How islands stir and fertilize the upper ocean

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[1] Large differences between the upstream and lee side flow characteristics of an isolated island in the Kuroshio have been identified from a three-dimensional velocity survey and from vertical profiles of fine- and micro-structure. In the island wake, the relative vorticity is $O(10f)$, the horizontal current divergence indicates upwelling of $O(0.01\ \mathrm{m\ s^{-1}})$, and the rate of dissipation of kinetic energy is $O(10^{-4}\ \mathrm{W\ kg^{-1}})$. Isopycnal surfaces shoal by 60 m on the lee side and surface nitrate concentration increases seven-fold. Flow blockage by the island and the Izu-Ogasawara Ridge on its flanks, induces horizontal and vertical flow separation. The associated lateral and vertical shear drive the upwelling and the vertical mixing in the wake and produces a very pronounced "island mass effect." *INDEX TERMS:* 4279 Oceanography: General: Upwelling and convergences; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 4576 Oceanography: Physical: Western boundary currents; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; 9355 Information Related to Geographic Region: Pacific Ocean. **Citation:** Hasegawa, D., H. Yamazaki, R. G. Lueck, and L. Seuront (2004), How islands stir and fertilize the upper ocean, *Geophys. Res. Lett.*, *31*, L16303, doi:10.1029/2004GL020143.

1. Introduction

[2] Fishermen have long known of the enhanced biological productivity in the vicinity of islands. This effect was scientifically documented by *Doty and Oguri* [1956], who coined the phrase "island mass effect". Soon after, *Uda and Ishino* [1958] correlated commonly recognized eddy patterns and frontal features with fishing grounds. The wake on the lee side of an island may consist of irregular motions for slow background currents, trapped eddies for moderate flows and detaching eddies for fast flows; features that are somewhat akin to the wake of a circular cylinder. Nutrients, such as nitrate, can be 10 times larger in the wake compared to upstream values [*Heywood et al.*, 1990], and isopycnals can shoal by as much as 100 m. It is conjectured that the nutrification of the euphotic zone leads to increased productivity.

[3] The characteristics of the wake depend on a number of parameters including far-field speed, planetary vorticity, island diameter, horizontal eddy viscosity, and surrounding depth. For islands in shallow seas, the upwelling may result from the well-known "tea-cup effect" [*Wolanski and Hamner*, 1988]. In an eddy, rotating in either direction, there is an inward pressure gradient supporting the centripetal acceleration of the fluid. Friction slows the flow near the bottom which reduces the centripetal acceleration. The pressure gradient remains, is unbalanced, and pushes the near-bottom fluid towards the center of rotation. This flow convergence drives the upwelling (and concentrates the "tea leaves" in the center of a cup). For a deep-sea island, bottom friction is unimportant and upwelling, if present, must be driven by a different mechanism. The eddies on the lee side of deep-water islands have been explained as hydraulic flow modified by rotation [*Heywood et al.*, 1990; *Coutis and Middleton*, 1999, 2002]. The supporting theories are formally correct only for small Ekman and Rossby numbers (weak friction and small inertial forces relative to Coriolis force). Planetary vorticity favors the formation of cyclonic eddies, and isopycnals must shoal in the center of these eddies to maintain a cyclo-geostrophic balance [*Boyer and Kmetz*, 1983]. The doming of isopycnals on the lee side of deep-water islands is well established [*Heywood et al.*, 1990], but there is no observational evidence of sustained upwelling.

[4] The Izu-Ogasawara Ridge, which extends more than 1000 km south from Tokyo and Sagami Bay, and the many islands that dot it, are a conspicuous topographic feature of the western North Pacific. The Kuroshio always crosses this ridge, while other western boundary currents (such as the Gulf Stream) do not encounter such a prominent obstacle. The lee side of islands on this ridge frequently show signs of upwelling, such as anomalously cold water with increased organic carbon and even shifts in phytoplankton community structures [*Furuya et al.*, 1986]. When the Kuroshio branches northward, deep-water eddies, which are cold and rich in chlorophyll-*a*, form on the lee side of Izu-Oshima [*Takahashi et al.*, 1980]. These eddies are anti-cyclonic [*Kimura et al.*, 1994]. So the cyclonic eddy mechanism is not applicable.

