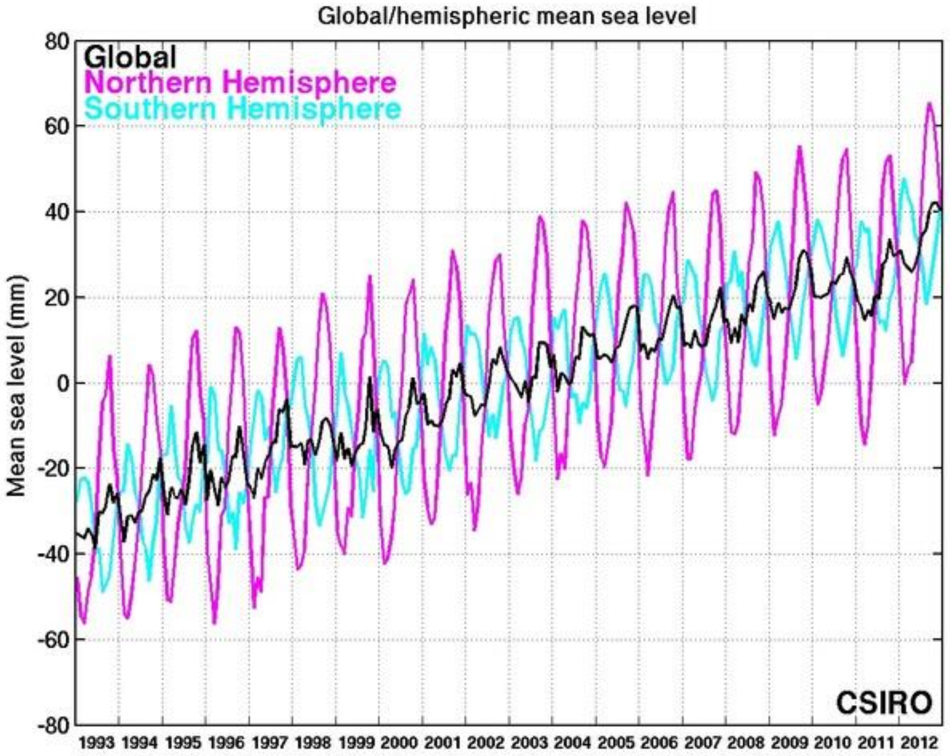
Aug - Feb SWH

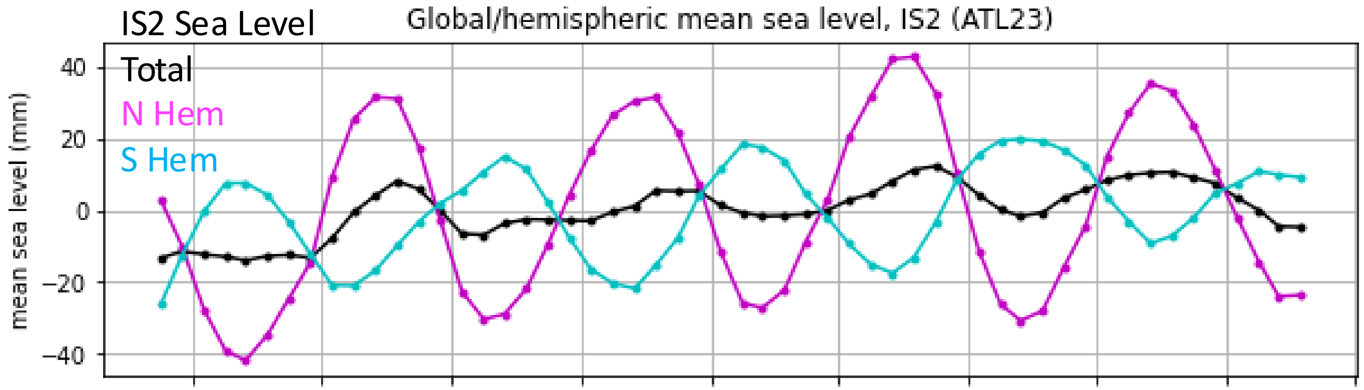


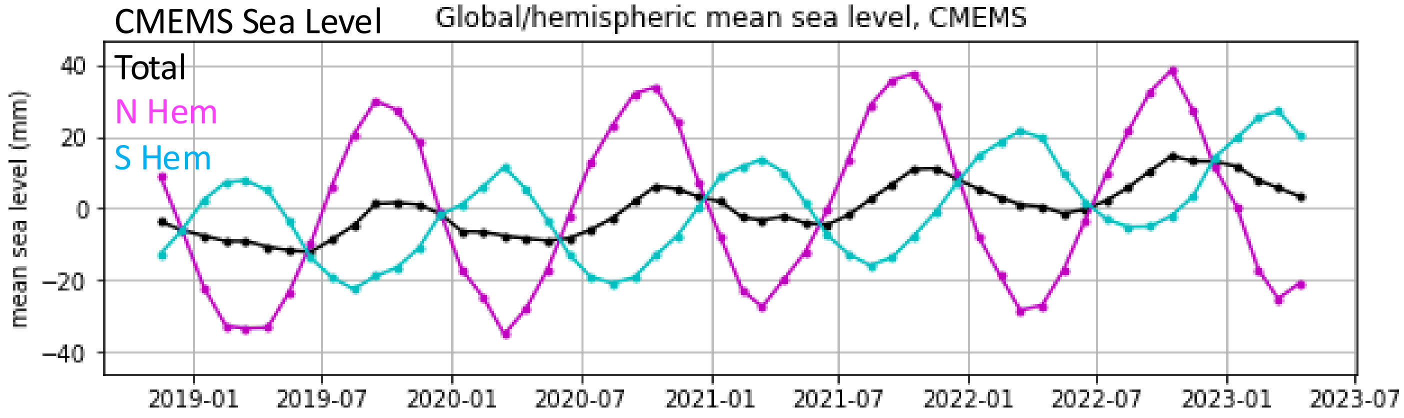
The sign of Aug-Feb DOT is the opposite of Aug-Feb SWH in each => Fundamental Negative DOT v. SWH Correlation

Comparisons with Mid-latitude AVISO Radar Altimetry

DOT is higher in the hemispheric summer because the water is warmer with the consequence that steric sea level (SSL) is greater.







