EXTENDED PDF FORMAT
SPONSORED BY
www.usbweb.com

Comment on "Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Blooms"

Amala Mahadevan, *et al.*

Science **320**, 448b (2008);
DOI: 10.1126/science.1152111

The following resources related to this article are available online at www.sciencemag.org (this information is current as of April 26, 2008):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/cgi/content/full/320/5875/448b

Supporting Online Material can be found at:
http://www.sciencemag.org/cgi/content/full/320/5875/448b/DC1

A list of selected additional articles on the Science Web sites **related to this article** can be found at:
http://www.sciencemag.org/cgi/content/full/320/5875/448b#related-content

This article **cites 13 articles**, 1 of which can be accessed for free:
http://www.sciencemag.org/cgi/content/full/320/5875/448b#otherarticles

This article appears in the following **subject collections**:
Oceanography
http://www.sciencemag.org/cgi/collection/oceans
Technical Comments
http://www.sciencemag.org/cgi/collection/tech_comment

Information about obtaining **reprints** of this article or about obtaining **permission to reproduce this article** in whole or in part can be found at:
http://www.sciencemag.org/about/permissions.dtl

Downloaded from www.sciencemag.org on April 26, 2008

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. Copyright 2008 by the American Association for the Advancement of Science; all rights reserved. The title *Science* is a registered trademark of AAAS.

Comment on "Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Blooms"

Amala Mahadevan,[1]* Leif N. Thomas,[2] Amit Tandon[3]

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 ζ, 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 ζ/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 typically manifest on horizontal length scales on the order of 1 to 10 km. A further effect of the relatively large relative vorticity ζ 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 τ 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 eddies with Rossby numbers greater than 0.01, nonlinear Ekman effects dominate the pumping velocity. For $Ro = 0.1$, a typical value for mesoscale eddies, the nonlinear Ekman effect would be about 10 times as important for the wind-induced vertical circulation as stress asymmetry from the air-sea velocity difference. Further, the nonlinear Ekman effect would be greatly enhanced in regions where the relative vorticity is locally intensified and is coupled with lateral density variations (*3*, *6*). High-resolution modeling studies show that the largest relative vorticity in eddying flows occurs in filament-like features along fronts and at the edges of eddies, rather than at eddy centers (*4*, *13*), and routinely equals or exceeds the planetary vorticity in magnitude, bringing submesoscale effects into play.

Notably, there is a diapycnal flux associated with submesoscale processes as evidenced from the downscale cascade of energy (*4*). As nutrients are upwelled into the euphotic zone, they are consumed by phytoplankton production on time scales on the order of a day. Because there is a mean, negative vertical gradient in the concentration of nutrient, and a sink near the surface, the vertical velocities sustain a net upward transport even though upwelling is countered by subduction. The rate of nutrient consumption and supply are a function of the phytoplankton growth rates.

Submesoscale physics suggests that the largest vertical velocities occur at the eddy's periphery, but the highest levels of chlorophyll were reported at the eddy center in (*1*). Using a numerical model of an eddying front with a nutrient profile characteristic of the subtropical oligotrophic ocean, we simulated the advection of nutrient and production of phytoplankton within the euphotic zone. Although upwelling and new production of phytoplankton are more pronounced where lateral density gradients support active frontogenesis, phytoplankton gathers up in an

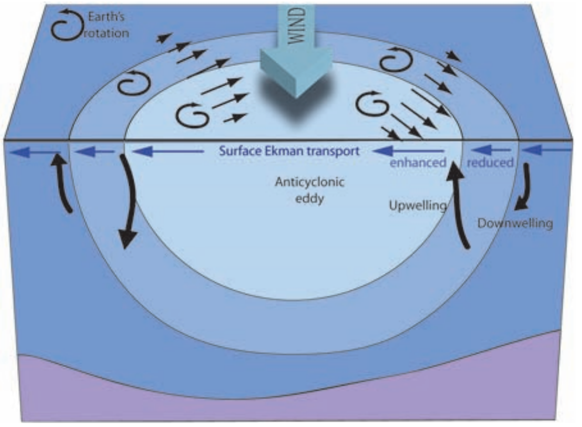

Fig. 1. The nonlinear Ekman effect generates upwelling and downwelling in a Northern hemisphere anticyclonic eddy, as schematically depicted. The Ekman transport in the surface layer is at 90 degrees to the right of the wind and inversely proportional to the net rotation of the fluid. The rotation of 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.

---

[1]Department of Earth Sciences, Boston University, Boston, MA 02215, USA. [2]Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA. [3]Physics Department and Department of Estuarine and Ocean Sciences, University of Massachusetts, Dartmouth, North Dartmouth, MA 02747, USA.

