

## Investigation Plans:

# Fluxes of Heat, Carbon, and Oxygen at SWOT Scales

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## Introduction and Objectives

There are many complex issues involved in maximizing the usefulness of SWOT observations. Our particular focus is on better understanding how SWOT may aid in better establishing the role played by submesoscale phenomena in mediating fluxes of the biogeochemical tracers. Can SWOT help determine submesoscale contributions to global budgets? What are the primary lateral and temporal scales responsible for transport? Which submesoscale processes play the most important roles in vertical fluxes? We are addressing these questions with suites of submesoscale-resolving regional simulations, described briefly below.

## Approach

Our approach is centered on carefully designed high-resolution numerical simulations, designed to probe the transport properties of mesoscale and submesoscale flows in a systematic way. These simulations are focused on two regions of the ocean that are known to be important for carbon and heat uptake and biological productivity, but are also poorly observed and understood: the *Southern Ocean* and the *Arabian Sea*. By conducting simulations at increasing resolutions, up to submesoscale resolving, we hope to reveal how small scale processes contribute to the transport of climate-relevant tracers. Once this scale-dependent diagnosis of transport is complete, our project will move on to ask how the transports can best be inferred from SWOT observations using a range of different frameworks, including simple diffusive models, scale-dependent closures, reconstruction methods and machine learning.

The Southern Ocean simulations are idealized in their geometry and forcing but grounded in observations. The basic setup for the simulations is derived from the model used in Abernathey et al. (2011) and Abernathey and Cessi (2014). The simulations use the MITgcm, and the domain consists of a zonally reentrant channel on a beta plane, forced at the surface with wind stress and heat flux, with either a free-slip wall or a sponge layer at the northern edge of the domain. By including a sponge layer at the northern boundary, a residual meridional overturning circulation can be induced. Configurations have been developed with a flat bottom, a meridional ridge, and random bottom topography.

The Arabian Sea simulations are based on the set up in Lachkar et al. (2016). Unlike the Southern Ocean simulations, these are set in a realistic domain with observed topography and open boundary conditions that are restored to hydrography. The numerical

model used is the Regional Ocean Modeling System (ROMS), forced at the surface with data from the Comprehensive Ocean-Atmosphere Data Set (COADs) and QuikSCAT winds, and restored at the open boundaries Simple Ocean Data Assimilation (SODA) dataset. The model relatively complex biogeochemistry model. Initial simulations, run with with 32 -levels and horizontal resolutions up to 1/24 , yield mean states that compare well to observed sea surface height, temperature, salinity and chlorophyll concentrations, producing the expected Somali spring bloom and the winter bloom in the north of the domain.

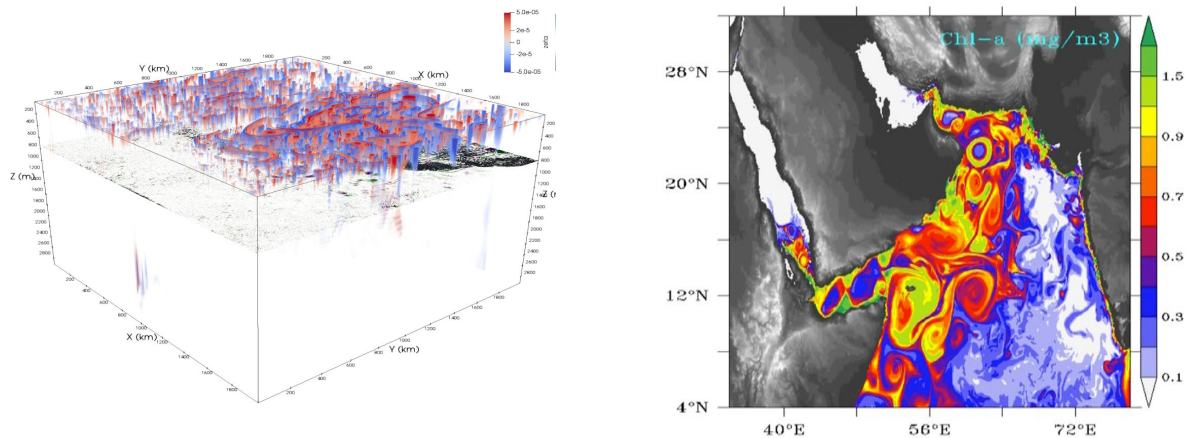


Fig. 1: (left) Snapshot of vorticity (red/blue) and vertical velocity (green/purple) from MITgcm channel simulation at 1.25km resolution. (right) Snapshot of chlorophyll in 4km ROMS Arabian Sea simulation.

