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

Dennis J. McGillicuddy Jr.,* James R. Ledwell, Laurence A. Anderson

The alternative mechanism proposed by Mahadevan *et al.* is an unlikely explanation for our observations because their model predicts a bloom at the periphery of the eddy, whereas the observations show it located at the eddy center, and because the vertical displacements caused by the nonlinear Ekman effect are too small to lead to an extraordinary biological response in this eddy.

McGillicuddy *et al.* (1) proposed that eddy/wind interactions enhance eddy-induced upwelling of mode-water eddies and can thus lead to extraordinary plankton blooms. Mahadevan *et al.* (2) suggest an alternative mechanism to explain an extraordinary phytoplankton bloom that we observed in the center of a mode-water eddy. They suggest that the primary influx of nutrients takes place along the periphery of the eddy in submesoscale upwelling zones and that phytoplankton are transported toward the eddy center. The mechanism of this inward transport is not described, nor does it appear to us to be taking place in their model. In contrast to the observations in (1), Mahadevan *et al.*'s model solution shows uplifted isopycnals and a phytoplankton bloom at the periphery of their simulated eddy [figure 2F in (2)]. The observed bloom was associated with domed isopycnals at the eddy center [figure 3, A and B, in (1)], where it persisted throughout six different occupations over a period of two and a half months. Our survey data show no evidence of inward transport of biogenic material from the periphery of the eddy. Given these discrepancies, the alternative mechanism proposed by Mahadevan *et al.* seems unlikely to be responsible for the observed bloom, especially because the mechanism we proposed is sufficient to explain our observations and is local to the center of the eddy where the bloom occurred.

There is no doubt that the magnitude of submesoscale vertical motions can be much larger than those that occur on the scale of the eddy itself and that these motions can have an impact on biological productivity (3–5). However, submesoscale vertical motion tends to be most active in frontal regions (such as the periphery of an eddy) where horizontal advection is strongest. Therefore, water parcels transported into the euphotic zone in submesoscale upwelling

zones can be rapidly advected into submesoscale downwelling zones and subsequently transported back out of the euphotic zone, unless the parcel encounters mixing strong enough to make the process irreversible. The key issue is whether the transit time from upwelling to downwelling will be long enough for a biological response to accumulate. Of course, that will depend on the dynamical regime as well as the local chemical and biological environment. There is a substantial literature on this topic [see the review by Williams and Follows (6)].

The region of high productivity studied in eddy A4 in (1) was on isopycnal surfaces at 90-m depth, at the base of the seasonal pycnocline, where mixing and heating are very weak. At the periphery of the eddy, the same isopycnals were at about 130-m depth. These isopycnals may be raised and lowered by submesoscale processes at relatively high velocities, as illustrated by the computations below. Assuming a steady wind for the 1-week period of rotation of the eddy, we estimate that a parcel of fluid would upwell ~2 m before it descended again in a downwelling zone. Of course, higher vertical velocities are possible for sharper fronts such as those simulated by Mahadevan *et al.* (2), but such fronts are also accompanied by swifter horizontal velocities. Nevertheless, the time and length scales of these processes in eddy A4 are such that virtually no fluid parcel would be lifted from 130 m into the euphotic zone (~100 m) before it turns around to descend again, much less allow time for a substantial biological response to accumulate.

Mahadevan *et al.* (2) correctly point out that we did not include the nonlinear Ekman effect in our estimates of the upwelling caused by eddy/wind interaction [figure 4 in (1)], for which we used a kinematic model proposed by Martin and Richards (7). To quantify the magnitude of our omission, we computed the vertical velocity caused by the nonlinear Ekman term and compared it to our estimate for a 5.2 m s^{-1} wind from the east (Fig. 1). As expected from the scale analysis described in (2), the magnitude of the nonlinear Ekman vertical velocity can be much larger than

the linear Ekman vertical velocity, with upwelling on the southern flank of the eddy and downwelling on the northern flank (Fig. 1, B to E). The configuration of these upwelling and downwelling centers depends on the direction of the wind and will therefore fluctuate with the wind forcing. Moreover, the eddy's azimuthal velocity will advect fluid through the upwelling and downwelling centers, such that water parcels experience those vertical motions for only a fraction of the eddy's 1-week rotation period. We therefore computed an azimuthal average to assess the net impact of these motions (Fig. 1F). Downwelling on the northern flank is slightly larger than upwelling on the southern flank (Fig. 1C) because the wind stress is higher where the wind opposes the surface ocean current. This results in a downward residual flow in the azimuthal average, which tends to decrease the productivity in A4, not increase it as Mahadevan *et al.* suggest. This amounts to a correction of only about 10% to the computations presented in figure 4 in (1). Thus, our fundamental conclusion remains intact: The primary mechanism of nutrient supply in eddy A4 is the persistent upward motion at the scale of the eddy driven by the mesoscale Ekman divergence.

