Diagnosing ocean eddy salt transport from satellite altimetry and surface salinity data

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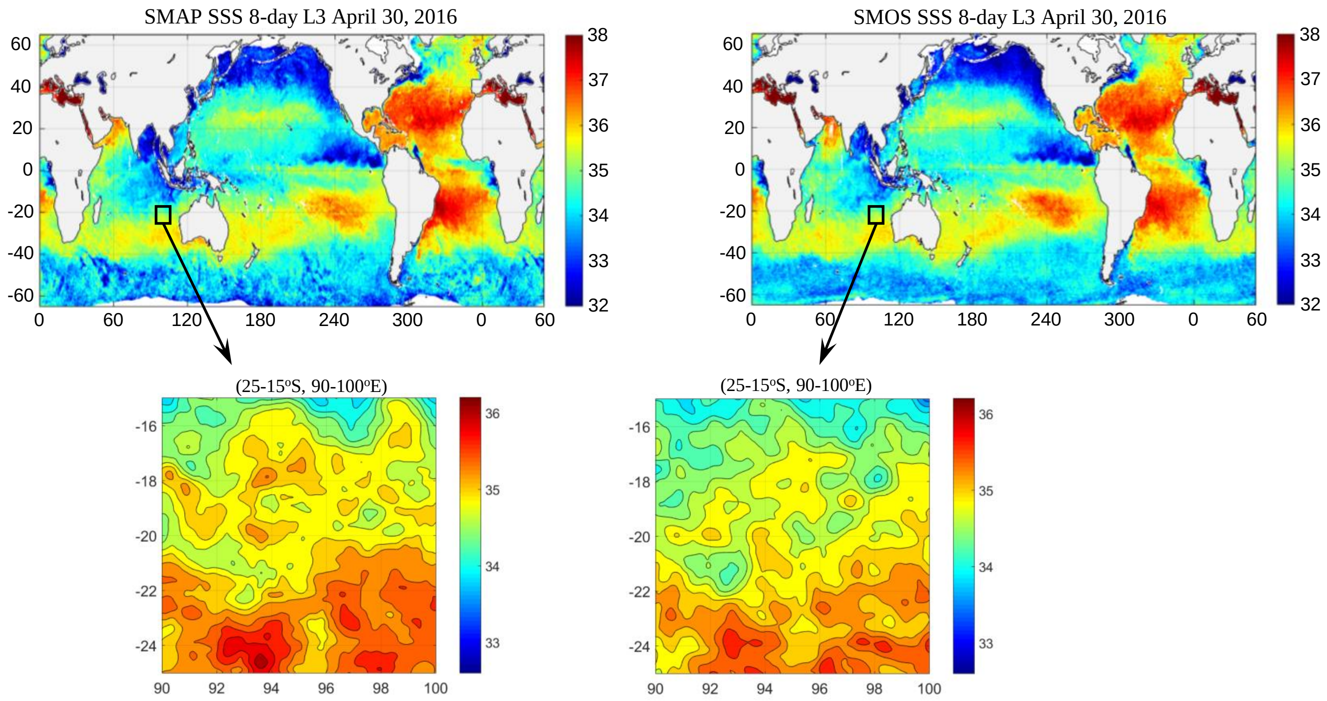
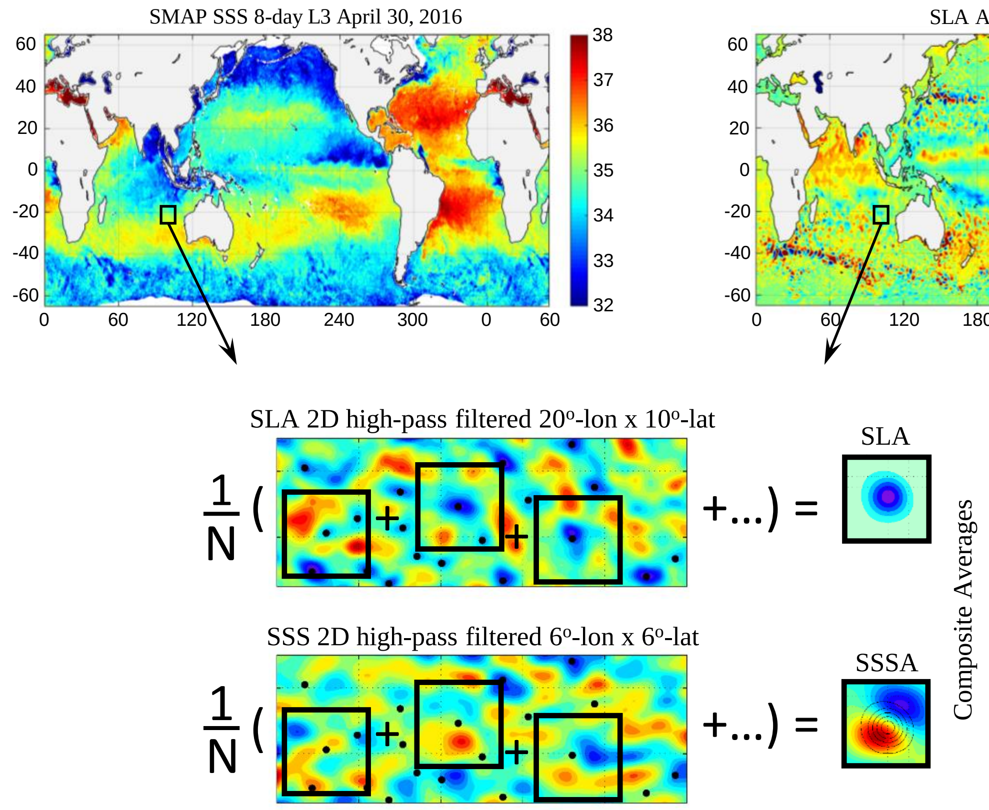
Where do ocean eddy salt fluxes matter?



