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COMMENTARY
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Key Points:

- A climate relevant direct energy pathway between atmospheric wind stress and mesoscale ocean eddies is diagnosed
- Fine scales in the wind stress due to the imprint of mesoscale ocean dynamics cause systematic damping of ocean eddies
- Large-scale wind stress shear systematically energizes ocean eddies whose rotation is in the same sense and vice versa

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Does the wind systematically energize or damp ocean eddies?

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Abstract Globally, mesoscale ocean eddies are a key component of the climate system, involved in transport and mixing of heat, carbon, and momentum. However, they represent one of the major challenges of climate modeling, as the details of their nonlinear dynamics affect all scales. Recent progress analyzing satellite observations of the surface ocean and atmosphere has uncovered energetic interactions between the atmospheric wind stress and ocean eddies that may change our understanding of key processes affecting even large-scale climate. Wind stress acts systematically on ocean eddies and may explain observed asymmetry in the distribution of eddies and details of their lifecycle of growth and decay. These findings provide powerful guidance for climate model development.

1. Introduction

Mesoscale ocean eddies (Figure 1) remain one of the most challenging aspects of global climate to understand and to simulate. Formed through flow instability, eddies have relatively small spatial scale (~10–200 km, mean ~ 60 km [*Chelton et al.*, 2011]) and growth period (15–55 days or shorter [*Williams et al.*, 2007]) and contain complex, nonlinear physics. Ocean eddies form a huge global energy reservoir of 13 EJ (1 EJ = 10^{18} J)—more than the 11 EJ contained by ocean surface waves and upper ocean small-scale turbulence [*Wunsch and Ferrari*, 2004]. Mesoscale ocean eddies are also profoundly important for global heat transport from equator to pole and from surface to deep ocean [*Bryan*, 1996; *Volkov et al.*, 2008; *Griffies et al.*, 2015]. Occurring globally, but concentrated in midlatitude "ocean storm tracks," eddies accelerate and decelerate ocean currents at least as strongly as the wind forcing [*Hughes and Ash*, 2001; *Williams et al.*, 2007] and sharpen and steer the strongest currents such as the Gulf Stream, Kuroshio, and Antarctic Circumpolar Current.

Previously, eddies were thought to get their energy *indirectly* from the wind and thermodynamic forcing that generates large-scale velocity shear of the background ocean circulation, leading to flow instability and eddy growth [*Gill et al.*, 1974]. The potential for *direct* energetic forcing of the eddies by the atmosphere was largely ignored. Also, the sink of eddy energy was unclear [*Wunsch and Ferrari*, 2004]. More recently, *Zhai et al.* [2010] proposed a sink of 0.1–0.3 TW (1 TW = 10^{12} W) at the western boundary of ocean basins, where eddies swept westward by Rossby waves interact with shallow coastal topography and dissipate.

Satellite observations of the ocean surface have given new insight to both ocean eddies (via altimetry and ocean color) and wind stress (via scatterometer measurements of surface roughness). *Chelton et al.* [2011] perform a global eddy census and find a mean eddy lifetime of around 8 weeks, which depends on growth and decay phases of the eddy lifecycle and therefore constrains the expected eddy energy decay rate. They also find asymmetry in the number of long-lived cyclonic/anticyclonic eddies. In terms of the overall energy budget for the ocean, the large-scale ocean circulation receives only a tiny fraction of its energy from thermal sources (0.06 TW) and the majority from mechanical energy due to the lunisolar tides (3.5 TW) and the atmospheric wind (20.6 TW) [*Munk and Wunsch*, 1998; *Wunsch and Ferrari*, 2004]. Tides are highly predictable, so there has been interest in using observations to calculate the details of the less understood 20.6 TW of work done by the wind on the surface of the ocean. Most of the wind work is dissipated in the upper 100 m of the ocean as turbulence, within the Ekman frictional boundary layer, and only about 0.8–1 TW reaches the large-scale geostrophic circulation below [*Wunsch*, 1998; *Hughes and Wilson*, 2008; *von Storch et al.*, 2007]. Interesting features seen in the wind stress observations show the imprint of ocean currents [*White and Annis*, 2003; *Chelton et al.*, 2004]. It was unexpected to find this signature of the ocean in a measure that was generally assumed to be dominated by the physics of the lower atmosphere.

