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Impact of submesoscales on surface material distribution in a gulf of Mexico mesoscale eddy

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ABSTRACT

Understanding material distribution at the ocean's surface is important for a number of applications, in particular for buoyant pollutants such as oil spills. The main tools to estimate surface flows are satellite altimeters, as well as data-assimilative ocean general circulation models (OGCMs). Current-generation altimeter products rely on the geostrophic approximation to derive surface currents. Recent modeling and experimental work revealed existence of ageostrophic submesoscale motions within the upper ocean boundary layer.

The next frontier is how submesoscales influence transport pathways in the upper ocean, which is a multi-scale problem involving the interaction of submesoscale and mesoscale coherent structures. Here we focus on a mesoscale eddy that exhibits submesoscale fluctuations along its rim. The high-resolution OCGM fields are then treated with two filters. A Lanczos filter is applied to velocity fields to remove the kinetic energy over the submesoscales. Then a Gaussian filter is used for the modeled sea surface height to simulate a geostrophic velocity field that would be available from gridded satellite altimeter data. Lagrangian Coherent Structures (LCS) are then generated from full-resolution and filtered fields to compare Lagrangian characteristics corresponding to different realizations of the surface velocity fields.

It is found that while mesoscale currents exert a general control over the pathways of the tracer initially launched in the mesoscale eddy, there is a leak across the mesoscale transport barriers, induced by submesoscale motions. This leak is quantified as 20% of the tracer when using the submesoscale filter over one month of advection, while it increases to 50% using the geostrophic velocity field. We conclude that LCS computed from mesoscale surface velocity fields can be considered as a good first-order proxy, but the leakage of material across them in the presence of submesoscales can be significant.

1. Introduction

Some of the most important scientific problems regarding ocean dynamics are driven by simple questions as such "where do substances come from and where do they go?". These questions are related to problems involving transport of pollutants and biogeochemical tracers in the ocean, as well as search and rescue missions in case of marine or airplane accidents. Tracking biogeochemical tracers moving with the ocean flow field finds use in understanding the global thermohaline circulation (Broecker et al., 1960), which is a slow transport phenomenon occurring at multi-decadal time scales. On the other hand, tracking pollutants may require rapid estimates in order to minimize socio-economic damage, such as in the response efforts to Deepwater Horizon (DwH) oil spill in the Gulf of Mexico (Crone and Tolstoy, 2010) or the radioactive leak into the ocean from the Fukushima meltdown (Rypina et al., 2014). Back-tracking debris from airplane accidents over the oceans, such as in the case of MH370 (Normile, 2014), can aid in narrowing down the location of the accident. These types of problems are best approached in the Lagrangian framework, the general methods of which are reviewed in the summary by LaCasce (2008).

Nevertheless, understanding how material moves under the action of ocean currents, or the Lagrangian transport prediction problem, is extremely challenging. There are at least three reasons for this difficulty. The first of these is the recognition that temporal variability of the flow field is very important in how material gets transported within the system. Aref (1984) showed that even spatially-simple flow fields can lead to chaotic mixing under the action of time dependence. Subsequently, a large number of methods have been developed in order to determine skeletons of

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transport, or so-called Lagrangian Coherent Structures (LCS) that may not be visible from velocity snapshots (Mezić and Wiggins, 1994; Haller and Poje, 1998; Haller and Yuan, 2000). These methods are deterministic in that they rely on the full knowledge of the Eulerian flow field in order to derive the Lagrangian structures. However, observing the oceanic flow field in full (all spatio-temporal degrees of freedom) is a daunting challenge (Sanford et al., 2011). Perhaps the most widely-available data sets with global coverage are gridded satellite altimetry products (Ducet et al., 2000), in which a geostrophic relation is used to convert sea surface height anomaly to surface velocity fields (Wunsch and Stammer, 1998). The impact of uncertainties arising from this simplification, as well as of the missing spatial and temporal motions between satellite tracks (Chavanne and Klein, 2010) on transport estimates concern the main motivations of the present study.