*To whom correspondence should be addressed. E-mail: amala@bu.edu

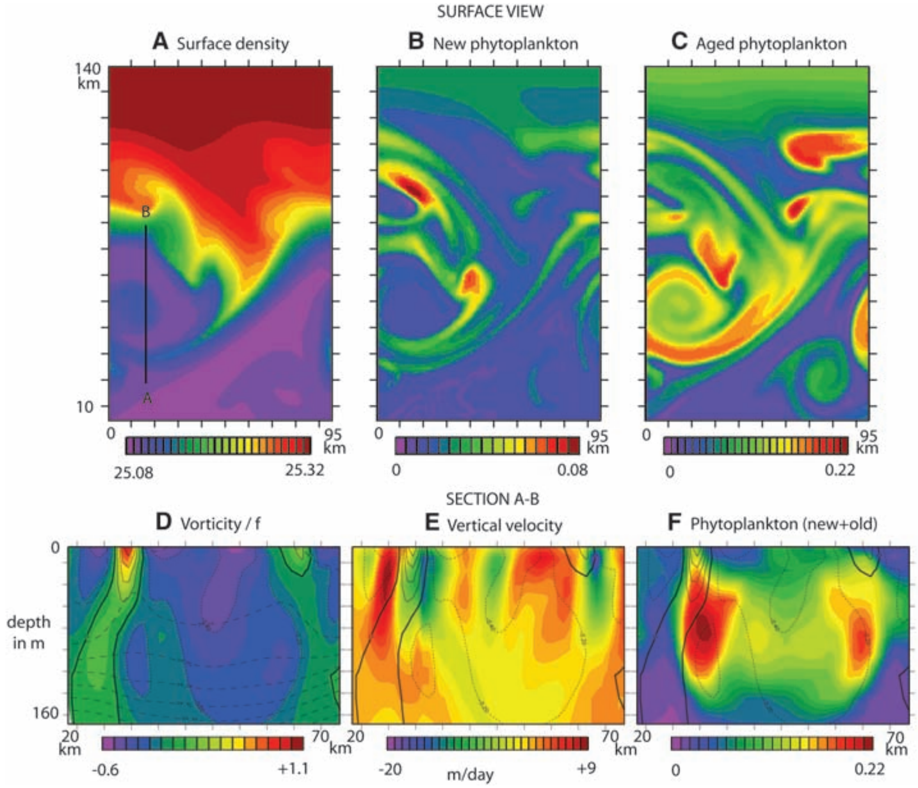

Fig. 2. A snapshot from a numerical simulation of a front with a uniform westerly wind stress of 0.1 N/m^2 (wind speed ~10 m/s) showing, in the top row, surface views of (**A**) density, (**B**) phytoplankton resulting from new production or the fresh supply of nutrients from beneath, and (**C**) phytoplankton 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 ζ/f, with dashed contours denoting density; (**E**) vertical velocity; and (**F**) phytoplankton. Contours of ζ/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 phytoplankon 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.

References and Notes

1. D. J. McGillicuddy *et al.*, *Science* **316**, 1021 (2007).
2. A. P. Martin, K. J. Richards, *Deep-Sea Res. II* **48**, 757 (2001).
3. A. Mahadevan, A. Tandon, *Ocean Model.* **14**, 241 (2006).
4. X. Capet, J. C. McWilliams, M. J. Molemaker, A. F. Shchepetkin, *J. Phys. Oceanogr.* **38**, 29 (2008).
5. G. Boccaletti, R. Ferrari, B. Fox-Kemper, *J. Phys. Oceanogr.* **37**, 2228 (2007).
6. H. Giordani, L. Prieur, G. Caniaux, *Ocean Dyn.* **56**, 513 (2006).
7. M. E. Stern, *Deep Sea Res.* **12**, 355 (1965).
8. P. Niiler, *J. Geophys. Res.* **74**, 7048 (1969).
9. L. N. Thomas, P. B. Rhines, *J. Fluid Mech.* **473**, 211 (2002).
10. L. N. Thomas, C. M. Lee, *J. Phys. Oceanogr.* **35**, 1086 (2005).
11. J. S. Sawyer, *Proc. R. Soc. London Ser. A* **234**, 346 (1956).
12. For flows with curvature, this formula is modified, but the qualitative result that spatial variations in vorticity lead to Ekman pumping still holds.
13. M. Lévy, P. Klein, A.-M. Treguier, *J. Mar. Res.* **59**, 535 (2001).
14. M. Lévy, P. Klein, *Proc. R. Soc. London Ser. A* **460**, 1673 (2004).
15. The authors are supported by NSF OCE-0623264 (A.T. and A.M.) and OCE-0549699 and OCE-0612058 (L.N.T.).

Supporting Online Material

www.sciencemag.org/cgi/content/full/320/5875/448b/DC1
SOM Text

1 August 2007; accepted 26 March 2008
10.1126/science.1152111