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Modeled interactions of mesoscale eddies with the East Pacific Rise: Implications for larval dispersal

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A B S T R A C T

Larval transport from distant populations is essential for maintenance and renewal of populations in patchy and disturbed ecosystems such as deep-sea hydrothermal vents. We use quasi-geostrophic modeling to consider the potential for long-distance dispersal of hydrothermal vent larvae in mesoscale eddies interacting with the northern East Pacific Rise. Modeled eddy dynamics were similar to the observed propagation dynamics of Tehuantepec eddies, including their ability to cross the ridge. Simulated surface anticyclones were associated with coherent cyclones in the deep layer with relatively strong current velocities that could significantly increase the dispersal potential of passive particles. Eddy interactions with ridge topography further enhanced tracer dispersal along the ridge axis through shearing and elongation of the eddy core. Simulations suggest that the passage of an eddy would result in local loss from the vent field and aggregate transport with potential enhancement of dispersal between vent fields separated by up to 270 km. Based on the latitude at which most Tehuantepec eddies cross the ridge, eddy-induced flows would enhance connectivity between the 13°N, 11°N, and 9°N vent fields along the East Pacific Rise asymmetrically with higher transport from northern vent fields to southern vent fields.

1. Introduction

Dispersal in mesoscale eddies has been shown to contribute to the connectivity of benthic populations with patchy distributions (e.g. reef and island fauna, Boehlert et al., 1992; Lee et al., 1994; Nakata et al., 2000; Sale, 1970). Eddies can propagate for weeks to months (Goni et al., 1997; Palacios and Bograd, 2005; Sangrá et al., 2005) potentially transporting water and associated larvae 100s–1000s of kilometers between populations. During this transport, high productivity induced by upwelling (Backus et al., 1981) and residual 'island mass effects' (Doty and Oguri, 1965; Heywood et al., 1996) in some eddies may enhance the growth and survival of larvae (Emery, 1972; Nakata et al., 2000). Since the larvae would be transported as a group within the eddy core, high numbers of larvae can be delivered in pulses as an eddy passes suitable recruitment sites (Sponaugle et al., 2005).

If eddies observed at the surface extend into the deep sea, they have the potential to effect dispersal between deep benthic populations in patchy habitats such as hydrothermal vents. Mesoscale eddies interact with portions of the mid-ocean ridge globally (e.g. Walvis Ridge and Mid-Atlantic Ridge, Goni et al., 1997; Schonten et al., 2000; Southeast Indian Ridge, de Ruijter et al., 2004; East Pacific Rise, Palacios and Bograd, 2005). Most eddies propagate to the west due to the latitudinal variation in the Coriolis parameter, called the β–effect (Cushman-Roisin et al., 1990; Nof, 1981). Since hydrothermal vents are primarily aligned north–south along a ridge axis (e.g. Juan de Fuca, East Pacific Rise, Mid-Atlantic Ridge), transport between vents due to mean eddy propagation seems unlikely. However, the clockwise or counter-clockwise rotation, hereafter referred to as the swirl, of an eddy could transport larvae between vent sites if the eddy encompasses two or more vent fields. Although, swirl velocities are generally considered to be relatively weak at depth (Mulhearn et al., 1986; Richardson and Fratantoni, 1999; Tracey et al., 2006) (order 10 cm s^{-1} at 4000 m compared to 100 cm s^{-1} at the surface), deep eddy-induced currents could be significant compared to the slow background current velocities, less than 10 cm s^{-1}.

Multiple eddies generated by wind jets (Ballestero and Coen, 2004; McCreary et al., 1989; Müller-Karger and Fuentes-Yaco, 2000) and baroclinic instabilities (Ballestero and Coen, 2004; Farrar and Weller, 2006; Hansen and Maul, 1991; Zamudio et al., 2006) in the Gulfs of Tehuantepec and Papagayo, off the coast of Central America (Fig. 1), propagate westward across the East Pacific Rise each year (Palacios and Bograd, 2005). Tehuantepec

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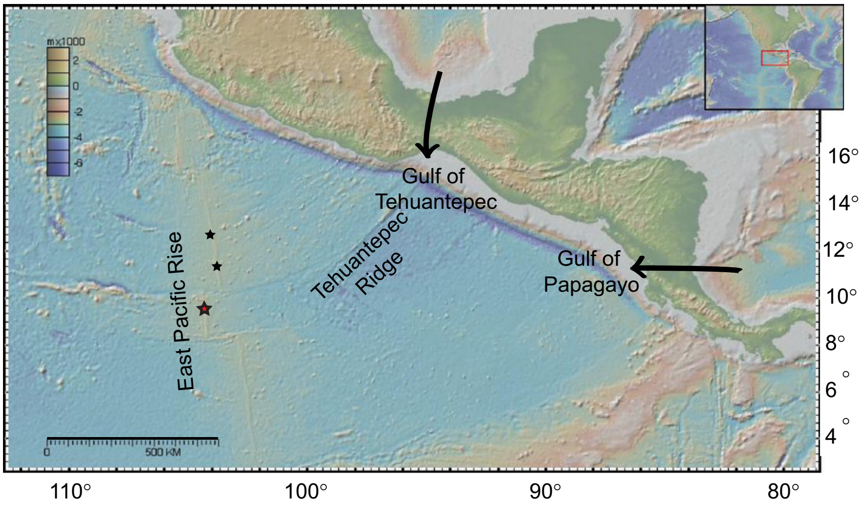