Satellite observations of SSS provide continuous time series with enhanced spatial and temporal resolution, not available by other components of the global ocean observing system. This is a new technology, however, and it is known that satellite-based observations of SSS are prone to significant errors. Typical errors in footprint measurements can be as large as 1 psu. Errors are reduced to 0.2-0.3 psu in gridded SSS maps, but they are still quite large, compared to the accuracy of in-situ measurements, such as from Argo profiling floats. The errors are comparable to a typical eddy-induced SSS anomaly of O(0.1-0.3 psu) and the signal-to-noise ratio for a mesoscale eddy signal appears to be low.

Satellite sea level anomaly (SLA) and sea surface salinity (SSS) data are used to characterize and quantify the contribution of mesoscale eddies to the ocean transport of salt (or, equivalently, freshwater (FW)). Given relatively large errors in satellite SSS retrievals, we evaluate the eddy transport of salt using two methods. The first method is based on the so-called eddy composite analysis. Because of the averaging over a large number of eddies in a given geographic area, composite eddies result in quite small standard errors, producing robust estimates of the associated transport of salt. The second method estimates the eddy transport of salt in a traditional way by computing pointwise covariances between eddy-induced velocity and SSS fluctuations.

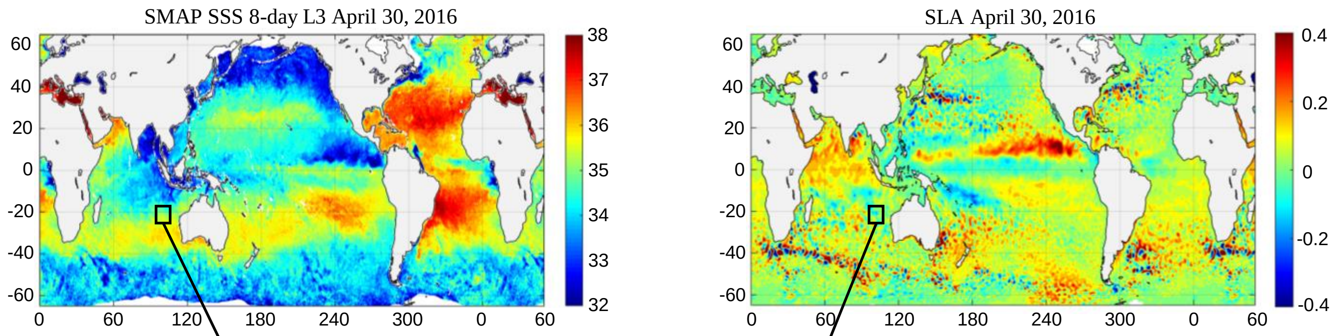
Eddy composite analysis



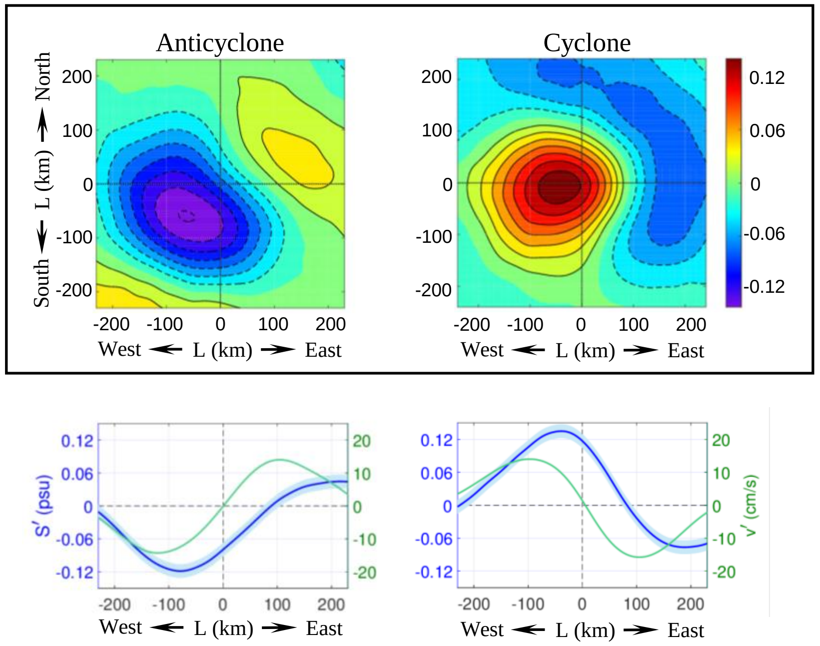
To suppress the noise, we average mesoscale SLA and SSS maps in the reference frame co-moving with eddies, which, in turn are identified and tracked in SLA maps.

The eddy composite analysis consists of a few simple steps and involves averaging over all snapshots of a variable of interest (in our case SSS and SLA) around individual eddies (eddy “realizations”) identified in SLA maps. Specifically, we use weekly SSS and SLA fields sampled in 500-km by 500-km boxes around the eddy centers identified in the eddy dataset (META 2.0). In each geographic area (bin), the averages include only eddies located inside the area’s boundaries. Also, in order to isolate the eddy signal and remove large-scale variability, prior to the composite analysis, the SSS and SLA fields are high-pass filtered using a 2-D Hanning filter of half-width of 6°.

