Wind-driven Near-surface Vertical Motion in the Ocean

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What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

The ocean is a fundamental component of the Earth's climate system. It supports productive fisheries that are essential to the global economy, and bears an increasing burden of human impacts, including pollutants associated with offshore resource extraction and, in coastal regions, high-density economic development and at-sea activity. In all of these contexts and more, the role of the near-surface ocean is paramount: it supports the exchange of heat and dissolved gases with the atmosphere, it supplies the primary biological productivity that drives fishery ecosystems, and it determines the spread and fate of surface pollutants. The vertical exchange of fluid and materials between the near-surface (the uppermost 10-100 m of the water column) and the deeper ocean, especially the systematic upwelling of nutrient-rich deeper waters into the upper ocean, strongly affects the properties and dynamics of the near-surface ocean and upper ocean ecosystems. Model-based assessments of near-surface/deep ocean vertical transports vary widely, in part because they rely on relatively sparse measurements relative to the appropriate space and time scales.

Progress in quantifying and understanding these vertical exchanges and the ocean's role in these broader contexts has long been restrained by the technical challenges associated with obtaining systematic global observations of the ocean's near-surface vertical motion field. The main impediment has been the smallness of vertical velocities relative to horizontal velocities, which scales like the vertical-to-horizontal aspect ratio of the flow. The challenge of this mismatch in scales is compounded by the fact that these flows are nearly in geostrophic balance, which implies a horizontal velocity field that is nearly nondivergent (i.e., there is minimal net horizontal inflow and outflow) which further reduces typical vertical velocities below the simple aspect-ratio estimate. Typical magnitudes of ocean upwelling velocities on horizontal scales on the order of 50 km and larger are believed to be approximately 10^{-4} cm/s, or less than 1 m/day. This speed is far too small to measure directly and is likely to remain so for the foreseeable future based on the fact that the measurement accuracy of the best current meters when deployed in the field (about 1 cm/s) has remained the same for the past few decades (Hogg and Frye, 2007), and yet is inadequate by orders of magnitude for this task.

Why are these challenge/questions timely to address now especially with respect to readiness?

We need systematic global observations to understand the ocean's near-surface vertical motion from the large scale through the mesoscale and into the submesoscale, which can be characterized as wavelength scales smaller than about 50 km. With recent advances in instrument design (e.g., Doppler scatterometry; see Bourassa et al. Winds and Currents response), this can be accomplished using two complementary methods to make independent estimates of the vertical motion field based separately on measurements of: 1) the surface ocean horizontal velocity divergence field and 2) the surface wind stress and surface ocean horizontal current vorticity. The first method allows the direct inference of near-surface vertical motion from the horizontal divergence at the sea surface. This near-surface vertical motion includes both internal dynamical and wind-driven components, and its inferred amplitude depends on the depth at which the estimate is made.

An important requirement for measurements of surface currents is that the divergent surface horizontal velocity that gives rise to near-surface upwelling is ageostrophic, meaning it does not assume a balance between currents and pressure or, in this application, sea surface height. Ageostrophic currents cannot be inferred from measurements of sea-surface height by satellite altimetry, including the future Surface Water Ocean Topography (SWOT) mission. Such measurements require an altogether new satellite technology. Moreover, in order to distinguish the vertical velocity from internal dynamics from wind-driven vertical velocity, winds and ageostrophic currents must be measured simultaneously. The wind-driven component of near-surface vertical velocity is inferred indirectly through well-established theoretical extensions (Stern 1965; Gaube et al. 2015) of classical Ekman-layer theory (Ekman 1905; Gill, 1982; Pedlosky 1987), which does not depend on estimates of boundary-layer depth. A Doppler scatterometer mission will provide global estimates of the total and the wind-driven vertical velocity fields over the full continuum, from ocean basin scales down to the smallest spatial and temporal scales that can be resolved within the limitations of the error characteristics of the surface velocity measurements.