The second issue that makes transport prediction so challenging in the ocean is related to the wide range of spatial scales in the ocean. Unlike classical turbulence, where a cascade of scales is generated by various fluid instabilities during the break down and dissipation of a primary coherent structure, the ocean contains a whole range of dynamically-distinct coherent structures that are forced by multiple processes, while coexisting and interacting together. In particular, the upper ocean boundary layer is stirred from below by mesoscale eddies, contains fronts that are created by surface and riverine buoyancy fluxes, convective plumes with a diurnal cycle, Ekman spiral by wind forcing as well as Langmuir circulations and Stokes drift by the action of surface waves. A particular class of processes, so-called submesoscales, received significant attention since they fall in between the relatively better studied 2D-like mesoscale motions and classical 3D turbulence (Müller et al., 2005). Submesoscale motions are defined as those having scales below the deformation radius, ranging from about tens of km down to the typical depth of the mixed layer, on the order of 100 m, for the dynamics of which, the effect of Earth's rotation is significant (McWilliams, 2008). Submesoscales have been initially explored on the basis of theoretical and modeling studies (Boccaletti et al., 2007; Thomas et al., 2008; Capet et al., 2008; Klein and Lapeyre, 2009; Taylor and Ferrari, 2010; Mensa et al., 2013; Sasaki et al., 2014), and are generally thought of as motions generated by frontogenesis and mixed-layer instabilities (Boccaletti et al., 2007; Fox-Kemper et al., 2008). A recent field exploration revealed the existence of submesoscale flows that are intensified in the upper ocean (Shcherbina et al., 2013). The question of whether submesoscales contribute significantly to surface material transport is studied in numerical models using relative dispersion metrics (Haza et al., 2008; Poje et al., 2010; Özgökmen et al., 2011; Özgökmen and Fischer, 2012). The primary findings from these studies is that it is still quite challenging to fit two distinct scales of motion, mesoscales and submesoscales, in numerical models due to computational expense, and that ocean experiments with a large number of drifters would be the only reliable approach to find the truth. An ocean experiment was conducted using 300 surface drifters, the Grand Lagrangian Deployment (GLAD), to verify or falsify the trends from modeling studies. Poje et al. (2014) concluded that submesoscales indeed contribute to relative dispersion near the Deepwater Horizon oil spill site. Nevertheless, the study by Poje et al. (2014) did not identify the exact mechanisms responsible for submesoscale dispersion.

The third complication for Lagrangian prediction in the ocean concerns the existence of strong vertical velocities acting on buoyant tracers. As initially shown by Zhong et al. (2012), and further studied by Huntley et al. (2015) and (Jacobs et al., 2015), convergence zones in the upper ocean create clustering of surface material. These convergence zones are linked to ageostrophic processes, indicating that geostrophic velocity fields (lacking vertical velocity component) cannot produce a realistic tracer distribution. Thereby the question arises about the errors in transport produced by missing scales of motion.

The main concept that truncating the spectrum of Eulerian motions can lead to differences in Lagrangian transport is not new, but was recognized by Griffa et al. (2004) in the context of a simple quasi-geostrophic model. Poje et al. (2010) analyzed a hierarchy of modeling approaches in order to gain more perspective on the matter, and concluded that relative dispersion is significantly impacted when both spatial and temporal scales of motion are truncated. Haza et al. (2012) developed and tested stochastic Lagrangian models to incorporate the effect of missing scales of motion on relative dispersion.

While the effect of submesoscales is highlighted by several metrics, in particular scale-dependent relative dispersion, it is not yet clear whether submesoscales have any effect on transport. Conceptually, smaller scale turbulent features are usually imbedded within larger scale turbulent features, and smaller ones are transported by the large ones, as opposed to following a completely different path. This general concept is in fact fundamental to the development of subgrid-scale models in the large-eddy-simulation community (Sagaut, 2006) in the context of homogeneous 3D turbulence. It remains unclear to which extent it is applicable in oceanic multi-scale flows.

One of the ways to address this question is to compare in-situ measurements of transport pathways and those derived from satellite altimeters, or data-assimilating ocean models. Such comprehensive data sets are rare, but few have been available recently. For instance, during the DwH event, Olascoaga and Haller (2012) were able to predict the main pathways of the oil spill on the basis of LCS derived from an ocean circulation model that resolved mostly the mesoscale currents. Olascoaga et al. (2013) concluded that LCS from geostrophic velocities derived from altimetry data imposed an important constraint to the motion of drifters from the Grand Lagrangian Deployment (GLAD) in the Gulf of Mexico. A similar conclusion is also reached during a smaller drifter deployment in response to another oil spill in the Gulf of Mexico (Romero et al., 2015). A re-analysis of the GLAD data set by Beron-Vera and LaCasce (2015) using other metrics than scale-dependent relative dispersion and with the help of a high-resolution ocean model further emphasizes the importance of mesoscale control over transport. Nevertheless, Berta et al. (2015) found significant differences between the reconstructed Eulerian flow fields from GLAD and those derived from altimetric geostrophic fields. These differences are especially pronounced within the DeSoto Canyon region in the northern Gulf of Mexico, the site of the DwH spill, while the agreement between satellite-derived and drifter-derived surface velocity field is quite good in the interior, deep Gulf. Berta et al. (2015) attributed deviations from geostrophic currents to possible presence of river discharges, upwelling events along the continental shelf, wind-forcing diurnal or faster times scales, as well as submesoscale dispersion identified by Poje et al. (2014). Conclusions by Berta et al. (2015) are also consistent with d'Ovidio et al. (2015), who validated transport pathways derived from altimetry against trajectories of more than a hundred drifters and chlorophyll images using global, regional, and Ekman-corrected altimetry data. They found that while the Ekman-corrected product was the most reliable, differences at the meso- and smaller scales were evident as well. Clearly, the issue of whether and how submesoscales influence transport is complex, perhaps because it is rather subtle, cannot be generalized easily, and therefore, deserves continued investigation.

In this study, we aim to make progress in addressing the following question:

- Are LCS derived from geostrophic currents robust barriers to transport? That is to say, do they leak under submesoscale