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# Comment on “Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Blooms”

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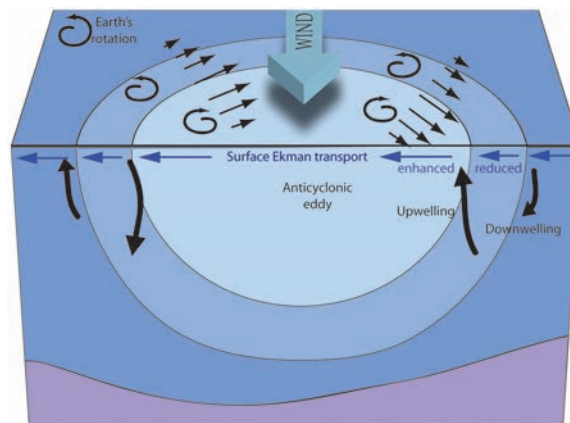
McGillicuddy *et al.* (Reports, 18 May 2007, p. 1021) proposed that eddy/wind interactions enhance the vertical nutrient flux in mode-water eddies, thus feeding large mid-ocean plankton blooms. We argue that the supply of nutrients to ocean eddies is most likely affected by submesoscale processes that act along the periphery of eddies and can induce vertical velocities several times larger than those due to eddy/wind interactions.

How do eddies, such as those described in McGillicuddy *et al.* (1), sustain their extraordinary concentrations of phytoplankton and biological productivity in an ocean whose surface is bereft of nutrients? As an explanation, McGillicuddy *et al.* invoke the mechanism of eddy/wind interaction (2), whereby the difference in the relative air-water velocity (and, consequently, wind stress) felt on diametrically opposite sides of an anticyclonic eddy, induces an upward Ekman pumping velocity. McGillicuddy *et al.* assert that the upward velocity, on the order of about 1 m/day at the eddy center, supports the nutrient flux to sustain the observed productivity.

Here, we point out that submesoscale effects (3–5), which include intensification of the ageostrophic secondary circulation (ASC) (6) and nonlinear Ekman transport (7–10), can result in vertical velocities on the order of 10 to 100 m/day. These velocities are 10 to 100 times as large as the linear Ekman pumping velocity due to the eddy/wind interaction mechanism. Submesoscale effects come into play for flows whose relative vorticity  $\zeta$ , defined as the curl or rotary component of the horizontal velocity field, is not much smaller in magnitude than the planetary vorticity  $f$ , arising from Earth’s rotation. At ocean eddies and fronts, the quantity  $\zeta/f$ , known as the Rossby number ( $Ro$ ), typically takes on values of 0.1 to 1.0. For such flows, the loss of geostrophy, the balance between pressure gradient and Coriolis effects, is restored by an overturning circulation across lateral density variations in the presence of straining. The strength of the overturning at a front, as described by the semigeostrophic Sawyer-Eliassen equation (11), continues to grow as the front intensifies until limited by mixing. Such submesoscale intensification is typ-

ically manifest on horizontal length scales on the order of 1 to 10 km. A further effect of the relatively large relative vorticity  $\zeta$  is that the wind-forced horizontal Ekman mass transport,  $M_E = -\tau/[\rho(f + \zeta)]$ , depends on the net (i.e., planetary plus relative) vorticity of the flow,  $(f + \zeta)$  (12). Consequently, lateral variations in the relative vorticity can result in a modulation of the Ekman transport, the divergence of which drives vertical motions even if the wind stress  $\tau$  is spatially uniform (Fig. 1).

To quantify the relative contributions of the nonlinear Ekman effect and eddy/wind interaction on the induction of vertical motions, we derived the ratio of scalings for their respective vertical velocities (see Supporting Online Material) as  $Ro (u_a/u_o)$ , where  $u_a$  is the wind speed,  $u_o$  is the maximum azimuthal velocity of the ocean eddy, and  $Ro$  is the Rossby number for the eddy. Typical water velocities for the eddy described in (1) are on the order of 0.1 m/s, whereas wind speeds are on the order of 10 m/s; therefore,  $u_a/u_o = O(100)$ . This implies that for

