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Horizontal stirring in the global ocean

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Abstract

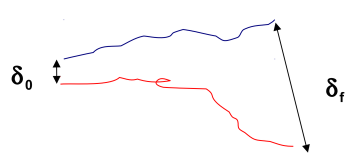
Horizontal mixing and the distribution of coherent structures in the global ocean are analyzed using Finite-Size Lyapunov Exponents (FSLE), computed for the surface velocity field derived from the *Ocean general circulation model For the Earth Simulator* (OFES). FSLEs measure horizontal stirring and dispersion; additionally, the transport barriers which organize the oceanic flow can roughly be identified with the ridges of the FSLE field.
We have performed a detailed statistical study, particularizing for the behaviour of the two hemispheres and different ocean basins. The computed Probability Distributions Functions (PDFs) of FSLE are broad and asymmetric. Horizontal mixing is generally more active in the northern hemisphere than in the southern one. Nevertheless the Southern Ocean is the most active ocean, and the Pacific the less active one. A striking result is that the main currents can be classified in two "activity classes": Western Boundary Currents, which have broad PDFs with large FSLE values, and Eastern Boundary Currents with narrower ranges and lower FSLE values. Both classes are also found when we correlate FSLE fields with Eddy Kinetic Energy (EKE) and vorticity ,ω, with particular *dispersion relations*. These relations characterize the dynamics of different ocean areas, which would influence the presence and evolution of biological markers, among other variables.

Data and Methods

FSLE:

$$\lambda(\mathbf{x}, t, \delta_0, \delta_f) = \tau^{-1} \ln(\delta_f/\delta_0)$$

δ_0 is the initial separation
δ_f is the final separation
τ is the time needed for two particles initially separated δ_0, to get separate δ_f
x_0 are the initial coordinates
t time



The δ_f used for the global computation depend to latitude (θ) : δ_f = 1.3$cos\theta$ degrees
The δ_0 used is δ_0 = 1/10°
Note that should δ_f be a decreasing function of the latitude, since mesoscale structures decrease in size with Rossby Deformation Radius (RDR).

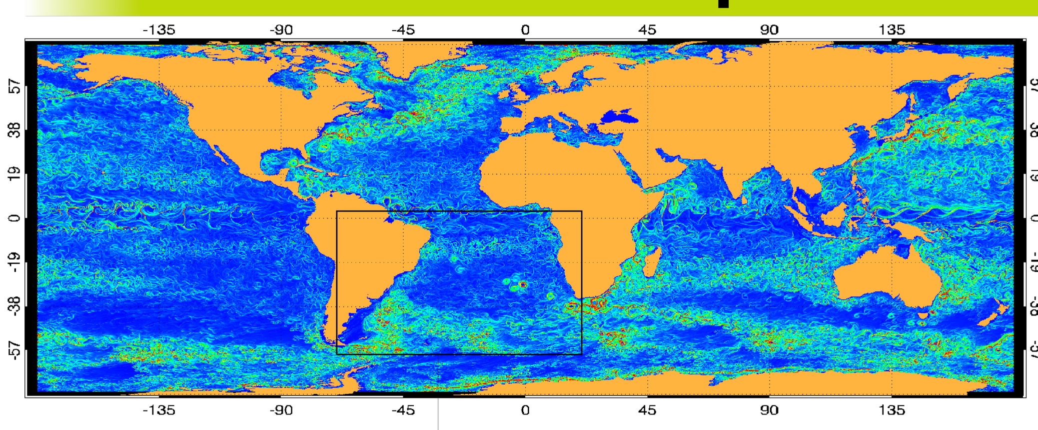
DATA:

The FSLEs are computed using daily surface velocity data from **Ocean general circulation model for the Earth Simulator (OFES)**. This is a global ocean model that has been run under climatological NCEP (United States National Centers for Environmental Prediction) forcing for 50 years, with daily output for the last eight years.