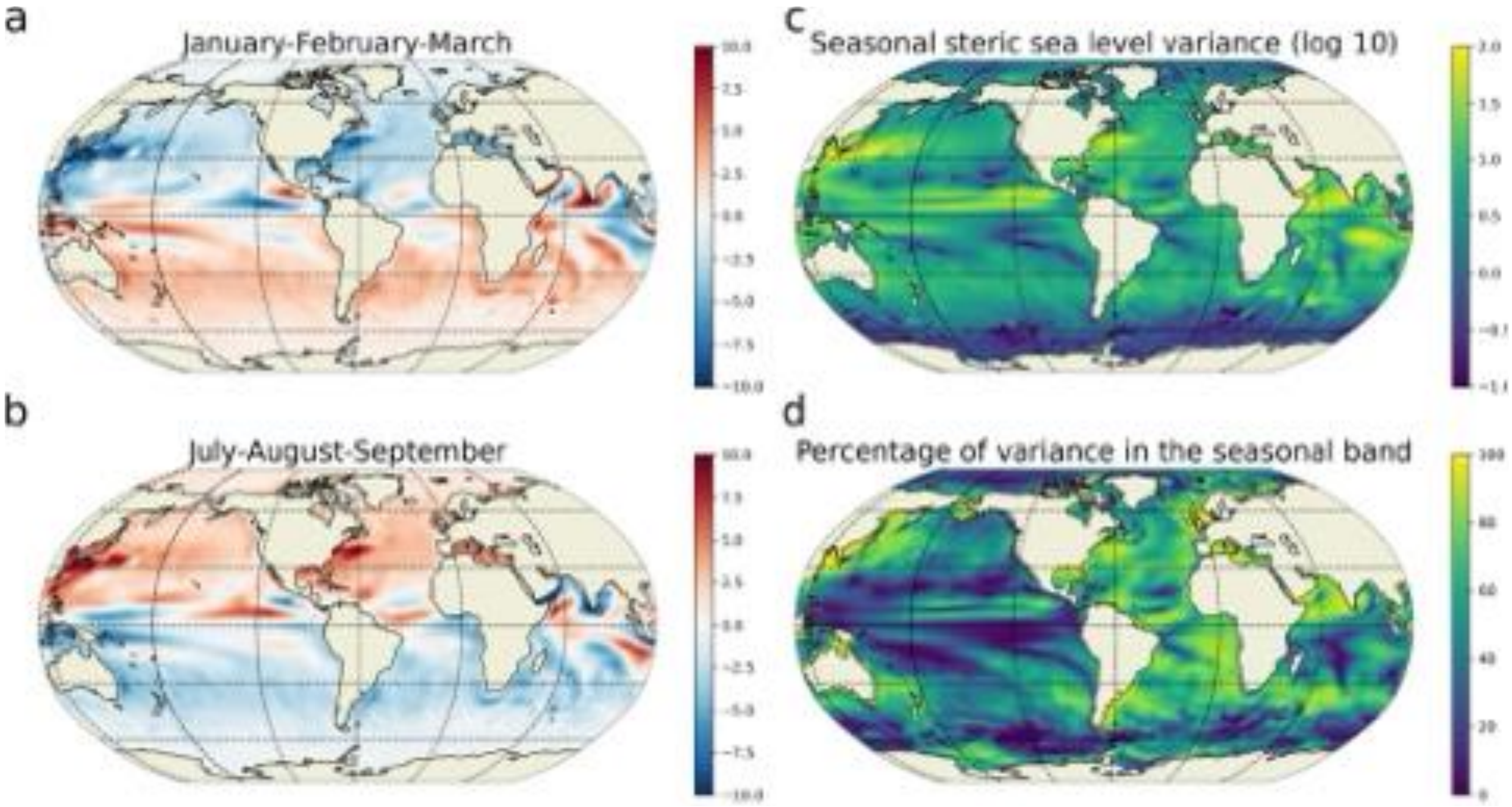
Global- and hemispheric-mean sea level from TOPEX/Poseidon and Jason-1, 1993-2012.

N. Hem. DOT is opposite phase from S. Hem. And twice the amplitude so the global is also a fraction the amplitude.

Annual cycles DOT in ATL23 and CMEMS are the same as in the 1993-2012 record. *Note: We are working on plots that also have hemispheric averages of SWH*

Comparisons with Mid-latitude AVISO Radar Altimetry

***Hochet et al*. (2024) show that steric sea level, which dominates DOT, is higher in the hemispheric summer because the water is warmer with the consequence that steric sea (SSL) is greater in summer.**