Eddy composite analysis



Composite averages of eddy-induced SSS anomalies

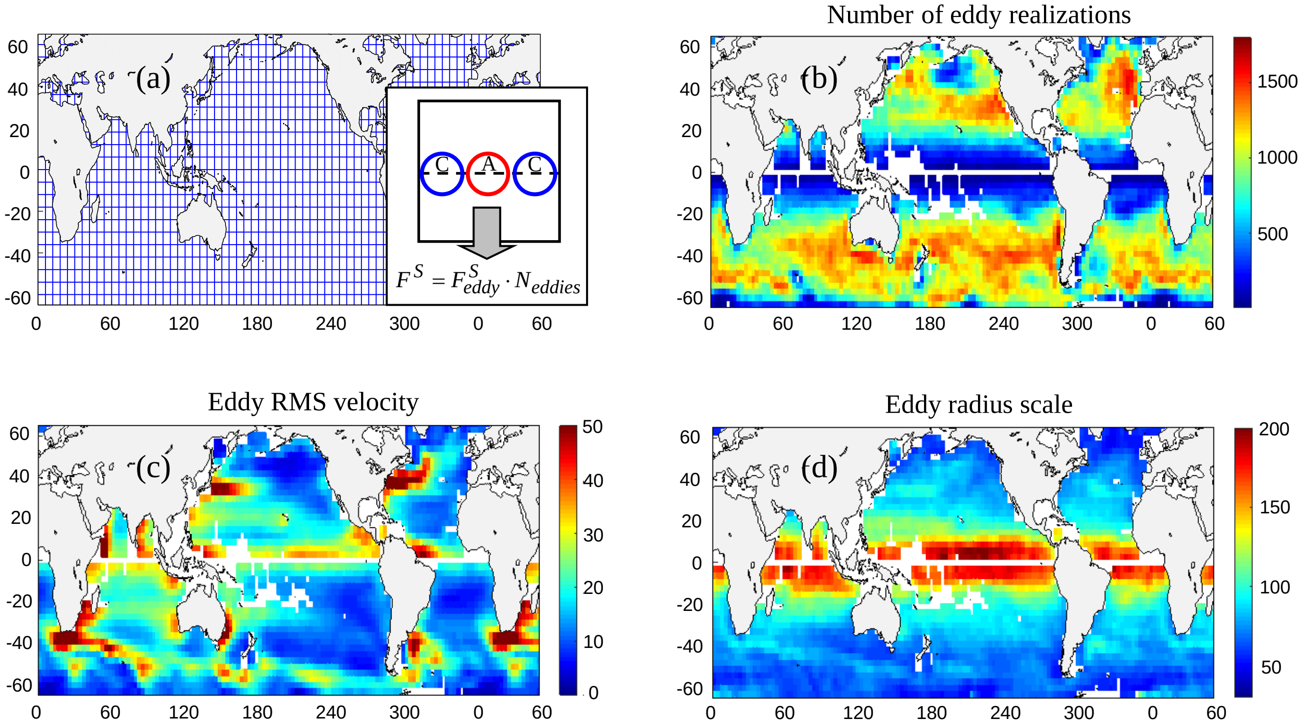


FW flux by an eddy

$$F_y = -\frac{h}{S_o}\int_{-L}^{L}\langle v'\rangle\langle S'\rangle dx$$

A net eddy flux of salt by an average eddy arises due to systematic phase differences between eddy-induced SLA and SSS perturbations such that the eddy velocity and SSS perturbations correlate over the eddy "wavelength". This is how westward-propagating eddies provide meridional transport of salt. To illustrate this effect, bottom panels show zonal sections across the composite eddies. The SSS anomaly (blue curves) is generally in phase with the eddy meridional velocity (green curves), producing in a positive correlation over the eddy length ($<v's'>_L > 0$; eddies pump salt northward).

