Sub-mesoscale coastal eddies observed by high frequency radar: A new mechanism for delivering nutrients to kelp forests in the Southern California Bight

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[1] Sub-mesoscale eddies are described along the mainland coast of the Santa Barbara Channel based on observations from a network of high frequency (HF), current-measuring radars and near-shore moorings. The eddies are 4–15 km in diameter and typically last about 2 days, although some last up to 6 days. Most eddies within the radar coverage area are anti-cyclonic with relative vorticities of $-0.4\ f$ to $-0.8\ f$ where f is the Coriolis parameter, but cyclonic eddies are also observed. Moored observations over the inner shelf (12 m water depth) of a sequence of two eddies in December 2001 show an increase in nitrate plus nitrite from the background levels of 1–2 μM to a maximum of 10–12 μM when the eddies are present. We speculate that these eddies are an important transport mechanism for nutrients and biogenic particles to inner shelf ecosystems of the Southern California Bight. **Citation:** Bassin, C. J., L. Washburn, M. Brzezinski, and E. McPhee-Shaw (2005), Sub-mesoscale coastal eddies observed by high frequency radar: A new mechanism for delivering nutrients to kelp forests in the Southern California Bight, *Geophys. Res. Lett.*, *32*, L12604, doi:10.1029/2005GL023017.

1. Introduction

[2] Identifying circulation patterns which produce flow across isobaths onto the inner shelf is important for understanding the maintenance of coastal ecosystems which rely on deeper, offshore ocean waters for input of nutrients, larvae, and biogenic particles. Sustained wind-driven upwelling is a dominant cross-isobath transport process in eastern boundary currents over the world's oceans such as the California Current and Peru Current systems [e.g., *Smith*, 1995]. Both of these systems sustain extensive and highly productive temperate reef ecosystems with habitat-forming macroalgal species such as *Macrocystis pyrifera*. In sheltered regions within eastern boundary currents, such as the Southern California Bight, extensive temperate reef ecosystems are also found, but wind-driven upwelling is weaker and intermittent [*Winant and Dorman*, 1997]. Therefore, other cross-isobath transport processes are likely to be important in maintaining these ecosystems.

[3] Internal waves are one such process that transport nutrients and larvae to kelp forests on the inner shelf (water depths $\leq$ 30 m) of the Southern California Bight [*Zimmerman and Kremer*, 1984]. *Zimmerman and Kremer* [1984] speculate that internal waves are important for sustaining kelp growth in summer and during El Niño conditions. E. McPhee-Shaw et al. (Mechanisms for nutrient delivery to the inner shelf: Observations from the Santa Barbara Channel, submitted to *Limonology and Oceanography*, 2005) conclude that about 15% of the annual nitrate delivery to kelp forests along the mainland coast of the Santa Barbara Channel results from internal waves. Other studies have shown that internal waves are important for transporting particles and larvae to the inner shelf [*Pineda*, 1999]. *Pringle and Riser* [2003] suggest that coastal trapped waves are important in the cross-isobath transport of nutrients, particles, and larvae in the Southern California Bight through a remote forcing mechanism. We describe another mechanism for producing cross-isobath transport near shore, sub-mesoscale eddies. We hypothesize that they are an important transport process in supplying nutrients and particles to near shore habitats of the Southern California Bight.

2. Field Sites and Methods

[4] Surface current fields (upper 1 m) of the eddies were observed from an array of high frequency (HF) radars deployed at three sites along the mainland coast of the western Santa Barbara Channel (SBC; Figure 1a). *Emery et al.* [2004] describe the performance of the SBC array and their data processing in more detail. Eddies were detected by subjective examination of evolving current patterns from 1998–2002. To produce maps such as in Figure 1, surface velocity time series were low-pass filtered with a 1/36 h^{-1} cutoff frequency to suppress tidal variations. Relative vorticity $\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$, where u (v) is the velocity component in the positive x (y) direction and is positive eastward (northward), proved to be a useful parameter for detecting the eddies due to their strong rotation. ζ at each grid point was

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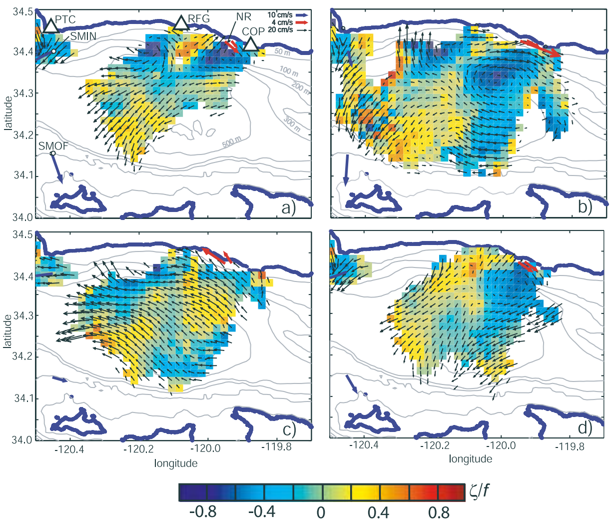