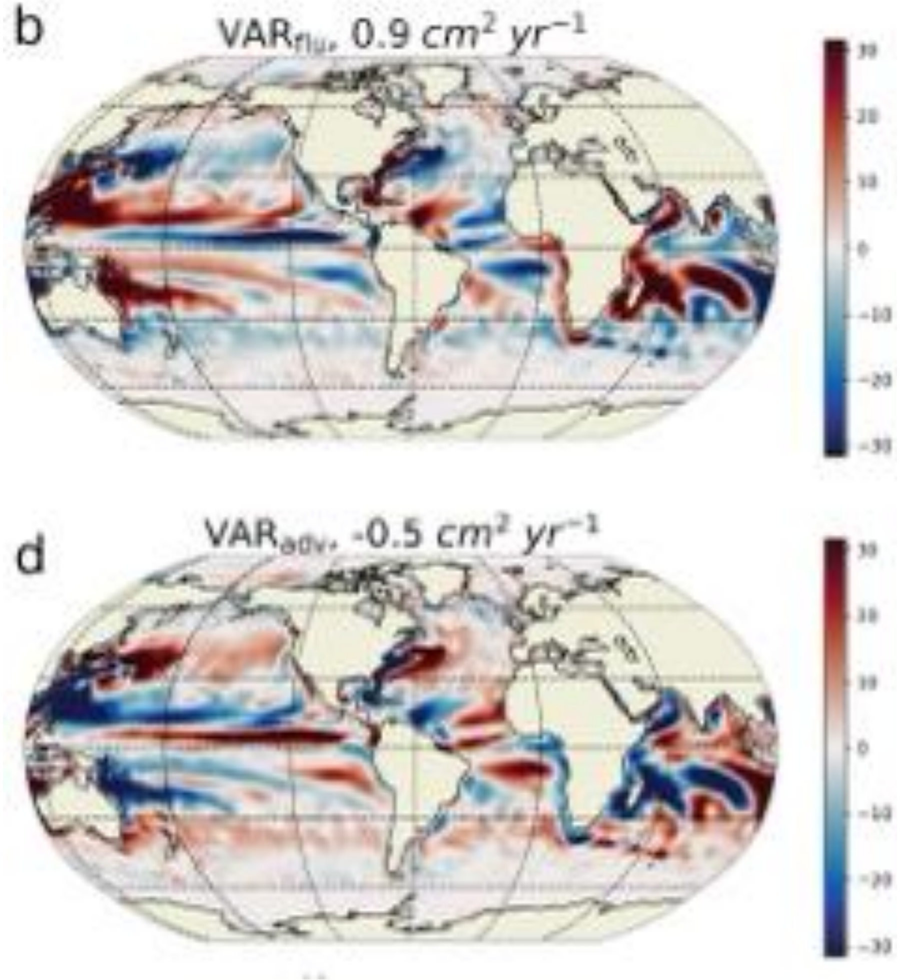


Steric Sea Level from ECCO2 for a) JFM and b) JAS (in cm), c) SSL variance (cm^2) and d) Percentage of SSL variance in the seasonal band. (from *Hochet et al*., 2024)

Hochet, A., Llovel, W., Huck, T., & Sévellec, F. (2024). Advection surface-flux balance controls the seasonal steric sea level amplitude. *Nature, Scientific Reports, 14*(1), 10644. https://doi.org/10.1038/s41598-024-61447-y

Comparisons with Mid-latitude AVISO Radar Altimetry

***Hochet et al*. (2024) show that steric sea level, which dominates DOT, is higher in the hemispheric summer because the water is warmer with the consequence that steric sea level (SSL) is greater in summer.**



