DIEGO: Data and dynamIcal synErGies for swOt

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1. Introduction and Objectives

SWOT was designed in order to perform a breakthrough in our ability to observe mesoscale and submesoscale (M/SM) processes. Crucially, SWOT may thereby validate the insight that has been gained, most often from numerical simulations, about M/SM dynamics as well as about their impact on the general functioning of the ocean. The first stages of the mission development have highlighted several challenges that will have to be overcome before SWOT original objectives may be reached [Klein et al. 2015, Arbic et al. 2015, Morrow et al. 2019]. Relevant to DIEGO are 1/ the overlap between IGW and M/SM processes at scales smaller than 100 km, 2/ SWOT sparse temporal sampling compared to temporal scales of newly resolved processes, 3/ the extrapolation of SWOT measurement of sea level at depth. It has also become clear that SWOT data will have to be combined with other sources of observations (e.g. sst, color, surface drifters, argo) in order to address these challenges and that new methods need to be developed to achieve such combinations.

DIEGO gathers researchers and engineers with backgrounds ranging from oceanography, geophysical fluid dynamics, numerical modeling, data and mathematical science in order to tackle several of the challenges expected with the analysis of SWOT data. State of the art numerical simulations, existing observations (in situ, satellite), novel dynamical insight and statistical approaches will be combined in order to develop and test methods leveraging SWOT-like data such that they are applicable when data is available. The project is organized around 6 work packages (WP): 1/ novel data synergies; 2/ 3d reconstructions for SWOT; 3/ dynamics - classification and reconstructions; 4/ internal tide mapping and predictability; 5/ learning based SWOT data analytics; 6/ SWOT for biology.

2. Planned activities and approaches

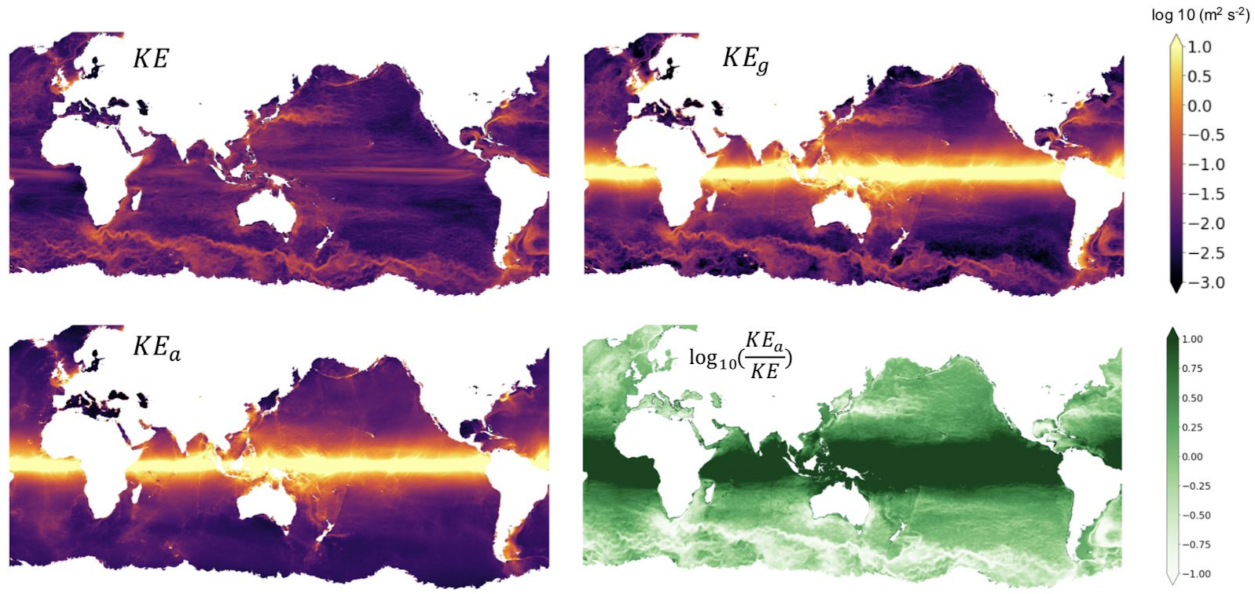
Novel data synergies

SWOT - drifter - tracers synergies. Diego's first objective is to push further the development of promising synergies between SWOT data and surface drifters (as deployed by the Global Drifter Program - GDP) and tracers (e.g. temperature, color). These synergies have been identified during SWOT scientific team last round by DIEGO members [Ponte et al. 2017, Yu et al. 2019] and are relevant to the issue of distinguishing slow from fast dynamics in SWOT data. Methods will be developed with idealized and realistic numerical simulations of the ocean circulation and eventually applied to SWOT data.