Fig. 1. Topography of Central America and bathymetry of the East Pacific. Arrows indicate the location of two mountain-pass wind jets near the Gulfs of Tehuantepec and Papagayo. Wind jets are formed when high pressure develops over the Gulf of Mexico causing air to flow rapidly through the passes down the pressure gradient. The bathymetry shows the Tehuantepec Ridge and East Pacific Rise. The 9°N, 11°N and 13°N vent fields are noted as stars. Map created in GeoMapApp.

and Papagayo eddies often reach diameters of 100–450 km at the surface. If the extent of the eddies were similar at depth, the size would be sufficient to encompass multiple vent fields along the East Pacific Rise.

The main goal of this study was to investigate the potential for mesoscale eddies to influence the near bottom transport of hydrothermal vent larvae. We specifically consider the interaction between anticyclonic mesoscale eddies resembling Tehuantepec eddies and the East Pacific Rise. Since Palacios and Bograd (2005) observed that Papagayo eddies, between 1992 and 2004, always dissipated or merged before crossing the East Pacific Rise, we focused on interactions of Tehuantepec eddies with the ridge and their potential to transport vent larvae. We use a two layer quasi-geostrophic model of an isolated vortex to investigate the flow in the deep layer and potential for larval transport in these flows. To verify that the model is consistent with observations of Tehuantepec eddies, we analyzed the general dynamics of the modeled eddies in the surface and at depth with a flat bottom and with averaged East Pacific Rise topography. We then introduced a tracer, with and without settlement behavior, into the bottom layer of the model to investigate the potential for larval transport along the ridge.

2. Methods

2.1. Quasi-geostrophic model

A rigid-lid, two-layer quasi-geostrophic model was employed to investigate the effects of an isolated vortex on the currents and transport in the deep sea. The quasi-geostrophic approximation assumes that the dominant forces, the Coriolis force and the pressure gradient force, are in geostrophic balance but accounts for ageostrophic corrections such as the inclusion of topographic effects and nonlinear forces associated with the rotation of the vortex. Based on these assumptions, the dimensional quasi-geostrophic equations for two layers were used in the following form (as in Pedlosky, 1996, Eqs. (3.2.34) and (3.2.36)),

$$q_1 = \nabla^2\psi_1 + F_1(\psi_2 - \psi_1) + \beta y$$

and

$$q_2 = \nabla^2\psi_2 + F_2(\psi_1 - \psi_2) + \beta y + \frac{f_0}{H_2} b$$

for

$$F_i = \frac{f_0^2}{g' H_i},$$

where q_i is the potential vorticity and ψ_i is the stream function in each layer ($i = 1$ and 2, surface and deep layers, respectively); f_0 is the Coriolis parameter at the center of the domain, β is the northward gradient of the Coriolis parameter, and y is the meridional (north–south) distance from the center of the domain; b is the topographic elevation; H_i is the mean depth of layer i, and g' is the reduced gravity. When the flow is geostrophic, ψ is related to pressure as $\psi = p'/(\rho_0 f_0)$, where p' is the pressure and ρ_0 is the density. The reduced gravity was not an explicit parameter, but was calculated based on the Rossby radius of deformation, R_D, and the relationship $F_1 + F_2 = 1/R_D^2$.

From these equations, the zonal (east-west, u_i) and meridional (v_i) components of the velocity in each layer are given by

$$(u_i, v_i) = \left(-\frac{\partial}{\partial y}\psi_i, \frac{\partial}{\partial x}\psi_i\right).$$

The stream function thus gives the direction (along the contours) and the speed (inverse to the spacing between contours) of flow. The potential vorticities are conserved following the geostrophic flow

$$\frac{\partial q_i}{\partial t} + u_i \frac{\partial q_i}{\partial x} + v_i \frac{\partial q_i}{\partial y} = 0.$$

Our two layer model was built on the Fortran-77 pseudospectral code of Dewar (1983), but has been substantially modified (e.g., Flierl, 1994). Friction was not explicitly modeled and no bottom friction was included, but an exponential wavenumber cutoff filter (Canuto et al., 1988) was employed to dampen variability at small spatial scales, similar to the effects of frictional viscosity. The vortices were modeled on a 1536 km × 1536 km domain, with periodic boundary conditions and a 3 km grid size.

The range of model parameters was set as follows to generally represent observations of Tehuantepec eddies from