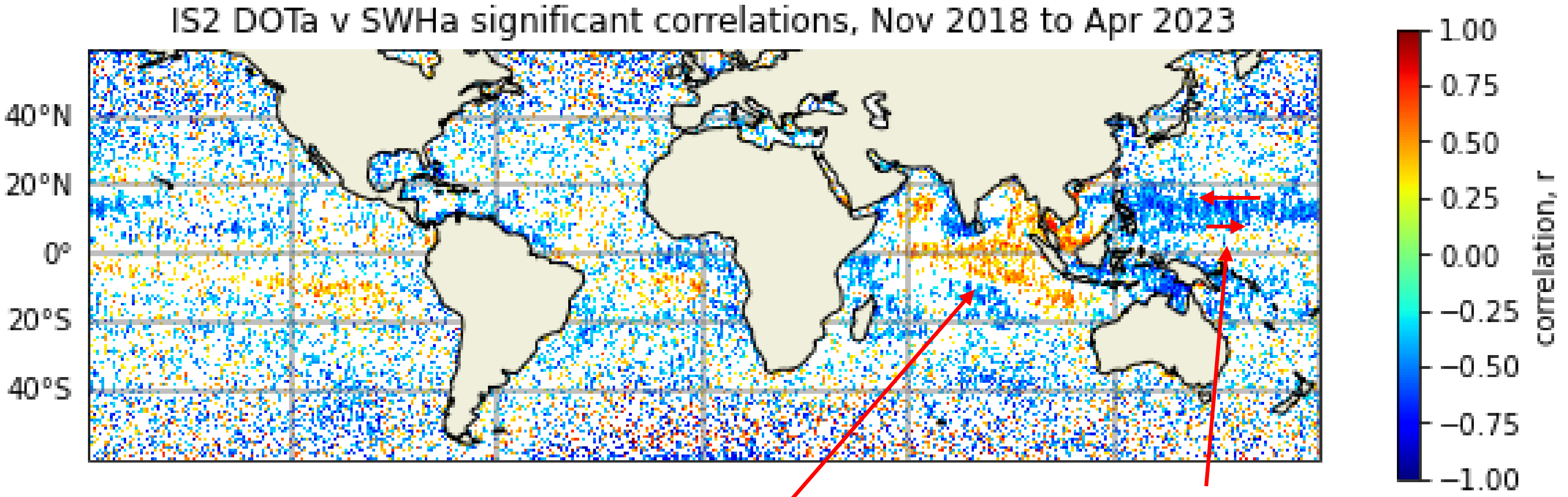
However, ECCO2 results suggest that <u>surface heat fluxes</u> are dominant in changing SSL,

<u>Ocean advection</u> contributes substantially to SSL change, especially at lower latitudes (from *Hochet et al.*, 2024)

Comparisons with Mid-latitude AVISO Radar Altimetry

5 years of ICESat-2 and CMEMS correlation maps => DOT is not independent of SWH.

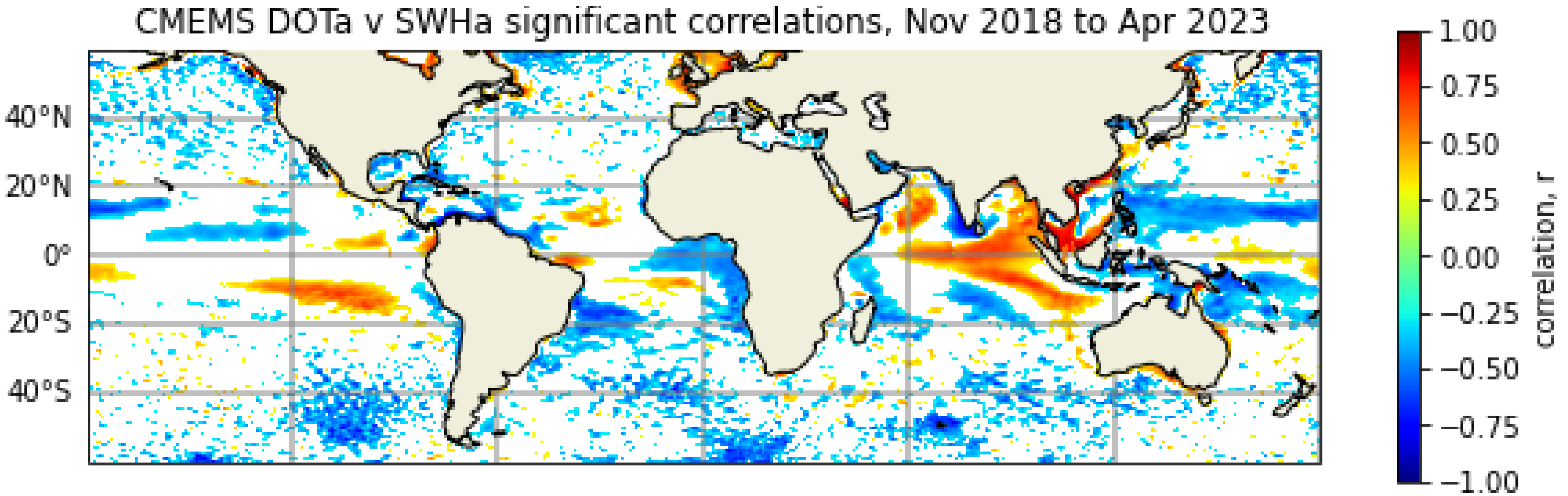
ICESat-2 ATL23 statistically ($p<0.05$) significant **correlations of DOT and SWH anomalies about their means are mainly negative**, but with definite positive and negative features, especially in the tropical zone.