Lagrangian advection and statistics with SWOT data. In order to compute large-scale horizontal transport, surface energy exchanges or global estimates of other Eulerian quantities, it appears crucial to assess how well horizontal velocities computed from SSH by geostrophic balance compare to actual surface currents and down to what length scale. For this purpose, Lagrangian dispersion approaches provide an ideal framework, especially in view of applications oriented to the quantification of transport properties. We will address the following two questions: i) Can we assess the extent to which SWOT SSH is a good proxy for surface horizontal velocity, as a function of spatial scale? ii) How can we compare surface drifters' statistics to statistics of synthetic tracer particles advected by the SWOT SSH? These questions will be answered thanks to an analysis of the dispersion characteristics of ensembles of synthetic Lagrangian tracer particles advected by the SWOT simulator as well as idealized (shallow water) or realistic (NATL60) models.

3D reconstruction for SWOT

We propose to take advantage of recent statistical developments in machine learning in order to combine satellite with in situ data and produce an accurate 3D time series of the ocean state at the mesoscale that preserves each dataset advantages. We will focus on western boundary current extensions (WBCE) because they represent the most dynamical regions of the ocean where key air-sea interactions (influencing the sub-mesoscale) and ocean transports and mixing are taking place (Kwon et al, 2013). WBCE are furthermore one of the largest sources of uncertainties for global climate indicators because of observation errors and high level of the chaotic component to the variability.



Decomposition of the surface kinetic energy (up-left) into geostrophic contribution (up-right) and ageostrophic contribution (lower-left) as predicted by a realistic numerical simulation of the ocean circulation (LLC4320). Lower-right shows the normalized amplitude of the ageostrophic flow which highlights in green areas were inferences of surface currents from SWOT will be complicated by energetic high frequency motions. X. Yu, ongoing work.

Dynamics: classification and reconstructions

Unbiased geostrophy assessment and higher order dynamical balances and velocity reconstruction. SWOT is expected, thanks to its sea level mapping capability, to significantly improve our ability to estimate the ocean surface circulation. The latter task is traditionally performed via an assumption of geostrophic equilibrium. With realistic numerical simulations (LLC4320, eNATL60, MEGATL-1km), we propose to quantify the validity of this assumption, investigate the validity of higher-order momentum balances for the surface flow depending on the type of dynamical regime, and, use this knowledge for the reconstruction of horizontal velocities and vertical velocities in the ocean surface layer.

Energy pathways and sinks estimates with SWOT. Geostrophic turbulence is mainly characterized by horizontal scales close to the 1st radius of deformation and is surface-intensified, in correspondence with the 1st baroclinic mode (Wunsch 1997 and Smith and Vallis 2001). Therefore, altimetry is a natural tool for addressing its properties and behavior. We propose to combine SWOT data with two regional numerical simulations to determine the geostrophic eddies energy sinks. To do so, we will perform a 3D Kinetic Energy budget for the 1st baroclinic mode in the region of the Gulf Stream and of the Agulhas Current. The numerical simulations will be used to diagnose each terms of the 3D Kinetic Energy Budget directly from the 3D momentum terms and also to develop a computation for estimating the energy fluxes from altimetry data.

Internal tide mapping and predictability

Amongst fast oceanic motions, internal tides will have the strongest signature on sea level in the open ocean. We propose to improve our ability to map and predicts internal tides. The focus will be on stationary internal tides and on the setup of an assimilating framework for its estimation based on emerging dynamical models of internal tide propagation and altimetric data (SWOT sea level observations included) ingestion. A central goal will be to quantify whether such framework can reduce the time windows for the estimation of stationary internal tides and/or improve the accuracy of these estimations. We also propose to quantify the degree of predictability of non-stationary internal tides. This predictability is a function of the accuracy of the internal tide dynamical model employed, and, of the accuracy of a priori estimates of the background oceanic circulation. Idealized numerical simulations will be analyzed for that purpose.

Learning-based SWOT data analytics

Our general objective is to develop an adapted framework in the context of the SWOT mission, building synergies with other observation and/or simulation datasets. As understood, SWOT will clearly involve an irregular space-time sampling with highly-resolved 2D snapshots. From a learning-based perspective, 2D snapshots naturally advocate the use of convolutional models, the core of deep learning models (i.e., CNN, Convolutional Neural Network). Overall, this WP aims to develop learning-based ocean dynamics analytics and practical neural network (NN) representation with a focus on multi-tracer synergies. The proposed approach will explore to the following specific questions:

- Q1. How to design and learn practical representations of upper ocean dynamics ?
- Q2. How to embed physical priors in the learnt NN representations ?
- Q3. How to better inform upper ocean dynamics from instantaneous multi-modal Earth observation snapshots ?

SWOT for biology

SWOT's high spatial resolution will allow to describe the deformation field associated to mesoscale eddies as it was never done before. In this context, we propose to focus on the effect of submesoscale fronts on primary surface production by addressing the following scientific question: Can surface primary production in sub-mesoscale structures be estimated from satellite data (altimetry and ocean color)? Based on recent results (Zhang et al. 2019) and on the forthcoming SWOT observations, we propose to use Lagrangian surface drifters in different oceanic regions (North Atlantic, North Pacific) combined with altimetry and ocean color products to evaluate the primary production and ageostrophic circulation in strong strain rate areas. This approach will also be combined with *in situ* and airborne observations collected during the NASA North Atlantic Aerosols and Ecosystems Experiment (NAAMES) (thermosalinograph, drifters and biogeochemical and optical tracers) in the North Atlantic (figure 2).