Figure 1. Evolution of the surface velocity field in 2001 on (a) 10 December 0000 GMT, (b) 11 December 0800 GMT, (c) 13 December 1600 GMT, (d) 15 December 0000 GMT. Black arrows indicate surface current vectors measured by HF radars (triangles) at Coal Oil Point (COP), Refugio (RFG), and Pt. Conception (PTC). Colors indicate normalized relative vorticity ζ/f scaled according to the color bar. Red arrows west of COP are current velocities measured 12 m above bottom by ADCP's at Naples (NR) and the nearby Ellwood mooring (not labeled). Blue arrows are current velocities measured at 5 m depth at moorings SMIN and SMOF (circles) as discussed by *Harms and Winant* [1998].

computed from centered finite differences of velocity from the surrounding four grid points. Strong shear of along shore currents $\left(\frac{\partial u}{\partial y}\right)$ near shore often produced large ζ with no eddy present, so the eddies could not be identified by a simple approach, such as finding times when ζ exceeded a threshold. Therefore, a subjective approach was employed in which eddies were identified visually as rotary flow patterns near shore.

[5] Time series of temperature, salinity, density, and chlorophyll fluorescence were measured in the radar coverage at a mooring at Naples Reef (NR, Figure 1a) at 8 m above bottom in a water depth of about 12 m. Temperature was also measured using thermistors at 0.5 m, 4 m, and 8 m above bottom. Nitrate plus nitrite (hereafter referred to as nitrate) were measured from a sensor mounted about 5 m above bottom within 10 m of the NR mooring. Current velocity was measured over the water column within 10 m of the NR mooring using an upward looking acoustic Doppler current profiler (ADCP). For a few months in 2001 a second ADCP was located near another mooring at Ellwood, about 1 km northeast of NR (Figure 1). Data from the various sensors were obtained over sampling intervals of 2–16 min, except the nitrate sensor which sampled at either 20 or 30 min intervals.

3. Results

[6] HF radar observations show that rotary, eddy-like circulation patterns frequently occur along the mainland coast of the SBC. Figure 1 shows the evolution of small anti-cyclones near COP during 10–15 December 2001. On 10 December, an anti-cyclonic eddy about 7 km in diameter was centered over the 75 m isobath on a steeply sloping section of the shelf (Figure 1a). Another anti-cyclonic eddy was also present about 15 km to the west, although it was only partially resolved due to reduced radar coverage. The ADCP at the NR mooring also showed that currents had reversed with eastward speeds of 0.1–0.2 m s^{-1} over the water column (gray lines, Figure 2a). Velocity time series obtained from the HF radar grid point nearest the NR mooring (black line, Figure 2a) were consistent with those from the ADCP. Velocity time series of Figure 2a derived from HF radar are hourly observations (i.e. not low pass filtered at 1/36 hr^{-1}); time series of Figures 1b–1d have been low pass filtered at 1 hr^{-1}. Rotation was strong with $\zeta/f \approx -0.8$, (Coriolis parameter $f = 8.2 \times 10^{-5}$ s^{-1}). By 11 December the eddy near COP on 10 December had moved offshore and expanded to 10–15 km in diameter (Figure 2b). The eddy coincided with eastward velocities of 0.2–0.4 ms^{-1} at the NR mooring (Figure 2a). The eddy to the west remained, but was not well resolved within the radar coverage. On 13 December the eddy off COP had