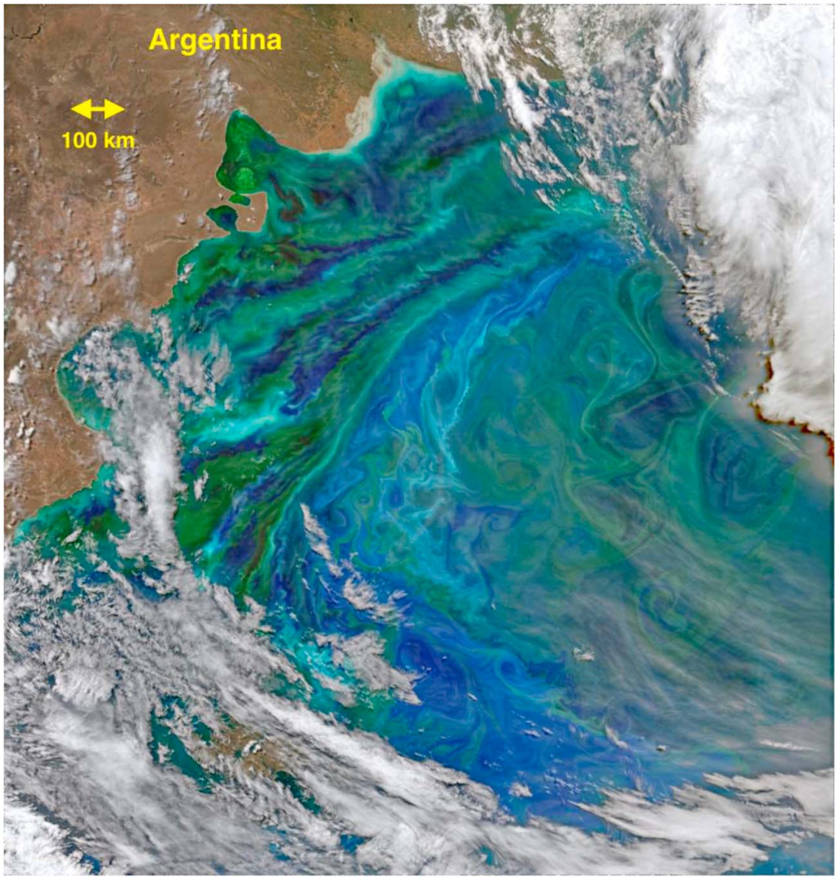

Figure 1. Mesoscale ocean eddies off the coast of Argentina, 2 December 2014, seen through a gap in the clouds (white) within this composite color image of a phytoplankton bloom. Eddies like these occur throughout the global ocean.

This motivated many to reconsider the wind stress bulk parameterization used in ocean models to account for surface wind motion *relative* to the ocean current. *Duhaut and Straub* [2006] predicted that including this correction would lead to a "relative wind stress effect" (Figure 2), systematically reducing wind work on the geostrophic circulation by 20–35%. This prediction was supported by observational analysis of *Hughes and Wilson* [2008] and model experiments [e.g., *Dawe and Thompson*, 2006; *Zhai and Greatbatch*, 2007]. Climate models that excluded this effect were likely to have spurious global circulation. Could further refinements to our understanding of boundary layer physics lead to similarly significant and systematic effects on circulation and climate? *White and Annis* [2003] considered systematic effects of sea surface temperature anomalies on destabilization of the atmospheric boundary layer and therefore on correlations between temperature anomalies and surface wind stress. However, for wind work energetics below the Ekman layer, thermal effects are thought to be of secondary importance to those of ocean currents [*Gaube et al.*, 2015]. Increasingly, the importance of the ocean mesoscale in wind work energetics was emerging, but it remained unclear whether the wind stress may directly transfer energy into (or out of) geostrophic ocean eddies by doing work on them (or vice versa). The wind work on the underlying ocean geostrophic circulation cannot be simply associated with energy transfer between atmosphere and ocean because of turbulent processes in the frictional boundary layers in each system. However, for the case of positive wind work the ocean boundary layer transfers energy to the ocean geostrophic circulation below. For negative wind work, the geostrophic circulation transfers energy to the ocean boundary layer above. There may be subsequent energy exchange with the atmosphere, but this will depend on the details of the boundary layer physics which are much more complex. Importantly, not only did this potential wind stress-eddy pathway remain as a gap in the ocean energy budget, but any systematic effects could have significant implications for climate modeling.

