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Generation and evolution of a topographically linked, mesoscale eddy under steady and variable wind-forcing

Amoreena MacFadyen*[,1], Barbara M. Hickey

University of Washington, School of Oceanography, Seattle, WA 98195, USA

A R T I C L E I N F O

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A B S T R A C T

Numerical simulations with the Regional Ocean Modeling System (ROMS) are used to study the initial spin-up and the evolution of a mesoscale, topographically linked eddy under steady and variable wind conditions. The development of a pool of dense water on the southern Vancouver Island shelf allows cyclonic eddies formed by coastal upwelling off Cape Flattery to spread westward, ultimately contributing to the shelf-wide circulation known as the Juan de Fuca Eddy. This dense water arises through upwelling of water present in the underlying canyon system and tidal mixing over several shallow banks to the north. Tidal mixing is critical to the separation of the eddy from the coast. Although steady upwelling winds with a seasonal mean magnitude (combined with estuarine flow and tides) produce an eddy, only fluctuating winds with timescales and magnitudes typical of the region result in an eddy with a westward extent similar to seasonal observations. With each period of upwelling-favorable winds, newly upwelled water from the coast is entrained into the eddy which grows in size and moves westward. Wind events also significantly affect the baroclinic structure of the eddy. Specifically, during typical summer wind reversals, model surface drifters continue to move cyclonically within the eddy for several days after each downwelling wind event. Under upwelling-favorable wind conditions, model drifters exit the eddy to the southeast as the eddy and coastal upwelling fronts merge into a continuous southeastward shelf break jet.

1. Introduction

Flow-topography interactions can generate mesoscale eddies in the coastal ocean that have profound impacts on local or regional ecosystems. Understanding the dynamics of these features is important for providing optimal scales for fisheries management or marine preserve design, scales that may vary among sites in relation to regional oceanographic variability and coastal topography. For example, eddies may modify regional circulation patterns forming coherent features in otherwise spatially and temporally variable current fields (Fossum, 2006; Harms and Winant, 1998; MacFadyen et al., 2005). These modifications may result in retentive circulation patterns, which can retain fishes during their pelagic stage, hence enhancing recruitment (Nishimoto and Washburn, 2002; Saetre, 1999). Eddies may translate away from their generation region with the mean flow (Crawford, 2005) or they may be quasi-stationary and linked to topography (Eide, 1979; Freeland and Denman, 1982). In either case, they are often biologically rich regions because they may transport or upwell nutrient-rich water and thus have high phytoplankton biomass (Correa-Ramirez et al., 2007; Crawford et al., 2005, 2007), elevated primary productivity (Marchetti et al., 2004), and enhanced higher trophic level biomass (Batten and Crawford, 2005; Nishimoto and Washburn, 2002). One such feature, the Juan de Fuca Eddy, has been the focus of a recent multi-disciplinary study that examined the eddy as a "hot-spot" for the initiation of harmful algal blooms (HABs), specifically, toxic species of the diatom *Pesudo-nitzschia* (MacFadyen et al., 2008; Trainer et al., 2009).

This eddy, called either the "Juan de Fuca" or "Tully" Eddy, was first identified by Tully (1942). It is a cyclonic, quasi-stationary feature located off the mouth of Juan de Fuca Strait on the southern British Columbia/northern Washington shelf (Fig. 1). This region has extremely complex bathymetry characterized by numerous shallow banks and deep canyons. At the shelf edge, the head of Juan de Fuca Canyon intersects a glacial trough that bisects the shelf (Carson and McManus, 1969). Consequently, depths exceeding 200 m extend completely across the shelf into Juan de Fuca Strait. Deep upwelled water passes through the canyon and enters the strait as a compensating flow to the surface estuarine outflow (Mackas et al., 1980).

Several observational programs have described the structure and circulation of the Juan de Fuca Eddy (Denman and Freeland,

* Corresponding author. Tel.: +1 206 526 6954.
E-mail address: amy.macfadyen@noaa.gov (A. MacFadyen).
[1] Present address: NOAA's Office of Response and Restoration, Emergency Response Division, 7600 Sand Point Way NE, Seattle, WA 98115-6349, USA.