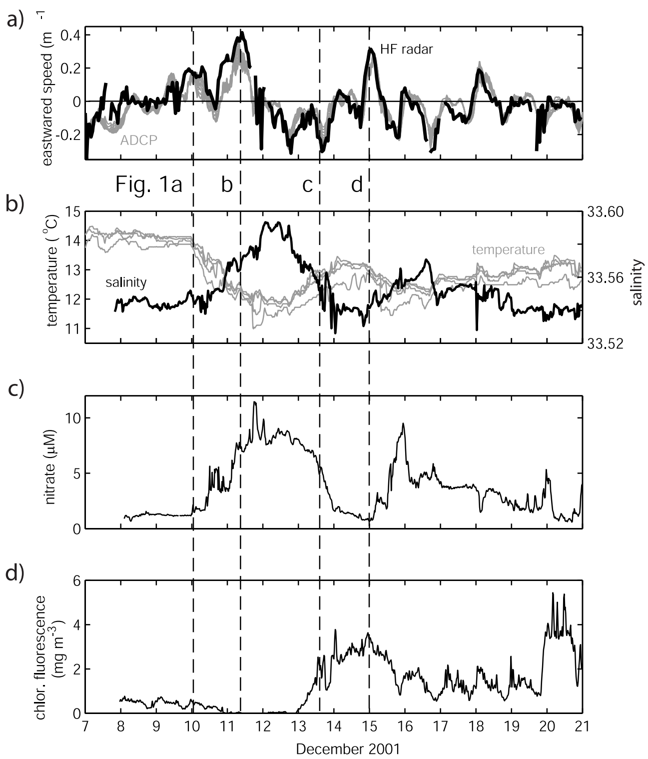

Figure 2. Time series during 7–20 December 2001. (a) Black line is the eastward component of current velocity measured by HF radar for the grid point nearest the NR mooring. Gray lines are the eastward components of current velocity from all ADCP bins (1 m depth intervals). (b) Black line is salinity (right hand scale) and gray lines are temperature (left hand scale) measured at four depths at the NR mooring. (c) Nitrate measured near the NR mooring. (d) Chlorophyll fluorescence measured at the NR mooring. Vertical dashed lines indicate times of panels in Figures 1a–1d.

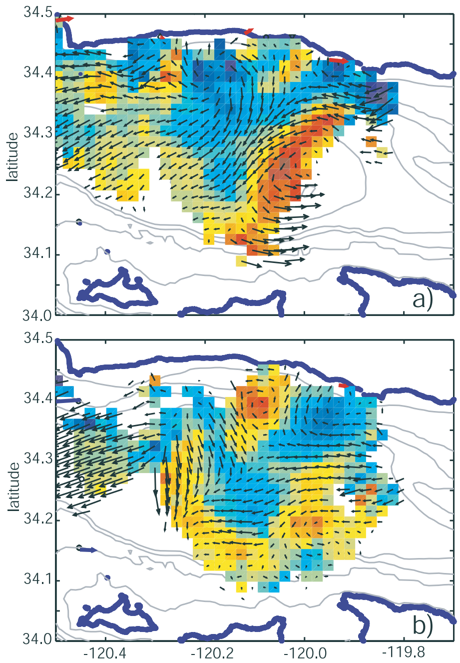

Figure 3. Surface velocity field on (a) 30 August 2002 0000 GMT, (b) 30 December 1999 1600 GMT. Velocity scales, relative vorticity scale, and other features are identified in the caption of Figure 1.

been replaced by westward flow, the prevailing current direction along this section of the coast [*Dever*, 2004; *Harms and Winant*, 1998], with little rotation near shore (Figure 1c). On 15 December another anti-cyclonic eddy was present, this one with a diameter of about 13 km and maximum $\zeta/f \approx -1$ (Figure 1d). The eddy was associated with eastward flow near shore with a maximum speed of $\sim$0.3 ms^{-1} at the NR mooring (Figure 2b). This eddy was centered over the 300 m isobath. By 16 December the eddy was gone and alongshore flow to the west prevailed near shore.

[7] Time series of water properties at the NR mooring indicate that these eddies can transport cooler, higher salinity, and higher nitrate waters to the inner shelf. Temperature dropped by about 2.5°C and salinity increased by $\sim$0.04 when the first anti-cyclonic eddy was at the NR mooring on 10–11 December (Figure 2b). Temperature dropped by about 1°C and salinity increased by $\sim$0.01 when the second eddy was present on 15 December. However, at the same time other processes such as larger scale water mass advection were also producing temperature and salinity variability at longer timescales. Nitrate concentration rose sharply when the eddies were present (Figure 2c). During the passage of the first eddy when eastward flow at the NR mooring was strong, nitrate increased from background levels of 1–2 μM to a maximum of around 12 μM over 10–12 December. Nitrate concentration then decreased to 1–2 μM by 14 December when westward flow returned. A pulse of nitrate with a maximum of 9 μM occurred on 15 December as the velocity at NR changed from eastward, during the passage of the second eddy, to westward. It is likely that the colder, more saline waters with higher nitrate originated at depth. The data suggest that the eddies advected previously upwelled water to the inner shelf although vertical mixing and advection within the eddies themselves may have also contributed. Chlorophyll fluorescence, expressed in Figure 2d as approximate chlorophyll concentration, increased following the first eddy, about 3 d after the initial nitrate increase.