The mathematical formulations for the two aspects of vertical velocity that can be measured by a Doppler scatterometer are as follows. The total vertical velocity is estimated from the divergence of the total surface velocity by integrating vertically downward to the base of the Ekman layer, on the order of 10 m. The wind-driven vertical velocity in the open ocean is traditionally determined from the ratio of the vector wind stress $\boldsymbol{\tau}$ to the Coriolis parameter f by $w_{\mathrm{Ek}}=\rho^{-1}\nabla\times(\boldsymbol{\tau}/f)$, where ρ is the water density. The stress in this equation is determined from the relative wind, i.e., the difference between the vector wind and the surface current velocity. On scales smaller than a few hundred kilometers, the classical formula above for Ekman pumping excludes the most important contribution to wind-driven upwelling. With assumptions of small Rossby number (i.e., the relative vorticity $\zeta << f$), Stern (1965) showed that the planetary vorticity f in the denominator of the classical expression for Ekman pumping should be replaced with the absolute vorticity $(f+\zeta)$. This adds a contribution to Ekman pumping that arises from the interaction of the wind stress with horizontal variations of the relative vorticity of the surface currents. The total wind-driven vertical velocity is then $w_{\mathrm{SE}}=w_{\mathrm{Ek}}+w_\zeta$, where

$$w_\zeta = (\rho f^2)^{-1} \left(\tau_x \, \partial\zeta/\partial y - \tau_y \, \partial\zeta/\partial x\right).$$

Here τ_x and τ_y are the eastward and northward components of the wind stress. With sufficiently accurate measurements of surface velocity, the combined measurements of surface winds and currents from a Doppler scatterometer will be ideally suited to estimation of w_ζ. The scale limitation of Stern-Ekman theory is not yet known, but the theory likely applies at least down to wavelength scales of 50 km.

On oceanic mesoscales, Gaube et al. (2015) showed that Ekman pumping from small-scale features in the wind field is generally negligible compared with w_ζ. They further showed that the magnitude of w_ζ increases rapidly with decreasing scale down to the ~200 km wavelength resolution limit of presently available satellite data (corresponding to an eddy radius of ~40 km).

To provide context for the importance of satellite estimates of w_ζ on mesoscales and submesoscales, long-term mean wind-induced vertical velocities (classical Ekman-pumping) at mid-latitudes on the ocean basin scale that arise from Ekman convergence between the tropical easterlies and mid-latitude westerlies and control the circulation and structure of the ocean's subtropical gyres, are of order 30 m/year or 0.1 m/day (Risien and Chelton 2008). The systematic effects of ocean surface currents on wind-driven vertical motion inferred for mesoscale eddies from feature-based compositing are of this same order in the global mean, and up to several times larger in regional means (Gaube et al. 2015). These composite estimates were constructed over thousands of realizations based on the relatively low-resolution winds and surface currents that are presently available (wavelength scales of about 200 km). Locally, instantaneous vertical velocities at mesoscales can be much larger. For example, in situ tracer measurements in a case-study of a mesoscale eddy in the subtropical North Atlantic (McGillicuddy et al. 2007) measured upwelling velocities as large as 0.4 m/day. It is likely that upwelling velocities often exceed 1 m/day in association with large-amplitude mesoscale eddies. Primitive equation model simulations suggest that submesoscale upwelling velocities often exceed 10 m/day (e.g, Ponte et al. 2013).

Why are space-based observations fundamental to addressing these challenges/questions?

Present model-based assessments of vertical velocity vary widely, in part because they rely on relatively sparse measurements at the appropriate space and time scales. The unique capability of a Doppler scatterometer that will allow simultaneous direct measurement of ocean surface currents and measurements of surface winds will provide a new and powerful approach that facilitates: 1) systematic measurements of surface horizontal current divergence, 2) global study of the surface current interaction with surface winds, and 3) study of the combined influence of the divergence and coupled wind and current variability on the near-surface vertical motion field. These mesoscale and submesoscale vertical motions are expected to be of great importance for ocean dynamics as well as ocean biology and chemistry (Levy et al., 2001). Additionally, the expected high-resolution capabilities of a Doppler scatterometer will allow extension of these measurements into the scientifically and economically important coastal zone, in which orographic (land topography) and ocean dynamical effects combine to produce rich and energetic mesoscale and submesoscale surface wind and ocean vertical motion fields.

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