In this model the **horizontal resolution** for velocity data is the same in both the zonal and meridional directions: **1/10°**

The velocity data correspond to the second output layer, at **7.56 *m* depth**

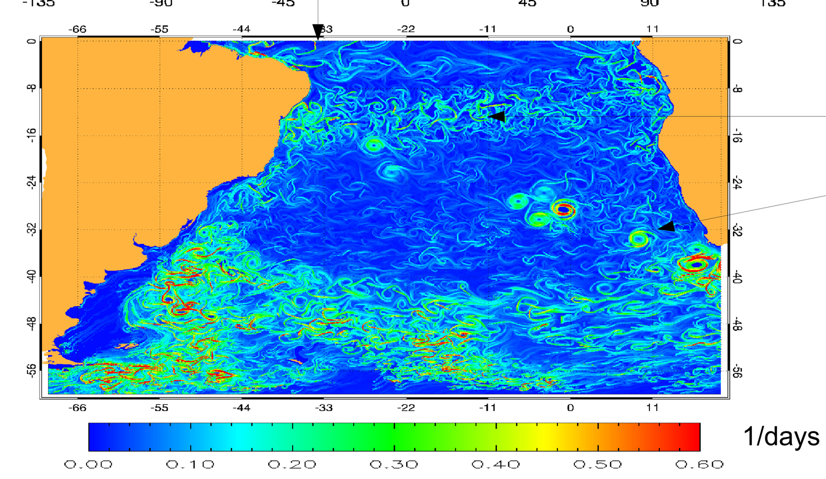
Global maps of LCS from FSLE



Lagrangian Coherent Structures, from mesoscale to larger ones, are clearly identified.

Horizontal mixing times of the mesoscale are in the range days/weeks.

High values of FSLE coincident with main strong ocean currents: Kuroshio, Gulf Stream, Antarctic Circumpolar Current, East Australia, Brasil....



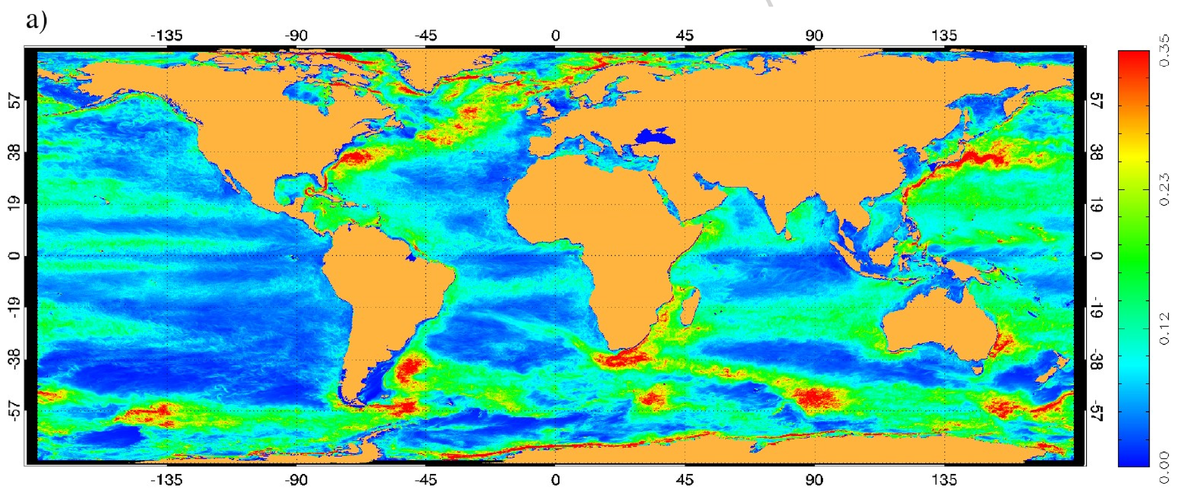
Large Filamental structures

Eddies: Agullas Rings

Geographical comparisons of horizontal mixing

Spatial distribution of Horizontal mixing: Temporal average of FSLE over different periods. Averages over the 51 weekly maps computed for the second simulation output year.

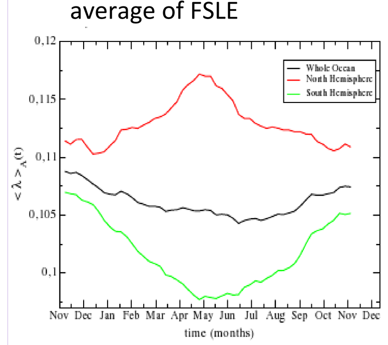
a)



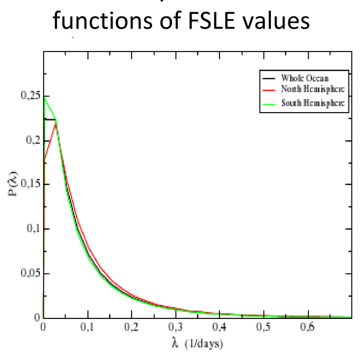
Regions of different mixing activity: High mixing values correspond to Western Boundary Currents (WBCs) and to Antarctic Circumpolar Current, while Eastern Boundary Currents (EBCs) display lower values.