[5] There are a few mechanisms for the nutrification of oligotrophic surface waters around islands in a strong flow, such as the Kuroshio, may be important for the resupply of nutrient rich water to the euphotic zone and the subsequent production of phytoplankton and other forms of organic carbon.

2. Results and Discussions

[6] We collected the first profiles of fine-structure (CTD with fluorometer and water bottles), micro-structure (TurboMAP [*Wolk et al.*, 2002]) and horizontal current (300 kHz ADCP) around Aoga-shima while the Kuroshio was centered on this island. Aoga-shima is the apex of a conic volcano. It measures 3.5 km north–south, 2.5 km east–west and it stands 1400 m above its submarine foundation at 1000 m depth (Figure 1).

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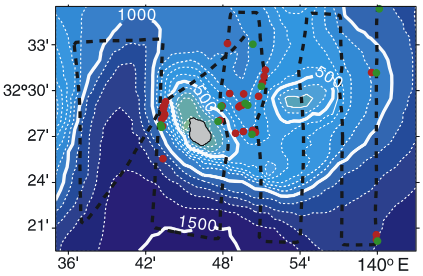

Figure 1. The bathymetry around Aoga-Shima with the ship track during the ADCP survey (black dashed line) and the locations of CTD profiles (green dots) and TurboMAP (red dots) stations.

[7] Quasi-synoptic velocity profiles taken with the ADCP (pattern shown Figure 1) over a 12-hour interval show the Kuroshio flowing northeastward at 1.5 m s^{-1}. The flow accelerates around the flanks of the island and reaches 2 m s^{-1} just downstream of the island. On the lee side of the island, currents are very weak and are directed against the prevailing upstream flow (Figures 2a and 2b).

[8] Behind the island, along section-a in Figure 2a, the average surface current direction is ENE (65°). When velocity components taken along section-a are projected on the orthogonal axes of the mean flow direction (ENE) and the across flow direction (NNW), one sees accelerated across section flows at the upper 75 m on the northern and the southern flank of the island (Figure 2b, left panel). In the lee of the island, the current is reversed and water flows back towards the island with speeds of up to 0.5 m s^{-1}. The flow component along section-a is divergent (Figure 2b, right panel). On the south side, there is a southward flow in the upper 100 m and a compensating northward flow below 100 m. On the north side, the flow is northward in the upper 60 m. A possible compensating flow is obscured by poor data return from the ADCP below 80 m. These features resemble the cartoon in Figure 3c (left half).

[9] Section-b in Figure 2a is oriented roughly along the line of flow. When horizontal velocity components taken along section-b are projected on the orthogonal axes of the mean flow direction and the across flow direction, we see that acceleration over the northern flank is confined to the upper 75 m and that the flow is vertically sheared (Figure 2c, upper panel). The zero isotach rises from 200 m over the flank, to 130 m on the down-stream side, and there is a deep counter flow. This flow separation resembles the cartoon in Figure 3c (right half). The flow across the mean flow shows a northward deflection just upstream of the northern flank and the return to northeastward flow on the lee side of the ridge (Figure 2c, bottom). This deflection upon shoaling resembles the cartoon of Figure 3c (left half). Thus, Aoga-shima, and its flanks, cause both horizontal and vertical flow separation.

[10] All vertical profiles taken with the CTD and TurboMAP show a shoaling of isopycnals on the lee-side of the island (typically 50 m), implying doming, upwelling and/or vertical mixing. The Rossby number at 20 m depth ($R_o = \zeta/f$), which is the relative vorticity ($\zeta = \partial v/\partial x - \partial u/\partial y$) normalized by the planetary vorticity f, is large and anticyclonic (cyclonic) in the northern (southern) half of the wake (Figure 3a). There is no preference for cyclonic relative