Southwest Monsoon Current, South Equatorial Countercurrent, and South Java Current converge here.

North Equatorial Current and Countercurrent positive stress curl draws surface down.

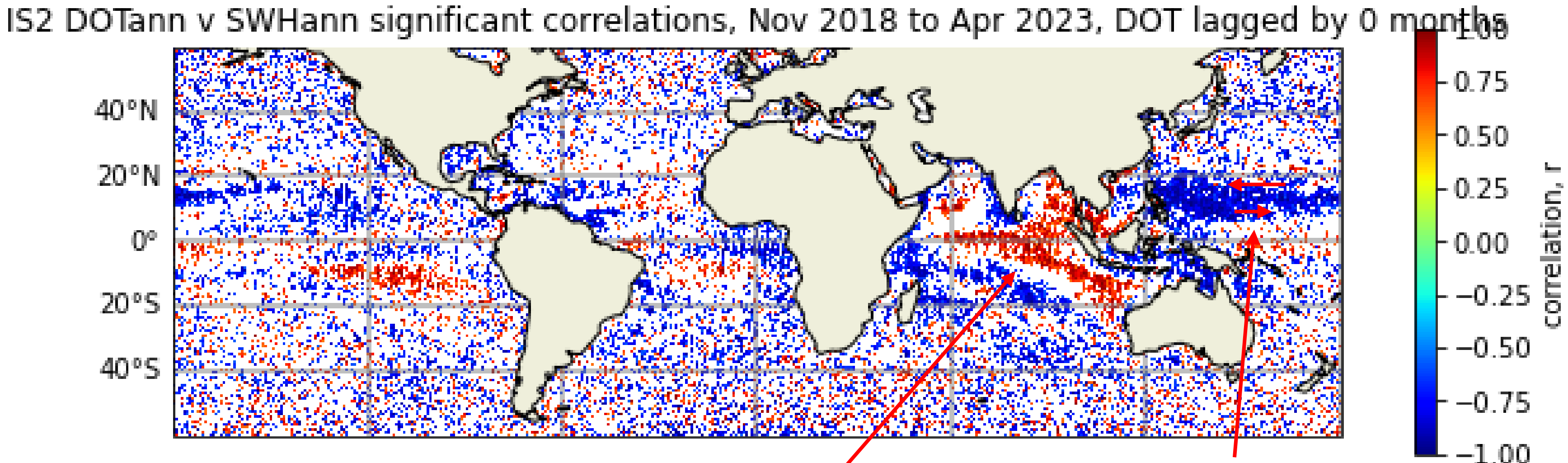
CMEMS statistically ($p<0.05$) significant correlations of DOT and SWH anomalies about their means are also mainly negative, but with much greater prevalence of zero correlations, especially in the tropical zone. **The RA SSB correction appears to have absorbed much of the natural DOT v. SWH correlation.**



Comparisons with Mid-latitude AVISO Radar Altimetry

5 years of ICESat-2 and CMEMS => DOT & SWH are negatively correlated.

ICESat-2 ATL23 statistically ($p<0.05$) significant **correlations of monthly mean DOT and SWH are strongly negative indicating the impact of the seasonal cycle**.