Comparison between hemipheres

Temporal evolution of spatial average of FSLE



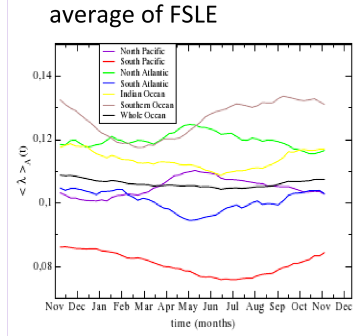
Probability distribution functions of FSLE values



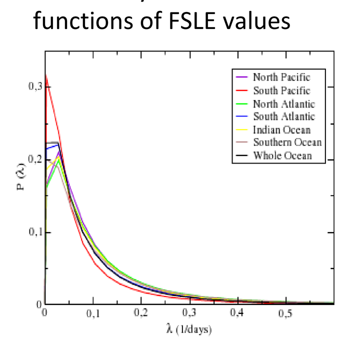
Mixing intensity is larger in northern hemisphere than in the southern one.
Seasonal variations: Maximum values of mixing are reached is early summer and minimum ones in the earky winter in both hemispheres.
PDFs are broad with heavy tails.

Comparison between oceans

Temporal evolution of spatial average of FSLE



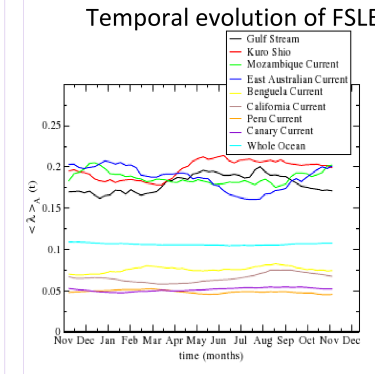
Probability distribution functions of FSLE values



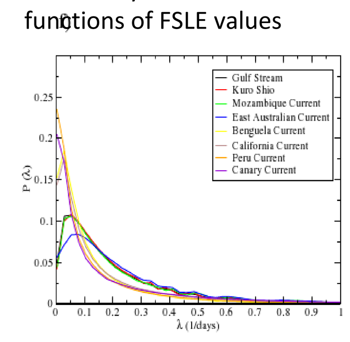
Southern ocean happens to be the most turbulent (because ACC), followed by the Atlantic and Indian Oceans, and finally the Pacific.
PDFs are broad and asymmetric, with a maximum at small values of FSLE, and heavy tails. The smallest modal value of λ correspond to the souther Pacific (less mixing activity). Largest FSLE values correspond to Southern Ocean.