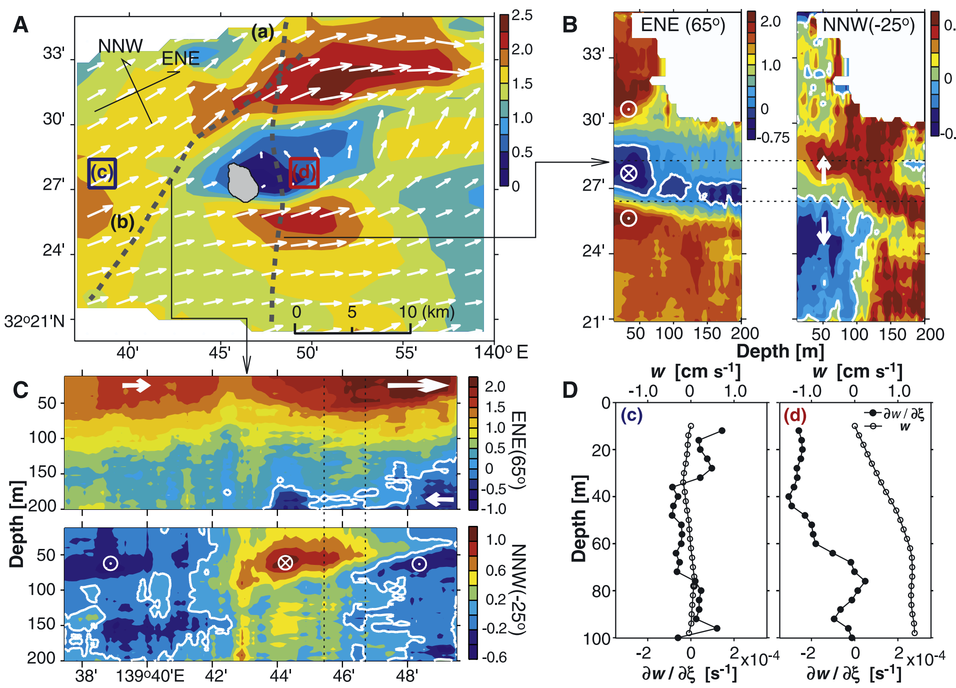

Figure 2. (A) Current speed and direction at 12 m depth (color scale in m s^{-1}). (B) Velocity section along line-a. Components are projected on the orthogonal axes of the mean flow direction (left panel) and the across flow direction (right panel). (C) Velocity section along line-b. Components are projected on the orthogonal axes of the mean flow direction (upper panel) and the across flow direction (lower panel). The center-line of the ridge is located between the vertical dotted lines. (D) Profiles of divergence ($\partial w/\partial \xi$) and estimated vertical velocity (w) at the up−stream (c) and the down−stream (d) corresponding to (c) and (d) on A.

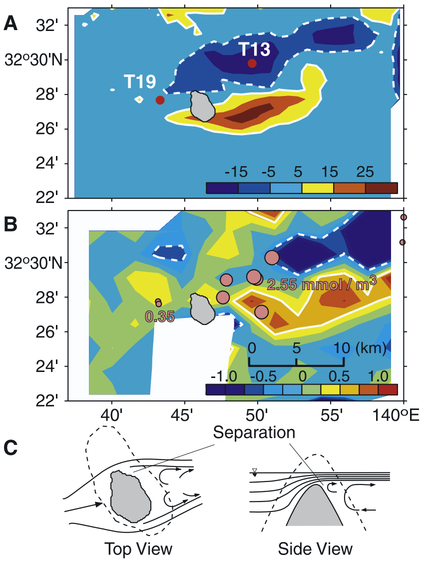

Figure 3. (A) Distribution of normalized vorticity ($Ro \equiv \zeta_z \cdot f^{-1}$). Solid (dashed) white contours enclose regions larger (smaller) than +5 (−5). Black dots labelled T13 and T19 are TurboMAP stations. (B) Vertical velocity field at z = 74 m in units of 0.01 m s^{-1}. The solid (dashed) contours enclose regions greater (smaller) than 5 × 10^{-3} m s^{-1} (−5 × 10^{-3} m s^{-1}). Pink circles indicate nitrate ion (NO_3^-) content at depths of 10 m. The circle sizes are proportional to the NO_3^- concentration. (C) Schematic illustrations of flow around the island. Solid lines are streamlines. The gray areas are the island (left panel) and the bottom (right panel).

vorticity, as reported previously [*Heywood et al.*, 1990], and the extreme values suggest that the earth's rotation is not important. Thus, the shoaling of isopycnals cannot be explained by a preference for cyclonic rotation.