Last, we recently conducted a numerical investigation of the mode-water eddy described in (1) using a primitive equation model in which both the linear and nonlinear Ekman effects are included, with the wind stress formulated as the difference between air and sea velocities. The numerical simulations confirm eddy/wind interactions as the cause of the observed upwelling, and the results agree with the observed evolution of SF_6 tracer injected into the eddy. Azimuthally averaged vertical velocity in the simulations shows upwelling at the eddy center, similar to the theoretical predictions presented in Fig. 1. Thus, the numerical results confirm that the linear Ekman term dominates the azimuthally averaged vertical velocity, which is the relevant quantity for assessing the net vertical transport of both biotic and abiotic tracers in this eddy.

References and Notes

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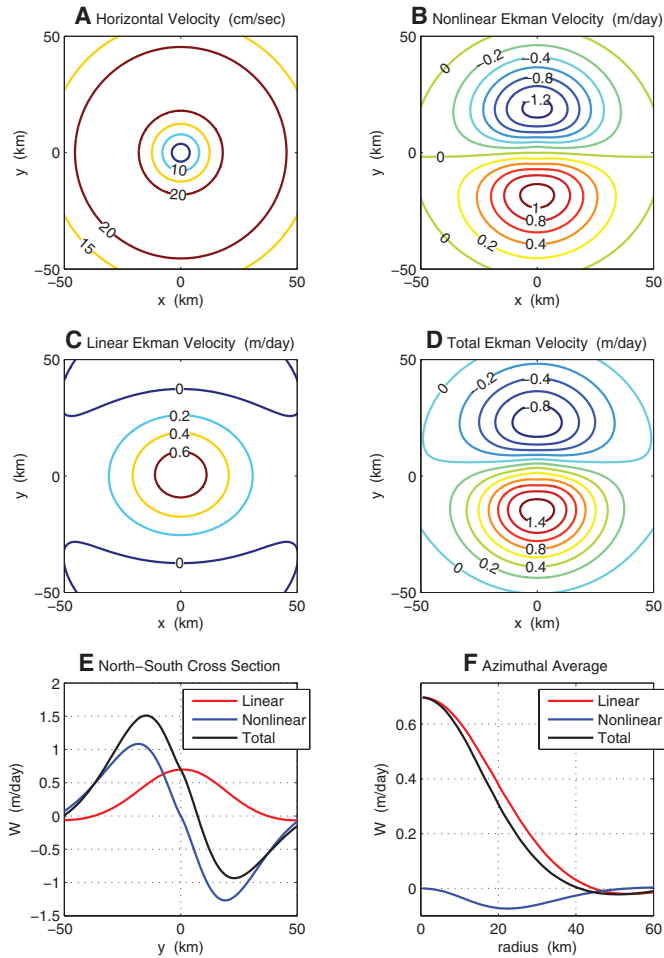


Fig. 1. Vertical velocities computed from a feature model of mode-water eddy A4 (**A**). The total Ekman vertical velocity (**D**) is given by

$$W_{\text{Total Ekman}} = \frac{\partial}{\partial x} \left[\frac{\tau_y}{\rho(f_0 + \zeta)} \right] - \frac{\partial}{\partial y} \left[\frac{\tau_x}{\rho(f_0 + \zeta)} \right]$$

from which the linear (**C**) and nonlinear (**B**) components can be derived:

$$W_{\text{Linear Ekman}} = \frac{1}{\rho(f_0 + \zeta)} \left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y} \right)$$

$$W_{\text{Nonlinear Ekman}} = \frac{1}{\rho(f_0 + \zeta)^2} \left(\tau_x \frac{\partial \zeta}{\partial y} - \tau_y \frac{\partial \zeta}{\partial x} \right)$$

where τ_x and τ_y are the eastward and northward components of the wind stress, ρ the density, and ζ the relative vorticity. The Coriolis parameter f is assumed to be constant (f_0) over the scale of the eddy. (**E**) and (**F**) show north-south cross sections and azimuthal averages of the linear and nonlinear contributions to the total Ekman vertical velocity.