## Analysis and Anticipated Results

**Spatiotemporal Scales of Vertical Fluxes:** A first step in our analysis is to diagnose the space and time scales of vertical fluxes of heat and passive tracers in the simulations. Many different physical processes can potentially contribute to vertical tracer transport, including: Ekman pumping, vertical advection by the residual circulation, mesoscale mixing along isopycnals, and submesoscale vertical transport (possibly enhanced by frontogenesis). There is no consensus regarding the relative importance of these different processes for the transport of climatically and biologically relevant tracers in different regions of the ocean.

Since these processes occupy distinct regions of the wavenumber / frequency spectrum, a straightforward method to diagnose their contributions in simulations is via spectral analysis. Spatiotemporal spectral analysis will be applied to the Southern Ocean and Arabian Sea simulations. Parseval's theorem ensures that the total flux is the same whether represented in space / time or wavenumber / frequency coordinates. By integrating over different spectral bands (e.g. mesoscale, submesoscale), we can therefore quantify the relative contributions of different physical processes to the total transport. We expect that comparing simulations at different resolution will be particularly revealing.

In addition to the spectral analysis, a complementary approach will be used to assess the

impact of small scales on vertical transport. Levy et al (2010) used *spatial coarse graining* of the velocity field to filter out submesoscale motions; they then performed offline advection / diffusion calculations of temperature and compared the results with a lower resolution simulation. This comparison revealed that, although the fluxes were stronger in the higher resolution simulation, the difference was *not* due to the direct advection by small scales—rather, the higher resolution allowed the larger-scale flow to become more energetic. We will apply this same approach to assess the importance of resolution on *vertical* fluxes. We anticipate that small scale advection plays a much more important role in vertical transport than it does in horizontal transport.

Understanding the spatial and temporal scales associated with vertical fluxes has important implications for how SWOT data will be used. A crucial issues is whether SWOT can resolve the dominant space and time scales directly; if so, there is some hope to infer the vertical fluxes *directly*, i.e. by reconstructing the vertical velocities using well chosen vertical modes. If, on the other hand, there are large contributions to vertical fluxes from scales that are beyond SWOT’s effective resolution, a statistical approach will be necessary to link the measurements of sea-surface height to the vertical transport of tracers. Informed by the spatiotemporal diagnostics of vertical fluxes described above, we will design an optimal strategy for inferring vertical fluxes from satellite-observable quantities.

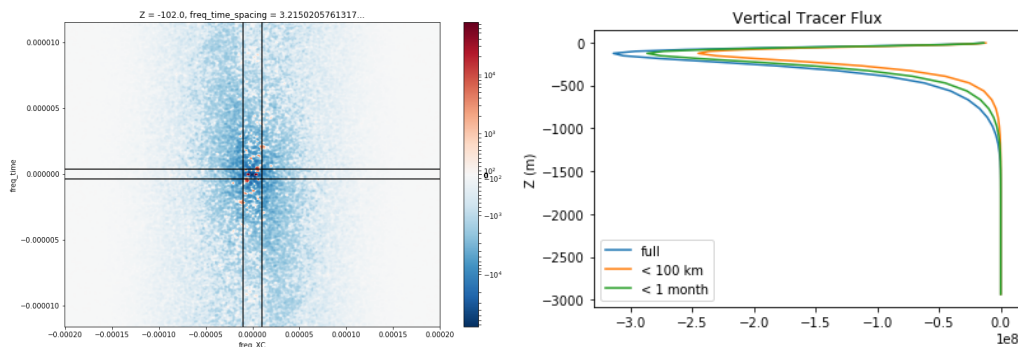


Fig. 2: (left) Wavenumber frequency cross spectrum of vertical flux of passive tracer. (right) global integrals of vertical flux, low-pass filtered in space and time.

**Inferring Vertical Fluxes with Diffusive-Type Closures:** When the dominant scales associated with eddy fluxes cannot be directly measured, diffusive closures can be used to make estimates based on the large-scale background gradients. This is how sub-gridscale parameterizations of eddy fluxes in climate models work. In particular, modern ocean models use at least three distinct eddy parameterizations related to meso- and submesoscale fluxes: the Redi (1982) scheme for isopycnal mixing, the Gent et al (1995) scheme for eddy-induced advection, and the Fox-Kemper et al. (2008) scheme for submesoscale mixed layer instability. Each of these represents a different contribution to the vertical flux from

different physical processes. These schemes can also be applied diagnostically to large-scale climatological observations of the real ocean. The crux of this approach is to accurately determine the appropriate diffusion coefficients. The past decade has witnessed significant progress on this problem (e.g. Ferrari and Nikurashin, 2010; Abernathey et al., 2013; Klocker and Abernathey, 2014). We will use our high resolution models to test and refine theories for eddy diffusivity and relate these theories to statistical quantities that can be observed via satellite altimetry. By simulating the sampling patterns of current generation altimetry along with the expected sampling of SWOT and using these data to estimate diffusion coefficients, we will be able to quantify how the improved spatial resolution of SWOT impacts the inference of vertical eddy fluxes. We will then apply these methods to current satellite observations on a global scale.

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