Eddy salt transport through the eddy composite analysis

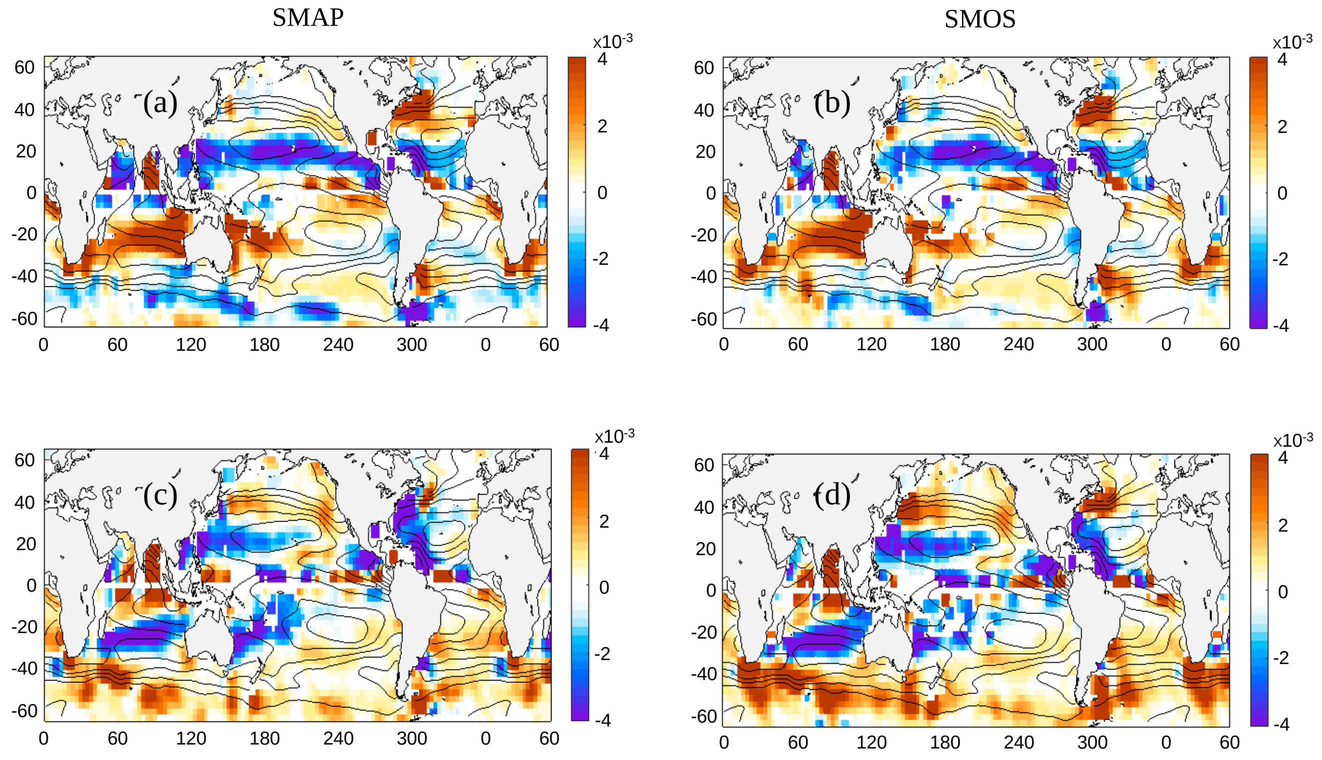


(a) Schematic illustration showing how eddy fluxes of salt are computed globally from eddy composites reconstructed in 6º-longitude x 6º-latitude bins. Blue lines show the boundaries of the bins. The insert illustrates how the meridional flux of salt in each bin is estimated. The flux through the zonal section of the bin is given by the flux per a composite eddy multiplied by the number of eddies that can fit into the section (blue and red circles show schematically cyclonic (C) and anticyclonic (A) eddies, respectively). **(b)** Number of eddy realizations observed in 6º-longitude x 6º-latitude bins over the 4-year period from April 2015 to May 2019. In each bin, the number of eddy realizations is defined as the number of eddy centroids found in the bin divided by the number of SLA (SSS) maps used to cover a 28-day period**(c)** Eddy RMS velocity (cm/s), estimated as 0.71 of the mean speed-based amplitude. **(d)** Mean eddy speed-based radius scale (km).

Using eddy composites reconstructed in different parts of the ocean, we can estimate the eddy transport of salt. The ocean is presumed to be densely packed with mesoscale eddies. A zonal or meridional section can therefore be treated as a sequence of cyclonic and anticyclonic eddies (panel (a)). In a limited geographic area (bin), eddies are assumed to be geometrically and dynamically similar such that their average effect can be represented by a "typical" (composite) eddy (Thompson and Young, 2007). The eddy flux across the section can then be computed as the flux per a composite eddy multiplied by the number of eddies that can geometrically fit into the section.

To utilize this idea globally, we divide the ocean into 6º-longitude x 6º-latitude geographic bins. The bin size of 6º (~600 km) is chosen because it corresponds to the average eddy propagation distance of 550 km derived from the satellite altimetry data (Chelton et al., 2011). Eddy composites are constructed in each geographic bin and the eddy flux across the bin is estimated using the idea of the ocean densely packed with eddies.