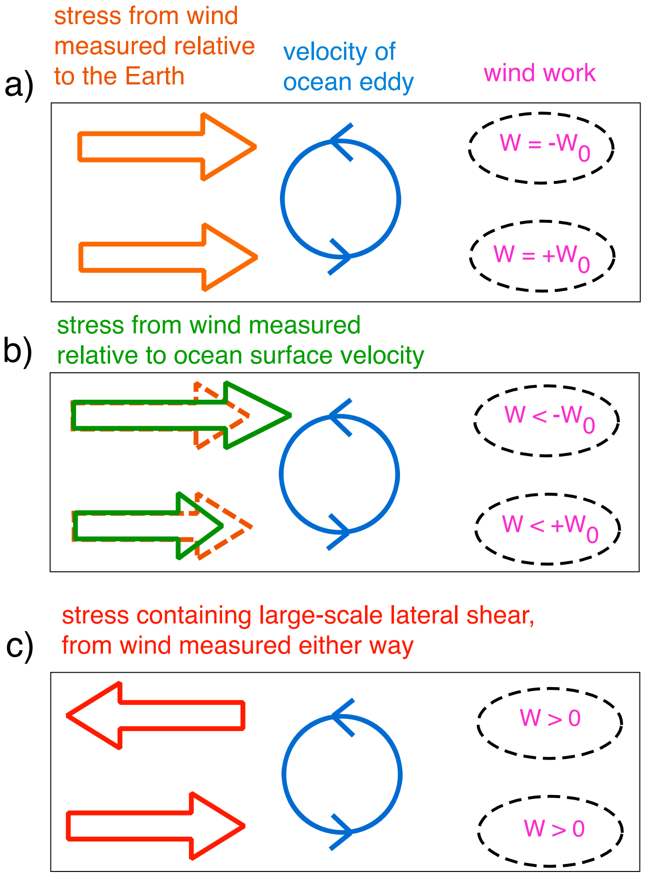

Figure 2. Three different mechanisms for wind work on an ocean eddy. Wind work is the scalar product of wind stress and ocean surface velocity, here assumed to be geostrophic. (a) Traditional parameterization of wind stress that depends on atmospheric wind velocity measured relative to the Earth, which is independent of ocean surface velocity—for a uniform wind stress (orange) acting on a circular eddy (blue), wind work is negative (from ocean to atmosphere) where the ocean flows in the opposite direction to the wind stress and positive where the ocean flows in the same direction (magenta). The size of this effect (an amount of wind work, W_0) is antisymmetric and cancels when averaged over the eddy. (b) A more realistic parameterization of wind stress that includes atmospheric wind motion *relative* to the ocean surface velocity gives, for the same wind field as in Figure 2a, wind stress that is comparatively stronger where the ocean velocity is in the opposite direction and weaker where the ocean velocity is in the same direction as the wind (green). This *relative wind stress effect* causes the negative wind work region to become more negative and the positive wind work region to become less positive—a systematic damping effect that occurs regardless of the sense of rotation of the ocean eddy. The effect depends on the imprint of the ocean mesoscale velocity (since velocity is strongest at the mesoscale) in the wind stress and its correlation back onto the ocean mesoscale eddy velocity. (c) Wind stress, based on wind measured either way, containing a large-scale lateral shear (red) generates wind work that is everywhere either positive, acting systematically to energize eddies that rotate in the same direction as the wind stress shear, or negative, acting to damp eddies that rotate in the opposite direction. This effect depends only on the large-scale shear of the wind stress and is not sensitive to the small scales in the wind stress associated with the relative wind stress effect.

