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Dispersion of deep-sea hydrothermal vent effluents and larvae by submesoscale and tidal currents

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ABSTRACT

Deep-sea hydrothermal vents provide sources of geochemical materials that impact the global ocean heat and chemical budgets, and support complex biological communities. Vent effluents and larvae are dispersed and transported long distances by deep ocean currents, but these currents are largely undersampled and little is known about their variability. Submesoscale (0.1–10 km) currents are known to play an important role for the dispersion of biogeochemical materials in the ocean surface layer, but their impact for the dispersion in the deep ocean is unknown. Here, we use a series of nested regional oceanic numerical simulations with increasing resolution (from $\delta x = 6$ km to $\delta x = 0.75$ km) to investigate the structure and variability of highly-resolved deep currents over the Mid-Atlantic Ridge (MAR) and their role on the dispersion of the Lucky Strike hydrothermal vent effluents and larvae. We shed light on a submesoscale regime of oceanic turbulence over the MAR at 1500 m depth, contrasting with open-ocean – i.e., far from topographic features – regimes of turbulence, dominated by mesoscales.

Impacts of submesoscale and tidal currents on larval dispersion and connectivity among vent populations are investigated by releasing neutrally buoyant Lagrangian particles at the Lucky Strike hydrothermal vent. Although the absolute dispersion is overall not sensitive to the model resolution, submesoscale currents are found to significantly increase both the horizontal and vertical relative dispersion of particles at $O(1–10)$ km and $O(1–10)$ days, resulting in an increased mixing of the cloud of particles. A fraction of particles are trapped in submesoscale coherent vortices, which enable transport over long time and distances. Tidal currents and internal tides do not significantly impact the horizontal relative dispersion. However, they roughly double the vertical dispersion. Specifically, particles undergo strong tidally-induced mixing close to rough topographic features, which allows them to rise up in the water column and to cross topographic obstacles.

The mesoscale variability controls at first order the connectivity between hydrothermal sites and we do not have long enough simulations to conclude on the connectivity between the different MAR hydrothermal sites. However, our simulations suggest that the connectivity might be increased by submesoscale and tidal currents, which act to spread the cloud of particles and help them cross topographic barriers.

1. Introduction

Hydrothermal vents form along mid-ocean ridges where tectonic plates diverge. They are unique sites with strong biogeochemical activity (e.g., iron source, Conway and John, 2004) and ecological settings contrasting with the surrounding abyssal landscape (Van Dover, 1995, 2000). As such, Mid-Atlantic Ridge (MAR) hydrothermal vent sites have been extensively sampled. In particular, the Lucky Strike vent field (37.30°N, 32.28°W) has been chosen by the European Multidisciplinary Subsea and water column Observatory (EMSO) to be a prototype for environmental monitoring. However, dedicated cruises have limited spatial coverage ($<10 \times 10$ km^2, e.g., Escartin et al., 2015) and focus on vents themselves and their associated near-field convective plumes. Consequently, the fate of released effluents in the far-field ($>1-10$ days and >10 km) remains uncertain. Yet several questions of biological and (bio)geochemical relevance need to be addressed, e.g., which processes control the transport and mixing of vent effluents? Can vent faunal communities be connected through larval transport at ecologically-relevant time scales?

Dispersion and connectivity issues are fundamentally multi-scale,

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from larval behavioural characteristics (vertical migration and change in buoyancy) to advection by basin-scale currents. Increasing the resolution of *reef-scale* models (Werner et al., 2007) to 0.1–1 km have demonstrated a significant improvement of the realism of physical processes related to interactions with topography, tidally-driven and small-scale currents. As such, the realism of Lagrangian dispersion and connectivity patterns has been improved, unveiling new perspectives on the functioning of reef ecosystems (Bode et al., 2006; Werner et al., 2007). However, this range of resolutions have not been reached so far in the context of deep-sea connectivity.

Oceanic submesoscale (0.1–10 km) processes have been extensively studied during the past decade, but most of the effort has been focused on the surface boundary layer (e.g., Buckingham et al., 2017). They are particularly energetic and have multiple implications on the oceanic state (See review in McWilliams, 2016). Among their implications, surface submesoscale currents strongly impact the transport and mixing of tracers in the surface layer (e.g., Poje et al., 2014; Haza et al., 2016), as well as the dynamics of planktonic organisms, including dispersing larval stages (Sponaugle et al., 2005; Mullaney and Suthers, 2013), and thus connectivity patterns of benthic populations on continental shelves.

Conversely, submesoscale turbulence in the ocean interior (below the surface mixed layer) remains poorly studied although it has been observed in the form of submesoscale vortices since the 1980s (McWilliams, 1985; D'Asaro, 1988; Testor and Gascard, 2003; Bosse et al., 2015, 2016, 2017). At the depth of mid-ocean ridges (i.e., 1000–3000 m), observations of submesoscale currents are rare. Far from boundary currents, the ocean is still widely believed to be very quiescent at these scales, although float trajectories (Reverdin et al., 2009; Bower et al., 2013) and mooring measurements (Lilly et al., 2003) have gathered evidence for locally strong submesoscale flows. Recent modelling studies confirm the existence of submesoscale turbulence in the ocean interior and point out current-topography frictional interactions close to the shelf break (100–500 m) as a source for this turbulence (Dewar et al., 2015; Gula et al., 2015b, 2016; Molemaker et al., 2015; Vic et al., 2015). Similarly to their role at the surface, submesoscale flows at depth play a role in tracer dispersion, as recently shown in numerical experiments in the Gulf of Mexico (Bracco et al., 2016; Cardona et al., 2016).