Eddy salt transport through the eddy composite analysis



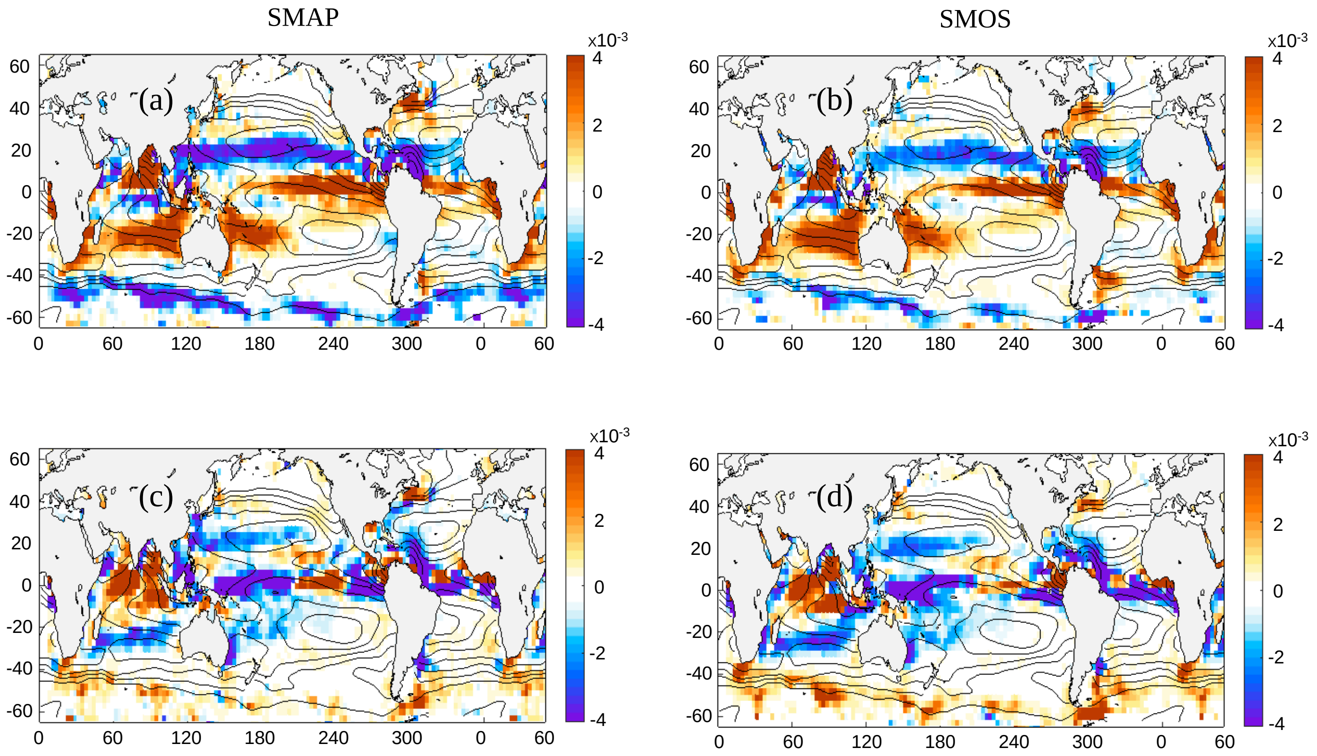
Eddy salt fluxes in the surface mixed layer estimated through the eddy composite analysis from SMAP (left; a,c) and SMOS (right; b,d) SSS data during the common observational period from 2015 to 2019. (Upper; a-b) Meridional salt flux. Positive (negative) values indicate northward (southward) salt flux. (Bottom; c-d) Zonal salt flux. Positive (negative) values indicate eastward (westward) salt flux. Units are kg m^{-2} s^{-1}. Shown on top of each figure are contours of mean SSS (C.I.=0.5 psu).

The estimates of the eddy salt flux agree very well between the two satellites and show physically meaningful structure. This includes both the meridional and zonal components of the flux.

In each of the five subtropical gyres (identified by the subtropical SSS maxima), the eddy flux is divergent - eddies pump salt out of the gyre. The zonal component also contributes to this process although its spatial structure is more complicated. We can see that the zonal component of the flux appears significant in the regions of strong zonal background SSS gradients, generally consistent with the “gradient-flux” relationship.

In the tropics, eddies tend to pump salt into the areas of low SSS, such as in the eastern Pacific Fresh Pool. Eddy fluxes in the sub-polar gyres are substantially smaller than in the tropics and subtropics. In the Southern Ocean, the eddy salt transport is poleward across the Antarctic Circumpolar Current (ACC) with the largest cross-ACC transport occurring in the Indian Ocean sector. The large poleward flux across the ACC suggests that eddies act to weaken strong background salinity gradients associated with the Sub-Antarctic Front (SAF).

Eddy salt transport by covariance analysis



Eddy salt fluxes in the surface mixed layer estimated by covariance analysis from SMAP (left; a,c) and SMOS (right; b,d) SSS data. (Upper; a-b) Meridional salt flux. Positive (negative) values indicate northward (southward) salt flux. (Bottom; c-d) Zonal salt flux. Positive (negative) values indicate eastward (westward) salt flux. Units are kg m^{-2} s^{-1}. Shown on top of each figure are contours of mean SSS (C.I.=0.5 psu).

The eddy transport of salt in the surface mixed layer can also be estimated in a traditional way by computing covariances between eddy induced velocity and SSS perturbations at a given geographical location. To separate the eddy signal from low-frequency variability (annual and longer time-scales), the analysis is made using decomposition in the frequency domain.