2. New Evidence of Direct Wind Forcing of Ocean Eddies

Seeking to fill this knowledge gap, *Xu et al.* [2016] estimated the direct energy pathway between wind and ocean eddies by combining wind stress data with ocean surface geostrophic velocity data within ocean eddies. *Xu et al.* [2016] identify eddies by using a very similar method to that of *Chelton et al.* [2011]. They perform two estimates of wind work on ocean eddies: one using the unfiltered wind stress, which depends on the relative wind, and another where the wind stress is spatially smoothed to remove the imprint of the ocean currents. The latter is the usual method for removing the relative wind stress effect, e.g., as in *Hughes and Wilson* [2008]. They find that the estimate of wind work using unfiltered wind stress is negative (meaning that the eddies are damped by the wind stress) almost everywhere and is strongest over midlatitude regions where atmospheric and oceanic storm tracks coincide. The second estimate of wind work, using the spatially smoothed wind stress, shows both positive and negative features, again concentrated in storm track regions, but now with a globally integrated effect indistinguishable from zero.

This wind work estimate, based on the spatially smoothed wind stress, may be more easily understood by further analysis, where *Xu et al.* [2016] repeat both of the wind work calculations using unfiltered and spatially smoothed wind stress separately on cyclonic and anticyclonic ocean eddies. Here the large-scale systematic effects stand out. Over the scale of ocean gyres, ocean eddies are systematically energized where the large-scale wind stress shear is in the same direction as their rotation and eddies are damped if the wind stress shear is in the opposite direction. This newly identified effect is due to the large-scale pattern of wind stress rather than fine scales because the result is very similar regardless of whether the unfiltered or spatially smoothed wind stress is used. Over the subtropical gyres the large-scale wind stress is anticyclonic; therefore, anticyclonic eddies are energized and cyclonic eddies are damped. The opposite is true over the subpolar gyres. *Xu et al.* [2016] find that for either type of eddy, integrated over the ocean gyres, the strength of this effect is comparable in magnitude to that of the relative wind stress effect. They also find that the strength of the newly identified effect is linearly proportional to the strength of the curl of the wind stress and investigate this further using a simple theoretical model of wind stress with uniform large-scale shear and an idealized rotating eddy. Their theory, supported by composite maps of observed wind work on eddies, shows that a simple combination of uniform wind stress shear and circular eddies is sufficient to explain their findings. Ocean eddies therefore play a crucial role in two different types of energetic interaction with the atmosphere (Figures 2b and 2c). *Xu et al.* [2016] and other studies such as *Zhai et al.* [2012] illustrate the sensitive dependence of the ocean state on details of wind work processes.

Xu et al. [2016] estimate the net work done by the wind on ocean eddies to be about −27.7 GW (1 GW = 10^9 W), combining both effects above but attributable in the global integral to the damping due to the relative wind stress effect. The 13 EJ reservoir of total ocean eddy energy is composed of about 1.4–3.3 EJ of kinetic energy [*Xu et al.*, 2014, supporting information], leading to a predicted eddy energy spin-down time of about 1.6–3.7 years, suggesting that this systematic damping may go some way toward explaining the typical eddy lifetime (~8 months) estimated by *Chelton et al.* [2011] from eddy tracking. However, as they discuss, other processes may also affect eddy energetics.

As computers gain performance, climate models inherit increased computational grid resolution that allows them to resolve the smaller physical scales, but this in turn captures the increasingly nonlinear components of fluid dynamics associated with geophysical turbulence. Such nonlinearity may bring increased sensitivity, requiring even more experiments to explore the role of chaos in ocean climate [e.g., *Grégorio et al.*, 2015; *Wilson et al.*, 2015]. There may therefore be a continued need for parameterization of mesoscale or submesoscale eddy effects for at least some climate experiments. Whether ocean eddies are explicitly simulated or parameterized, the need for validation against observations is crucial. New satellite observations and diagnostic studies such as *Xu et al.* [2016] and *Chelton et al.* [2011] are only beginning to fill the gaps and provide the necessary physical constraints to identify systematic eddy effects and asymmetries previously overlooked.

Acknowledgments
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