[11] The horizontal divergence of the current provides a measure of the rate of vertical straining of the water column and this can be used to estimate the vertical velocity over the depth range of the ADCP profiles. That is,

$$w(z) = \int_z^{z_0} \frac{\partial w}{\partial \xi} d\xi = \int_z^{z_0} -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) d\xi \, , \qquad (1)$$

where the surface vertical velocity $w(z = z_0) = 0$. Both horizontal strain components contribute about equally to the vertical strain. Profiles of divergence and vertical velocity at Grid-(c) and (d) on Figure 2a are examples of the far field undisturbed flow and the surface divergence flow in the wake (Figure 2d). The vertical velocity at 74 m depth is extremely large for open ocean conditions (Figure 3b). Upstream of the island, the velocity is small and mostly positive which reflects the flow blockage by the ridge. Downstream, there is a 5 km × 15 km wake of strong upwelling with a preference for downwelling on the northern edge of this wake. Peak upward velocity reaches 0.01 m s^{-1} and the vertical transport in the wake is 0.4 × 10^6 m^3 s^{-1}. The upwelling brings deep nutrient rich water to the surface. Nitrate levels at the surface in the wake (2.55 × 10^{-3} mol m^{-3}) are seven times larger than upstream. Concentrations are typically 11 × 10^{-3} mol m^{-3} at 100 m depth (Figure 3b).

[12] The observed rate of upwelling is consistent with the vertical velocity induced by a fast current (2 m s^{-1}) that shoals by 60 m over a horizontal distance of 10 km. Previously reported oceanic upwelling speeds are, however, much smaller. For example, the total upwelling rate along the Gulf Stream is 1–2 × 10^6 m^3 s^{-1} [*Olson*, 2001] and typical vertical speeds are 5 × 10^{-4} m s^{-1} [*Hall*, 1986]. Even regions of conspicuous upwelling, such as the west coast of North America, show only $O(10^{-4}$ m $s^{-1})$ vertical velocity [*Dewey et al.*, 1991; *Pond and Pickard*, 1986]. Thus, the upwelling created by only one island, and its local flank, is significant, and the flow of the Kuroshio over the Izu-Ogasawara Ridge may be a major source of nutrient-rich deep water replenishing the oligotrophic surface zone in the down stream region.

[13] The doming of isopycnals and upwelling may not be effective in raising productivity if they occur episodically and with a duration short compared to the time scale of biological growth [*Takahashi et al.*, 1980]. However, turbulent mixing will not only enhance the vertical flux of nutrients, but will also produce a thermodynamically irreversible conversion of water type which has a lasting effect. Turbulence in western boundary currents has long been considered to be small, due to the large Richardson number of these currents, and this notion has been confirmed by the few observations available [*Gargett and Osborn*, 1981]. Upstream of Aoga-shima, the Richardson number, $R_i = N^2/S^2$, is approximately 10 and well above the critical value of 1/4, where $N^2 \equiv -g/\rho_o \cdot \partial\sigma_\theta/\partial z$ is the buoyancy frequency squared, σ_θ is the potential density, ρ_o is the density, g is gravity and S^2 is the mean squared vertical shear. Aft of the flanks, R_i < 1/4 (Figure 4d) and the flow is unstable to shear instability. There are numerous thermal inversions (Figure 4c) and the rate of dissipation of kinetic energy reaches ϵ = 1 × 10^{-4} W kg^{-1} (Figure 4b), which is the largest value ever reported for the open ocean. Upstream dissipation rates are moderate with peak values of 3 × 10^{-7} W kg^{-1} (Figure 4a), and most of the turbulence is confined to the surface mixing layer which is present because of the strong (15 m s^{-1}) easterly winds present during the observations.