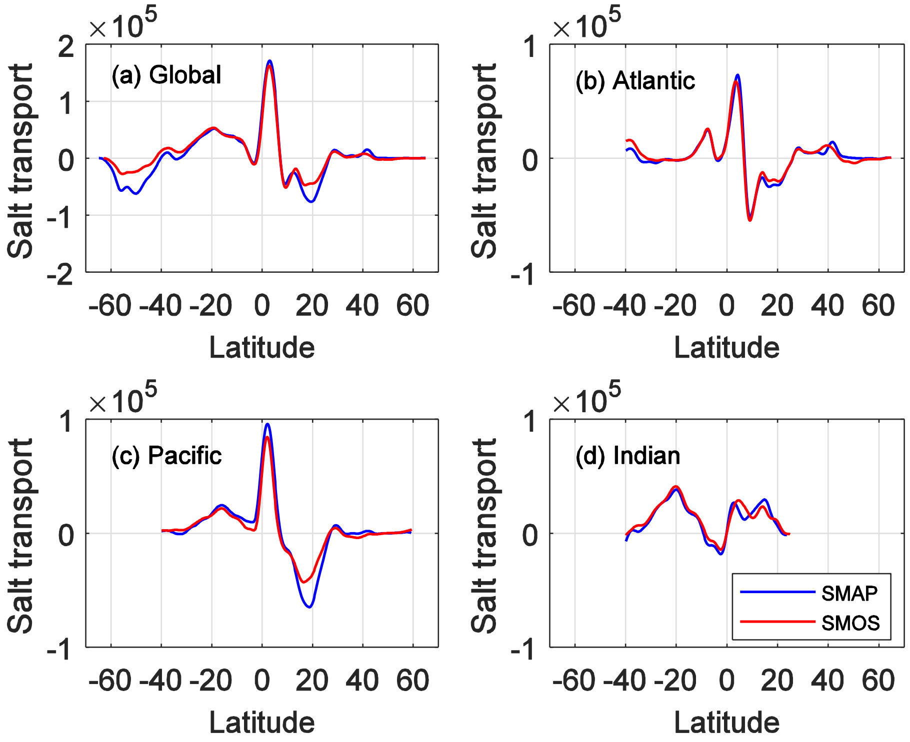
$$\overline{u'S'} = \int_{\omega_1}^{\omega_2} \mathrm{Re}[\hat{u}(\omega)\hat{S}^*(\omega)]d\omega, \qquad \overline{v'S'} = \int_{\omega_1}^{\omega_2} \mathrm{Re}[\hat{v}(\omega)\hat{S}^*(\omega)]d\omega$$

The integration is over the frequency band associated with the eddy variability, taken in our study to be time scales shorter than 6 months.

The maps of the eddy salt fluxes from SMAP and SMOS nearly mirror each other. Some quantitative differences are in the Southern Ocean along the ACC, where SMOS data demonstrate systematically lower meridional fluxes and somewhat stronger zonal fluxes. This can partly be related to the longer period of averaging in the case of SMOS data and/or higher level of noise. Other than that, the comparison is remarkably good.

We find that the estimates of the eddy salt transport by the two methods agree very well, particularly in the tropics and subtropics. Such a good comparison between the two methods also validates the assumption that the ocean is densely packed with mesoscale eddies and the eddy transport is mainly due to large eddies.

Where do ocean eddy salt fluxes matter?



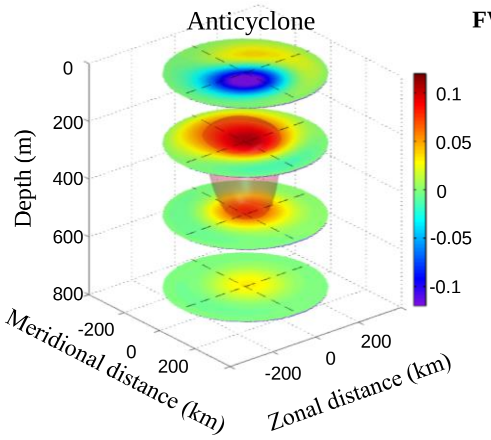
Zonally integrated eddy salt fluxes in the surface mixed layer evaluated (a) globally and over the (b) Atlantic, (c) Pacific, and (d) Indian Ocean from SMAP (blue) and SMOS (red) SSS data. The fluxes are in 1-m layer. The units are kg m^{-1} s^{-1}