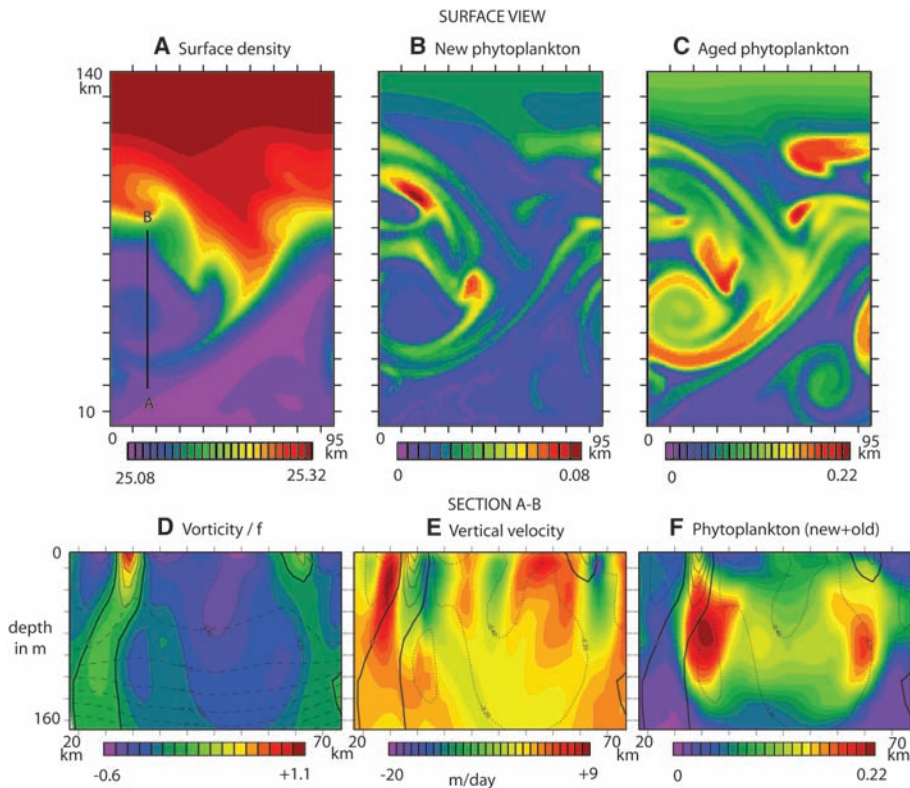


**Fig. 1.** The nonlinear Ekman effect generates upwelling and downwelling in a Northern hemisphere anticyclonic eddy, as schematically depicted. The Ekman transport in the surface layer is at 90 degrees to the right of the wind and inversely proportional to the net rotation of the fluid. The rotation of the eddy is anticyclonic and opposite to Earth’s rotation. It reduces the net spin,  $(f + \zeta)/2$ , felt by the fluid toward the inside of the eddy. At the periphery, the shear between the eddy and ambient fluid generates a spin in the fluid that is in the same sense as Earth’s rotation, thus

enhancing the net spin of the fluid. Hence, the Ekman transport is enhanced on the inside of the eddy and weakened toward the outside. The divergence/convergence of the Ekman transport drives up/down motion as shown. The vertical motion associated with an anticyclonic eddy is greater than that with a cyclonic eddy of similar strength because decreasing the magnitude of the net rotation solicits a greater response than increasing it by the same amount.

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**Fig. 2.** A snapshot from a numerical simulation of a front with a uniform westerly wind stress of  $0.1 \text{ N/m}^2$  (wind speed  $\sim 10 \text{ m/s}$ ) showing, in the top row, surface views of (A) density, (B) phytoplankton resulting from new production or the fresh supply of nutrients from beneath, and (C) phytoplankton that has been in the euphotic layer longer than 3 days or is formed from nutrients recycled within the euphotic layer. In (C), the phytoplankton and nutrients upwelled along the front are being entrapped in an anticyclonic eddy. In the lower row, a vertical section A-B through the eddying structure marked in (A) shows (D) the ratio of the relative to planetary vorticity  $\zeta/f$ , with dashed contours denoting density; (E) vertical velocity; and (F) phytoplankton. Contours of  $\zeta/f$  are overlaid in (E) and (F) to demonstrate that the largest vertical velocities are where the vorticity changes sign and thus result from submesoscale effects. The nonlinear Ekman effect results in upwelling and downwelling at the eddy's periphery, as depicted in Fig. 1. Although this simulation does not represent a specific coherent eddy, it demonstrates how submesoscale processes intensify vertical velocities and phytoplankton accumulates at the center of an anticyclonic eddy structure.

anticyclonic eddy as it is being formed. The preponderance of phytoplankton in anticyclonic eddies was also seen in previous model results [see figure 5 in (14)]. By tracking the age (i.e., time since new production) of the phytoplankton in our model, we are able to distinguish between

where the phytoplankton is formed and where it accumulates over time. Although the largest vertical velocities occur at the eddy's periphery, a small radially inward component of velocity causes plankton to be transported toward the eddy center. The mesoscale eddy itself forms a

closed vortex whose outer edge inhibits lateral exchange (Fig. 2). Thus, the eddy entraps and isolates a water mass that displays an "older" stock of phytoplankton in the model. Therefore, the largest concentrations of plankton can build up in the eddy center even with nutrient supply at the periphery.

Although nutrient replenishment in eddies occurs largely at the periphery in this mechanism, the biological response is sensitive to the time scales of nutrient growth and uptake. Numerical experiments with varying biological time scales of growth and persistence are needed for characterizing the effects of submesoscale processes on biogeochemistry and phytoplankton distributions. Future measurements that resolve the submesoscale variability, as well as nutrient pathways and the ensuing distribution of phytoplankton in terms of age, size, and species, would also be helpful in clarifying these issues.

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#### Supporting Online Material

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