[8] Eddies occurred elsewhere in the radar coverage area, although variable coverage made observing them more difficult. Figure 3a shows a small anti-cyclonic eddy on 30 August 2002 which was farther west in the SBC, this one centered over the 100 m isobath with $\zeta/f \approx -0.5$. The cyclonic pattern southeast of this eddy, only partly resolved by the radar coverage, is a persistent feature of the SBC circulation [*Beckenbach and Washburn*, 2004; *Dever*, 2004; *Harms and Winant*, 1998]. A pair of eddies, one cyclonic the other anti-cyclonic, occurred just east of COP on 30 December 1999 (Figure 3b). The centers of these eddies were about 13 km apart and onshore advection occurred between their centers with current speeds of $\sim$0.1–0.2 m s^{-1}. Evolution of this eddy pair suggests they may have resulted from a meander-like instability of the prevailing westward flow.

[9] The coast west of COP had the most complete spatial and temporal HF radar coverage and was used to examine the occurrence, frequency, and duration of sub-mesoscale eddies from a 4-year time series radar observations. Over 1998–2001, a period which spans part of an El Niño event (1998) and a La Niña event (1999), eddies occurred 11% of the time or $\sim$41 dy^{-1}. No clear seasonal trend in eddy occurrence was found. Eddies ranged in diameter from 4–15 km and were typically centered between the 50 m and 300 m isobaths. They persisted from 1–6 d, averaging about 1.5–2 d. Typical azimuthal velocities were 0.1–0.2 m s^{-1} corresponding to spatially-averaged ζ/f of about -0.5 to -1 for a 10 km diameter eddy. Maximum azimuthal velocities were $\sim$0.4 m s^{-1}.

4. Discussion

[10] Sub-mesoscale eddies, mostly anti-cyclonic, are common features over the slope and inner shelf of the northern coast of the SBC. Previous studies have shown that sub-mesoscale eddies on comparable spatial scales, but mostly cyclonic, are ubiquitous in the upper ocean [*DiGiacomo and Holt*, 2001; *Eldevik and Dysthe*, 2002; *Munk et al.*, 2000; *Shen and Evans*, 2002]. Details of their generation are not well understood due in part to a lack of *in situ* observations. We speculate that the anti-cyclonic relative vorticity of the eddies near COP results from bottom friction acting on the prevailing westward current with a coastal boundary to the north. One component of vorticity production by bottom friction is the "slope torque" which produces a change in relative vorticity $\Delta\zeta$ on a time scale, $\tau_P = \Delta\zeta\left[-\frac{C_D|\vec{u}|}{H^2}(\vec{u}\times\nabla H)\right]^{-1}$, where C_D is the depth-averaged friction coefficient, $\vec{u} = u\mathbf{i} + v\mathbf{j}$, $\mathbf{i}$ and $\mathbf{j}$ are north and east unit vectors, and H is the water depth [*Signell and Geyer*, 1991]. With $C_D = 2.5 \times 10^{-3}$ (from SG91), $\nabla H = -1.7 \times 10^{-2}\mathbf{j}$ (mean southward slope offshore of COP between 20–500 m depth), $\vec{u} = -0.2\mathbf{i}$ m s^{-1}, $\Delta\zeta = -0.5f$ (typical vorticity of these eddies), H = 50 m (typical

depth inshore of eddy centers), $\tau_P \approx 1$ day which is comparable to formation time of the eddy shown in Figure 1a. The timescale for vorticity dissipation by bottom friction adapted from SG91 is $\tau_D = \Delta\zeta C_D|\vec{u}|H^{-1} \approx 1$ day using the previous values. τ_D is comparable to the time over which the eddy shown in Figure 1d disappeared. The similarity of τ_P and τ_D estimates suggests that bottom friction is an important process in the evolution of the eddies. Clearly other processes are also important since cyclones are occasionally observed near shore (e.g. Figure 3b). Moreover, the eddies can move offshore (e.g. between Figures 1a and 1b) where deeper water depths reduce effects of bottom friction. An alternate explanation is that the anti-cyclonic and cyclonic eddies, such as shown in Figure 3b, form in meanders of the prevailing westward coastal current, although bottom friction is probably also important.

[11] These observations indicate that the eddies can transport high concentrations of nitrate to the shallow waters of the inner shelf which is important habitat for beds of the giant kelp, *M. pyrifera* in the Southern California Bight. *M. pyrifera* is an important habitat forming species along the California and Baja California coasts. In summer, especially during El Nino events, when nitrate concentrations fall below ~1 μM, nutrient limitation inhibits growth of *M. pyrifera* [*Hernández-Carmona et al.*, 2001; *Zimmerman and Kremer*, 1984; *Zimmerman and Kremer*, 1986]. Thus, the eddies may be an important mechanism for sustaining *M. pyrifera* beds under otherwise nutrient limiting conditions.

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