Comparison between main currents

Temporal evolution of FSLE



Probability distribution functions of FSLE values

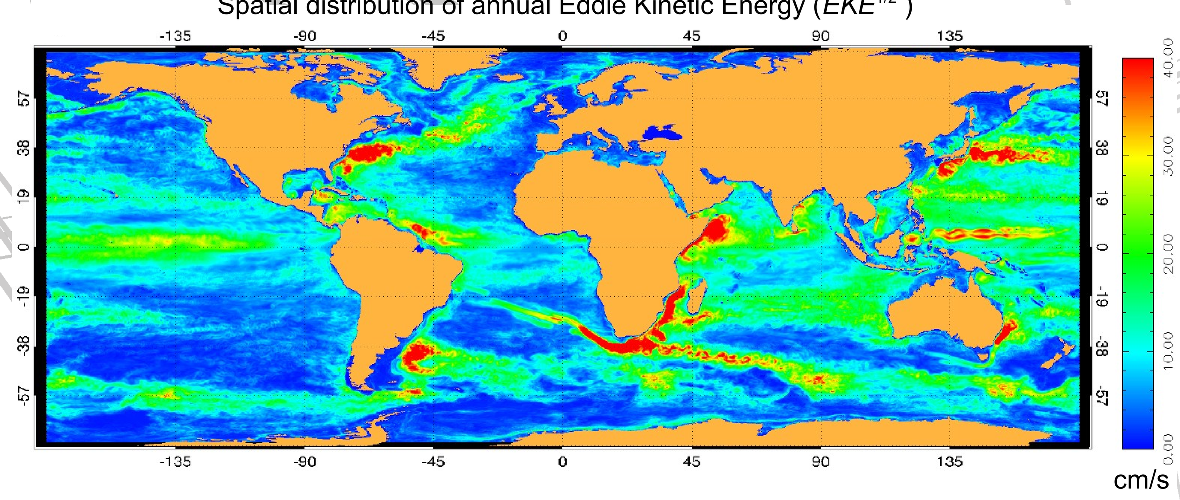


Two groups splited withdifferent horizontal mixing:
- High values for WBCs
- Low values for EBCs

Two groups of PDFs clearly distinguish:
- one with a high peak for small values of λ (EBCs)
- other group with a lower peak for small values of λ, and the distribution are broader (WBCs).

Dispersion relations

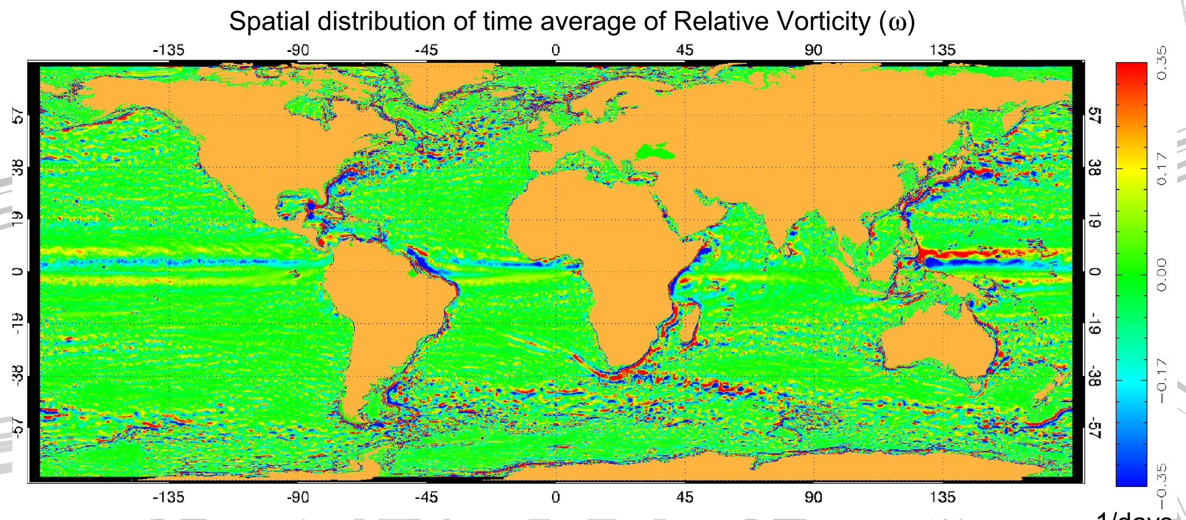
Spatial distribution of annual Eddie Kinetic Energy ($EKE^{1/2}$)



$$EKE = \frac{1}{2}\langle u'^2 + v'^2 \rangle$$

Where u' and v' are the instant deviations on zonal and meriodional velocities from their one-year average, and the brackets denote average over that year.

Spatial distribution of time average of Relative Vorticity (ω)