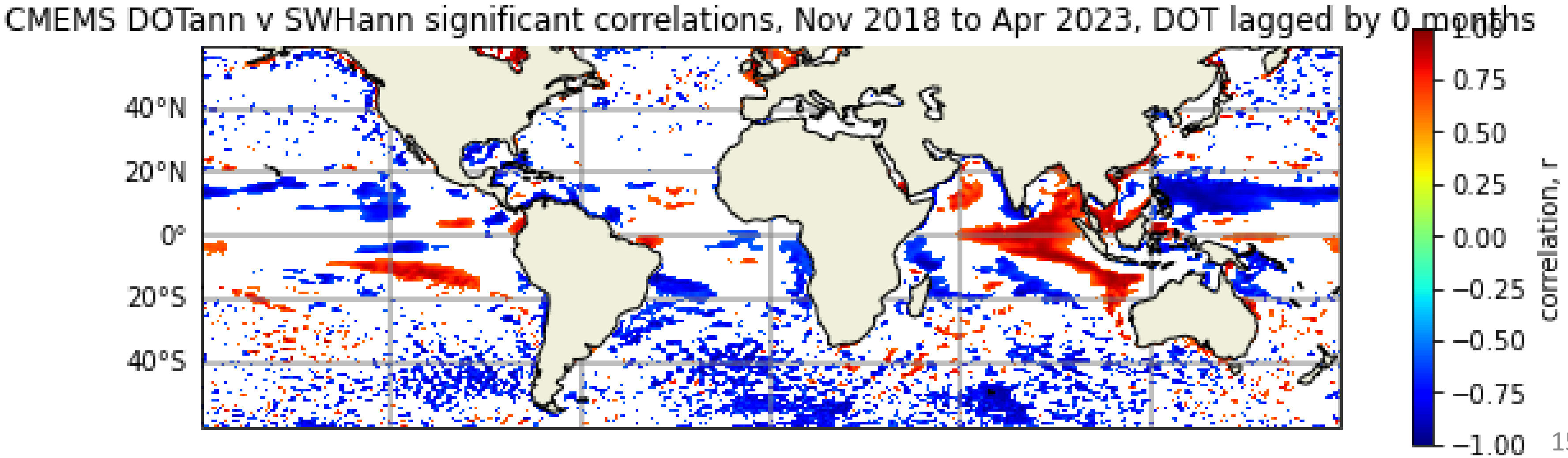


Southwest Monsoon Current, South Equatorial Countercurrent, and South Java Current converge here.

North Equatorial Current and Countercurrent positive stress curl draws surface down.

CMEMS statistically ($p<0.05$) significant **correlations of monthly mean DOT and SWH** are reduced to zero in many regions but especially the tropic zone.

<u>RA SSB correction has absorbed all the natural seasonal correlation in these areas.</u>



Comparisons with Mid-latitude AVISO Radar Altimetry

Conclusions

- **Radar satellite DOT is biased high relative to ICESat-2.**
- **The bias is due to the way the radar satellite sea state bias is estimated assuming natural independence of sea level anomaly or DOT and SWH.**
- **In fact, averaged over the mid-latitude ocean, the natural DOT v. SWH correlation is substantially negative due seasonal changes in water temperature with increasing summer temperatures increasing at the same time SWH is low, and the opposite occurs in winter. Most of this is due to seasonal heat flux variability, but dynamic advection also plays a significant part for example with the shifting of ocean mass equatorward away from regions of increased SWH in the regions of the Easterlies and Westerlies.**
- **As a result, the radar altimeter SSB estimation approach interprets a significant part of the naturally negative DOT v. SWH correlation as sea state bias, and thus the SSB correction is excessively positive.**
- **The natural DOT v. SWH correlations tend to be smaller at short time scales due to latency in the response of DOT to stress (or SWH). Therefore, because the negative DOT v. SWH correlations in the average seasonal signals are so strong, a first step in reducing the radar altimeter SSB correction bias would be to compute SSB using not the DOT, SWH, and wind speed anomalies about their means, but on anomalies about their means plus their seasonal variations.**