3. Expected outcomes

SWOT - drifter - tracers synergies. The minimum expected result is to improve our understanding about the signatures of fast/slow motions on 1/ SWOT sea level, 2/ drifters trajectories and velocities, and, 3/ tracers (e.g. SST), as well as about their relationships. We expect to be able to provide flags for SWOT data in order to indicate whether fast motions are present and may “contaminate” surface current estimates. The ultimate expectation is to provide a method that allows, under favorable experimental conditions, to distinguish fast/unbalanced and slow signatures in SWOT data.

Lagrangian advection and statistics with SWOT data. The proposed research aims at exploring how the Lagrangian approach and turbulence theory predictions can help in separating balanced and unbalanced motions at small scales and in determining the extent to which the SWOT SSH signal well represents horizontal surface ocean currents, as a function of scale. We expect to identify a critical length scale above which the possibly unresolved motions in the signal do not significantly affect the dispersion process and, consequently, the geostrophically derived velocity correctly accounts for transport and mixing of passive tracers at the surface of the ocean. By means of the Lagrangian methodology that we plan to develop, we further expect to provide indications on the dynamically relevant ageostrophic processes at small scales.

3D reconstruction for SWOT. Recent statistical developments in machine learning will be leveraged in order to combine satellite with in situ data and produce an accurate 3D time series of the ocean state at the mesoscale that preserves each dataset advantages. We will focus on western boundary current extensions (WBCE) because they represent the most dynamical regions of the ocean where key air-sea interactions (influencing the sub-mesoscale) and ocean transports and mixing are taking place (Kwon et al, 2013). WBCE are furthermore one of the largest sources of uncertainties for global climate indicators because of observation errors and high level of the chaotic component to the variability.

Dynamics: classification and reconstructions. A central result we wish to obtain is an unbiased global map of the accuracy of the geostrophic relationship. We will also obtain an “atlas” of the first-order balances between the terms of the momentum equation in the Atlantic Ocean. In addition to a better knowledge of the dynamical regimes, it will also provide a framework to reconstruct surface velocities that will be used directly with SWOT data.

Internal tide mapping and predictability. The minimum result expected is to know whether dynamical models for internal tide propagation can indeed improve the accuracy of stationary internal tides mappings in configurations of varying realism. We will identify difficulties and potential blocking points and bring more rationale to approaches that have relied so far on pure statistical or dynamically empirical choices. If deemed like a feasible task, we will also provide specifications for the development of systems that will improve the accuracy of stationary internal tide predictions.

Learning-based SWOT data analytics. We expect major breakthroughs in the analysis and exploitation of SWOT data, alone and/or combined with in situ data, other satellite-derived data as well as simulation data, from the design and implementation of appropriate learning-based and data-driven schemes, possibly combined with state-of-the-art model-driven approaches. This WP shall contribute to investigating and demonstrating this potential.

SWOT for biology. The anticipated results are a better quantification of surface primary production in submesoscale fronts induced by the mesoscale eddy field deformation and how this quantification is affected by parameters such as currents intensity and scales (from Nadir to Wide Swath altimetry of SWOT), mixed layer depth, and seasonality.

4. References

- Arbic, B. K., Lyard, F., Ponte, A., Ray, R., Richman, J. G., Shriver, J. F., Zaron, E., and Zhao, Z. Tides and the swot mission: Transition from science definition team to science team. Tech. rep., CNES-NASA, 2015.
- Klein, P., Morrow, R., Samelson, R., Chelton, D., Lapeyre, G., Fu, L., Qiu, B., Ubel- mann, C., Traon, P.-Y. L., Capet, X., Ponte, A., Sasaki, H., d'Ovidio, F., Farrar, T., Chapron, B., D'Asaro, E., Ferrari, R., McWilliams, J., Smith, S., and Thompson, A. Mesoscale/submesoscale dynamics in the upper ocean. Tech. rep., CNES-NASA, 2015.
- Morrow, R., Fu, L.-L., Ardhuin, F., Benkiran, M., Chapron, B., Cosme, E., d'Ovidio, F., Farrar, J. T., Gille, S. T., Lapeyre, G., et al. Global observations of fine-scale ocean surface topography with the surface water and ocean topography (swot) mission. Frontiers in Marine Science 6 (2019), 232.
- Ponte, A. L., Klein, P., Dunphy, M., and Gentil, S. L. Low-mode internal tides and balanced dynamics disentanglement in altimetric observations: Synergy with surface density observations. J. Geophys. Res., Oceans (2017).
- Yu, X., Ponte, A. L., Elipot, S., Menemenlis, D., Zaron, E., and Abernathey, R. Surface kinetic energy distributions in the global oceans from a high-resolution numerical model and surface drifter observations. Geophys. Res. Lett. (2019).
- Zhang, Z., B. Qiu, P. Klein and S. Travis (2019). *Nature Communication*, 10 :2838. doi:10.1038/s41467-019-10883