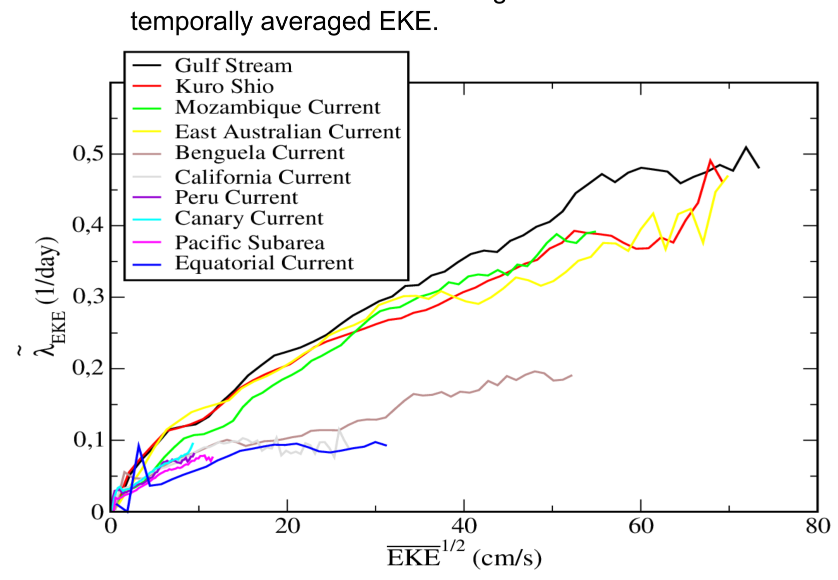


$$\omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$$

Positive (negative) ω associated to cyclonic (anticyclonic) motion in the Northern Hemisphere (opposite sign in the Southern Hemisphere.

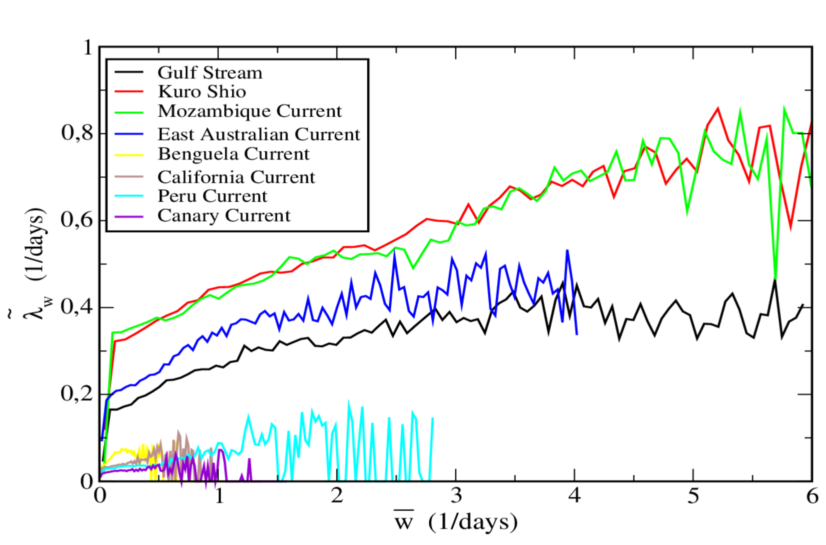
Areas with higher and lower values of EKE and Vorticity (maximum and minimum) are coincidents with higher and lower FSLE values: Variations in horizontal mixing are closely related to variations in mesoscale activity.

Conditional average obtained from the temporally average values of FSLE by further averaging the values at the different locations sharing the same value of temporally averaged EKE.



The figure show two rather well defined functional relationships between λ and EKE.
WBCs are associated with one type of dispersion relation λ -EKE and the EBCs with the other one.
Power low $\lambda \propto EKE^{\alpha}$ α (0.30-0.35)

Conditional average of the temporally averaged values of FSLE values at the different locations sharing the same value of the temporally averaged ω.



The correlation λ -ω is well defined.
The same two types of groups appear (WBCs and EBCs).

A clear dynamical behaviour is present in these two categories of oceanic regions, raising the possibility of a bi-modal mechanism of dispersion in the ocean.

Conclusions

- Computations of FSLE at global scales show that the horizontal mixing is highly non-uniform, with maximum values in the western, and low values in the eastern boundary currents
- The PDFs of FSLEs for the whole ocean, hemispheres, and main currents are broad, asymmetric, with long tails which are extend to high FSLE values.
- The Northern hemisphere has generally higher values of horizontal mixing than the Southern one, and a seasonal behaviour for both hemispheres is present.
- Correlation FSLE-EKE and FSLE-*w* has found and characterized by dispersion relations. Two groups of oceanic regions, associated to different mesoscale activity, split according to these relations, which could be relevant to understand global dispersion behaviour of biogeochemical tracers and biological activity.
- Similar results are also found when we use velocity fields corresponding to a layer at 100m depth, where wind forcing action is not so relevant.

References: *Hernández-Carrasco, I. , López, C., Hernández-García, E., Turiel, A.* Horizontal Stirring in the global ocean. arXiv:1103.5927 (2011) http://arxiv.org/abs/1103.5927