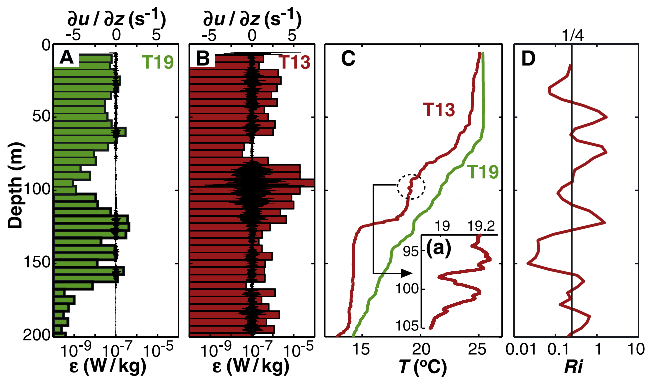

Figure 4. Profiles of microstructure shear, $\partial u/\partial z$, and dissipation rate ϵ upstream at T19 (panel A) and downstream at T13 (panel B) (see Figure 3a for location). Temperature profiles up- and down-stream of the island (panel C). Profile of the gradient Richardson number, R_i, downstream at T13 (panel D).

[14] Upstream of Aoga-shima, the temperature decreases monotonically with depth below the surface mixed layer (Figure 4c) but, in the wake, there are quasi-homogeneous layers indicative of strong vertical mixing. The potential energy of these layers compared to upstream conditions is

$$\Delta PE = \frac{1}{12} \cdot \rho_0 \cdot \left(N_1^2 - N_2^2\right) \cdot h^3 \quad (2)$$

where, N_1 and N_2 are the buoyancy frequency up- and down-stream, respectively, and h is the layer thickness. If the observed dissipation rates are typical, and if we assume that the rate of production of potential energy is 20% of the rate of dissipation [*Osborn*, 1980], then the time scale for the observed mixing in the water column is 420 s. The fluid transit time from the ridge to station T13 is 5000 s. Thus, the turbulence and upwelling have more than enough time to modify the water mass characteristics of the upper 200 m.

[15] Finally, what drives the upwelling? The water is too deep to apply the ''tea-cup'' mechanism and there is no preference for cyclonic circulation. Because the Rossby number is very large, stratified hydraulic flow may explain the observations. The pair of horizontal surface jets behind the island entrain water from the lee side of the island and cause surface divergence in the wake. The ambient stratification is too weak to suppress upwelling (and confine the flow to horizontal layers). In addition to the horizontal divergence, the vertical separation of the jets downstream of the shoals adjacent to the island also draws fluid up from below.

[16] The upwelling due to the surface divergence is analogous to a selective withdrawal problem in engineering applications [*Turner*, 1973], where a stratified fluid is drawn through a circular orifice of diameter D at a rate Q, the shoaling H of the fluid is given by

$$H = \left(\frac{Q^2}{4.5^2 \cdot D \cdot N^2}\right)^{\frac{1}{5}}. \quad (3)$$

Using the discharge rate, Q, derived from the vertical transport in the wake, the average buoyancy frequency from the upper 200 m at station T13, and $D = 1 \times 10^4$ m (which is equivalent area of the wake) gives an isopycnal rise of $H = 100$ m, which is consistent with the observed shoaling. This very rough calculation suggests that the stratification is not strong enough to inhibit the upwelling due to the horizontal divergence.

3. Conclusions

[17] The flow of the Kuroshio past Aoga-shima and the adjacent Izu-Ogasawara Ridge is strongly ageostrophic, produces horizontal and vertical flow separation, and exhibits strong upwelling and vigorous turbulence. This results in a seven-fold increase in near-surface nutrients and extensive homogenization of the water column, thereby significantly modifying the local physical and biological conditions. The induced upwelling from just this small island is almost of the same order as the upwelling predicted for the entire Gulf Stream. We have only highlighted some of the stunning features of this region and considerable effort, including more observations and modelling, are required to fully grasp the significance of the persistent flow of the Kuroshio over this remarkably long ridge.

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