Although tidal currents are weak in the deep ocean, they are locally enhanced over mid-ocean ridges. Over the MAR in the North Atlantic, barotropic tidal currents are dominated by the semi-diurnal frequency M_2 and reach 3–5 $\mathrm{cm\,s^{-1}}$ (as inferred from TPXO7.2, Egbert and Erofeeva, 2002). The interaction of the barotropic tide with the rough topography of the MAR generates strong internal tides – i.e., internal waves at tidal frequencies – that are responsible for high levels of mixing (Laurent and Garrett, 2002; Vic et al., 2018). However, tidal impact on Lagrangian dispersion in the deep ocean has not been documented.[1]

The objectives of this paper are twofold : (i) we aim to characterize submesoscale and tidal currents over the MAR and (ii) investigate their impact on the dispersion of the Lucky Strike hydrothermal vent effluents and larvae. To address these objectives, we set up a series of nested regional primitive-equation simulations and performed Lagrangian dispersion experiments at two different horizontal resolutions, 6 km and 0.75 km. The latter resolution allows to make a step forward in the range of resolved scales, comparatively to numerical models dedicated to deep-sea Lagrangian studies (e.g., Breusing et al., 2016, recently used a 5-km resolution model of the MAR). Furthermore, the domain covers a large area ($1500 \times 1500\ \mathrm{km}^2$) that allows to get a widespread picture of currents at different scales and perform Lagrangian advection over several months. The configuration at 0.75-km resolution is run with and without a realistic barotropic tidal forcing in order to assess the impact of tides on Lagrangian dispersion. Overall, this study adds insights on key processes governing Lagrangian dispersion in the deep ocean over mid-ocean ridges.

The paper is organized as follows. The model setup is presented in section 2. A characterization of dynamical regimes on/off the MAR and with/without tides is carried out in section 3. Observational datasets are used to assess the model capability to generate realistic fields. In section 4, Lagrangian dispersion regimes are investigated, and connectivity issues are discussed in section 5. Conclusions are drawn in section 6.

2. Numerical framework

We use the hydrostatic primitive-equation Regional Oceanic Modelling System (ROMS, Shchepetkin and McWilliams, 2005) in a series of one-way nested simulations, following the procedure in Mason et al. (2010). The use of a sigma coordinate system with significant grid stretching at the bottom allows to accurately resolve flow interactions with the seafloor (e.g., Molemaker et al., 2015). The coarsest simulation covers most of the Atlantic Ocean and has a mean horizontal resolution of $\delta x = 6$ km. It is extensively described in Gula et al. (2015a) and referred to hereafter as ROMS6. Two successive grid refinements are performed with horizontal resolutions of $\delta x = 2$ km (ROMS2) and $\delta x = 0.75$ km (ROMS0.75 without tides and ROMS0.75T with tides). Domains are shown in Fig. 1a. ROMS2 is used as a buffer between the low and high-resolution simulations, in order to maintain a grid refinement coefficient ($\delta x_{parent}/\delta x_{child}$) around 3 (Debreu and Blayo, 2008).

The ROMS0.75(T) (ROMS6) grid has 2000×2000 (2000×1500) points on the horizontal and 80 (50) vertical levels with stretching parameters $\theta_s = 6$ and $\theta_b = 4$. We use a quadratic bottom stress parameterization $\tau = \rho_0 C_D \parallel \mathbf{u} \parallel \mathbf{u}$, where ρ_0 is a reference density and $\mathbf{u}$ is the bottom layer horizontal velocity. The drag coefficient C_D uses the Von Karman-Prandtl logarithmic formulation $C_D = [\kappa/\log(\Delta z_b/z_r)]^2$, where $\kappa = 0.41$ is the Von Karman constant, Δz_b is the bottom layer thickness and $z_r = 1$ cm is the roughness parameter. Bathymetry is constructed from the Shuttle Radar Topography Mission dataset at a 30-sec resolution (SRTM30_PLUS, (Becker et al., 2009)). SRTM30_PLUS is based on the 1-min (Smith and Sandwell, 1997) dataset, incorporating higher resolution data from ship soundings wherever available. Surface heat and freshwater fluxes are provided by the ICOADS monthly climatology (Worley et al., 2005). The wind stress forcing is constructed from a climatology of QuikSCAT scatterometer winds (Scatterometer Climatology of Ocean Wind (SCOW), Risien and Chelton, 2008) with the addition of daily winds that have the right amount of climatological variance (methodology described in (Lemarié et al., 2012)). Tidal elevation and barotropic currents are added to the boundary forcing of ROMS0.75T. They are interpolated from a global inverse barotropic tidal model (TPXO7.2, Egbert and Erofeeva, 2002) and contain 8 frequencies (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1).

ROMS6 and ROMS0.75(T) are used to perform Lagrangian advection simulations (code described in Gula et al., 2014). The code computes particles' trajectories using the model currents. Particles are neutrally buoyant with no internal dynamics. For this purpose, model outputs are stored with a frequency of 6 h during 2 years in ROMS6 and 1.5 h during 10 months in ROMS0.75(T). The latter frequency is a good compromise between an accurate sampling of semi-diurnal tides – the root-mean-square error due to undersampling is 3.6% of the true signal amplitude – and storage capabilities. Outputs are further linearly interpolated in space and time. For instance, in ROMS0.75(T), a time step of 27 s is chosen to respect the vertical Courant-Friedrichs-Lewy (CFL) condition[2] imposed by a minimum vertical grid size of $\delta z \sim 10$ m near

[1] Tidal impact on Lagrangian dispersion has been more examined on continental shelves where tides often dominate advective processes (e.g., Geyer and Signell, 1992).

[2] Notice that the vertical CFL condition is more limiting than the horizontal CFL condition imposed by $\delta x = 0.75$ km and maximum model horizontal velocities of 1 $\mathrm{m\,s^{-1}}$.