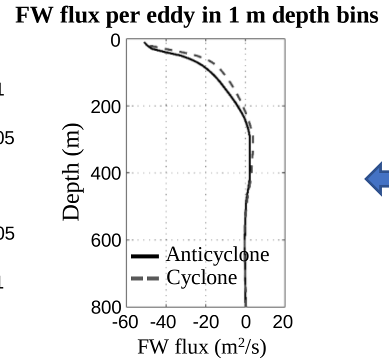
Our analysis confirms that the eddy transport of salt (or, equivalently, freshwater) is an essential component of the marine hydrological cycle. The regions of major eddy transport of salt occur in the tropical belt, across the equatorward limbs of the subtropical gyres, and across the ACC. The eddy transport in the sub-polar gyres is substantially smaller than the eddy transport in the tropics and subtropics.

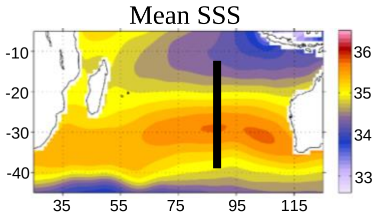
In the interiors of the subtropical gyres, the role of mesoscale eddies in balancing the mean E-P flux can be significant. The highest surface forcing compensation is observed in the North Pacific and South Indian Ocean, around 15% and 25%, respectively.

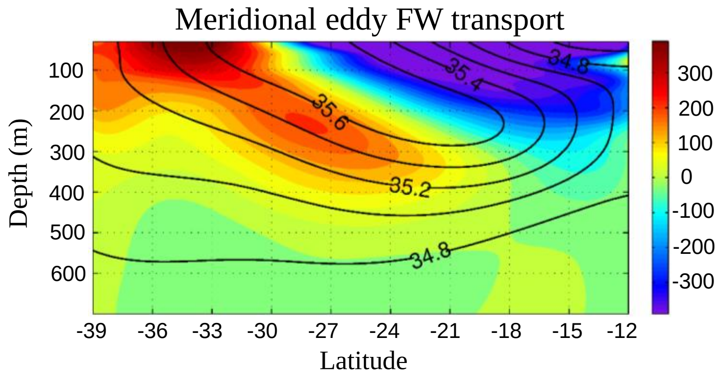
Comparing the eddy salt transport in different basins we note large maxima in the Atlantic and Pacific near-equatorial belt peaking at about 2-3^{o}N. These are the largest peaks and are likely associated with the signal of tropical instability waves (TIWs) that are active in both the Atlantic and Pacific. It appears that TIWs can play a very significant role in the local salt budget in the tropical Pacific and Atlantic.

Where do ocean eddy salt fluxes matter?









Eddy composite analysis can be utilized to assess the vertical distribution of the eddy FW transport (e.g., across a zonal section).

One possible implication of our analysis is also a potential to reconstruct a three-dimensional (3D) structure of the eddy-induced transport of salt using in-situ data, such as Argo profiling float data. Although the spatial resolution of the Argo data is obviously not sufficient for direct estimates, it might be quite sufficient to construct 3D eddy composites, which in turn can be used to reconstruct a 3D distribution of the eddy transport. Such a reconstruction would be meaningful as shown in our study by the comparison with direct estimates at the sea surface. This technique, yet for the eddy heat flux, was successfully used by Müller and Melnichenko (2020) to reconstruct the eddy transport of heat across a zonal section along 47°N in the North Atlantic.

Conclusions

- Satellite observations of SLA and SSS were used to characterize and quantify lateral eddy salt transport (or, equivalently, freshwater) in the ocean surface layer.

- Two methods (via eddy composites versus direct covariance computations) and two satellites (SMOS and SMAP) produce consistent estimates.

- The role of mesoscale eddies in the ocean freshwater transport can begin to be assessed from existing satellite data. We presented examples for the subtropical gyres, where the eddy FW flux contribution versus surface E-P forcing in the surface mixed layer budget can be as large as 25%, such as in the South Indian Ocean.

- The role of mesoscale eddies in the ocean FW transport can begin to be assessed from existing satellite data. Yet, better resolution and accuracy are required to accurately capture eddy processes in high latitudes.

Reference:

Melnichenko, Oleg, Peter Hacker, and Vasco Müller. 2021. "Observations of Mesoscale Eddies in Satellite SSS and Inferred Eddy Salt Transport" *Remote Sensing* 13, no. 2: 315. https://doi.org/10.3390/rs13020315