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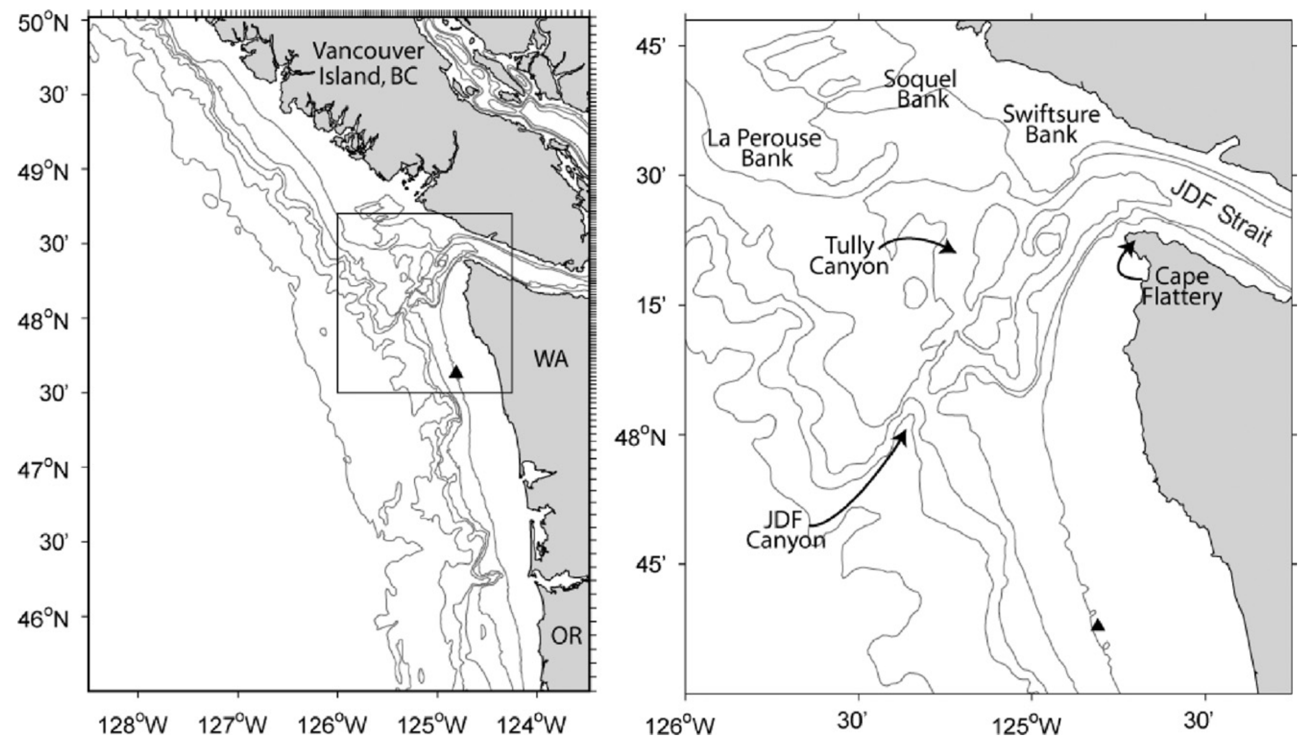

Fig. 1. Model domain and bathymetry with geographic locations mentioned in the text. The ticks on the top- and right-side axes in the left panel illustrate the enhanced model resolution in the study area (ticks represent 2 grid cells). The Juan de Fuca Eddy region (small rectangle) is expanded in the left panel. This is the region depicted in subsequent figures. The location from which wind time series data are extracted is also shown (black triangle). Bathymetric contours in this and subsequent figures are: 2000, 1000, 500, 250, 150, and 100 m.

1985; Freeland and Denman, 1982; Freeland and McIntosh, 1989; MacFadyen et al., 2008). The first of these studies described the eddy as a seasonal, topographically confined feature, which develops around the time of the spring transition and declines during the fall (Freeland and Denman, 1982). During this time, typical alongshelf winds are from the northwest and force a seasonal-mean, southeastward-flowing, baroclinic current over the slope and outer shelf. Nearshore, the buoyancy-driven Vancouver Island Coastal Current flows to the northwest. By mid to late summer, the eddy is evident at mid-depth (50 m) as a cold, saline, high-nutrient water mass with its center located approximately over the Tully Canyon (Fig. 1) (Freeland and Denman, 1982; MacFadyen et al., 2008). Using results from an array of current meters deployed over the Tully Canyon, Freeland and McIntosh (1989) found relative vorticity variations in this region to be related to vortex stretching originating from vertical velocities at the head of the canyon. They suggested that these vertical velocities were driven by up-canyon flow resulting from the large-scale cross-shelf pressure gradient.

More recently, Foreman et al. (2008) conducted numerical simulations using the ROMS model to examine the forcing mechanisms involved in the generation of the Juan de Fuca Eddy. In their study, a simulation forced with average summer upwelling-favorable winds, tides, and a boundary condition that maintained an estuarine flow in the Juan de Fuca strait produced an eddy and mean currents that were in reasonable agreement with observations. Their analysis suggested that the eddy was generated through enhanced upwelling off Cape Flattery, which resulted in a dome of relatively dense water that grew westward and detached to form an eddy when it reached a sufficiently large diameter. They investigated the mechanisms for the enhanced upwelling in this region and suggested that it was a result of upwelling-favorable winds, vertical tidal rectification and strong tidal mixing.

In this paper, we examine in detail the initial stages of eddy generation off Cape Flattery. We also consider the subsequent evolution of the eddy under both steady and fluctuating wind conditions. We begin with a description of the model configuration (Section 2) and a summary of individual simulations discussed in this study (Section 3). In Section 4, we examine the structure and dynamics of a "mature" eddy, generated from a base case run similar to that from Foreman et al. (2008). In this scenario, the model is initialized from summer climatology that already includes a weak signature of the eddy. In Section 5, we examine the effect of these initial conditions on eddy development. Finally, in Section 6, we examine the evolution of the modeled eddy under constant and time-variable wind-forcing. In particular, the effect of alternating strong upwelling-favorable wind periods with typical (summer) wind reversals is considered.

2. Model configuration

The model utilized in this study is the Regional Ocean Modeling System v2.2 (ROMS): a three-dimensional, free-surface, terrain-following numerical model that solves the Reynolds-averaged Navier–Stokes equations using the hydrostatic and Boussinesq approximations (Haidvogel et al., 2000, 2008; Shchepetkin and McWilliams, 2005). ROMS is widely used within the ocean modeling community and has been applied in a number of regional simulations (Di Lorenzo, 2003; Haidvogel et al., 2008; Marchesiello et al., 2003; Wilkin, 2006). The model grid and configuration (described below) are similar to that used in Foreman et al. (2008).

The model domain (Fig. 1) extends from northern Oregon to northern Vancouver Island, a north–south extent of ~500 km. The western boundary is located ~350 km offshore in the south and ~80 km offshore in the north. The horizontal resolution varies