WINDS AND CURRENTS MISSION: ABILITY TO OBSERVE MESOSCALE AIR/SEA COUPLING

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Abstract
The motivation for a satellite mission to measure surface winds (stress) and surface currents is described. The mission concept is explained, and a successful example is shown based on simulated satellite sampling of the output a high-resolution ocean model with and without anticipated measurement noise.

Index Terms— Vector winds, currents, vorticity, ocean, mission, satellite

1. INTRODUCTION

The air-sea interface is a critical link in the Earth's climate system; incomplete knowledge of the dynamics at this interface causes significant errors in the representation of horizontal and vertical mass and heat transports in the upper ocean, and limits the accuracy of climate and seasonal forecast models. Global surface currents are the most important and least directly observed ocean currents. The global relation between the surface wind and the speed and direction of wind-driven surface currents is unknown and unobserved. Theory and inferences from near-surface measurements suggest that velocity differences comparable to the magnitude of the wind-driven current itself likely often occur over the upper few meters of the ocean. Observations of coincident winds and currents are needed to move forward on these issues and others discussed below.

A novel method for determining coincident vector winds and currents will be presented. The mission concept will be explained, accuracy estimates will be provided, and it will be shown that the instrument can be used to examine mesoscale ocean vorticity (the curl of surface ocean velocity), which is challenging to measure but of great interest for understanding ocean dynamics, including vertical velocity.

2. FURTHER MOTIVATION

Evidence exists that near-surface currents due to momentum exchange between the ocean and the atmosphere are substantially different from those inferred from existing, indirect observational techniques [1], and that these differences have important implications for vertical and horizontal transports of upper-ocean heat. Theoretical differences are also substantial. The lack of understanding of surface currents and their relation to surface winds limits our ability to represent in predictive models such phenomena and processes as: meridional and zonal tropical heat transport; equatorial currents and upwelling; ENSO and MJO dynamics; tropical eastern Pacific and Atlantic sea-surface temperature and air-sea interaction, as well as dispersal of pollutants and floating marine debris.

Wind-driven circulation accounts for much of the poleward heat transport by the ocean [2]. Vigorous air-sea exchanges of heat and carbon dioxide preferentially take place over upwelling and western boundary regions because of wind-driven circulation. Through momentum and heat fluxes, surface winds are a key variable mediating the interaction of the ocean and atmosphere. The interaction gives rise to observed climate variability such as El Nino/Southern Oscillation and is the physical basis for climate prediction. Scale interaction remains a challenge for atmospheric and climate dynamics, with well documented upscale effects from meso-scale cloud clusters to the planetary-scale intraseasonal Madden-Julian Oscillation (MJO). The circulation of the former is poorly sampled in time by existing satellite scatterometry. By exciting large-amplitude planetary-scale waves in the equatorial ocean, MJO affects the evolution of ENSO events and is an important source of uncertainty in ENSO prediction [3, 4]. Both ENSO and the MJO influence the likelihood of hurricanes forming. Hurricanes can have a large impact on property and infrastructure. ENSO has a large impact on interannual shifts in weather and hence large impacts on agriculture as well as aquaculture.

The upper ocean 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. Ocean surface currents and wind coupling are also important to the transport of ice and melt water in high latitudes. These Arctic wind and currents strongly influence the vertical and horizontal heat transport in the Arctic Seas, and have been hypothesized to influence similar transports in the North Atlantic Ocean. 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.

With climate projected to warm, regional information on climate change is in high demand but remains highly uncertain. A recent review identified the atmospheric circulation change as the leading cause of the regional uncertainty [5]. Measurement errors and large internal variability prevent ship-based historical observations from providing strong constraints on surface wind change [6, 7]. The decadal cooling of the tropical Pacific, coupled with strengthened equatorial trade winds and temporarily slowing down the global temperature increase, is a sober reminder of the complex interaction of anthropogenic climate change and internal variability. Sustained, cross-calibrated global observations of surface wind vectors from space are essential to reduce measurement and sampling errors and constrain climate model projections regarding the atmospheric circulation change and the interaction with the ocean.

Surface winds drive ocean circulation both locally through Ekman dynamics and remotely through planetary waves. Both the local and remote mechanisms are at work in generating the equatorial cold tongue, home to El Nino/Southern Oscillation. While satellite altimetry offers global observations of planetary wave propagation and estimates of geostrophic current, surface currents include a large ageostrophic component (especially in regions of energetic submesoscale variability and on large scales in the climatically important equatorial oceans), and have never been observed globally from space. Concurrent observations of evolving winds and currents will open new opportunities to study their interaction and three-dimensional advective processes that generate sea surface temperature variability.

3. MEASURED GEOPHYSICAL VARIABLES

Surface stress is the rate per unit area at which atmospheric momentum is transferred to the ocean. Surface stress is largely dependent on the vertical shear between winds and currents; that shear and the other considerations are well captured by scatterometer observations [8]. This stress is very closely related to equivalent neutral winds [9] which is the traditional measurement of scatterometers. The second key observation is the vector surface ocean current.

Geostrophy is the assumption that the currents result from a balance between a horizontal pressure gradient (closely related to a sea surface height gradient, which can be determined from altimetry) and the Coriolis force. This assumption is not well-suited for application near the surface or when there are changes in the wind stress and/or currents on small spatial scales: wind-driven upper ocean currents, known as Ekman currents cause ageostrophic flow. On large scales, Ekman currents are typically the largest departure from a geostrophic current. These contributions often combine to cause substantial departures in both speed and direction from the geostrophic currents. Therefore, a measurement of the actual surface current is needed. The ageostrophic component of the Ekman winds is very important in ocean upwelling, and cannot be estimated from altimetry.

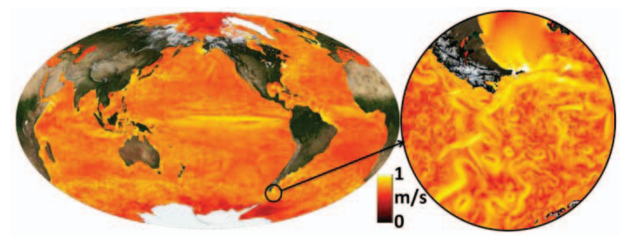

Fig. 1. High resolution model simulations from the Massachusetts Institute of Technology (MIT) and NASA Ames Research Center (D. Menemenlis personal communication, 2015) show the ocean is rich with strong currents. However, the accuracy of the modeled surface currents is unknown

4. MISSION CONCEPT

The **Winds and Currents Mission (WaCM)** will employ Doppler scatterometry to simultaneously measure ocean surface vector winds (which can easily be converted to an ocean surface vector stress) and ocean surface vector currents. The mission will utilize a U.S.-developed Ka-band instrument that uses Doppler capability to measure currents. The nominal wind and current geophysical products will be observed at a much finer resolution than the ~200 km wavelength and monthly resolution limitations of presently available fields of surface winds and surface velocity from satellite scatterometer and altimeter data [10]. The anticipated wavelength resolution of the WaCM estimates of surface velocity is 10km, which corresponds to a footprint size of about 5km for estimates of both surface winds and surface ocean currents. This fine resolution capability is critical for producing accurate estimates of key Earth system processes related to winds and currents. Global observation of currents on the proposed scale is extraordinary in that it will provide the actual surface current (rather than just the geostrophic currents inferred from altimetry data) and improved descriptions of surface currents currently obtained from in situ and satellite systems.

Traditional scatterometry will provide wide swath observations of ocean surface vector stress and ocean surface vector winds over a roughly 1800km swath (similar is width to QuikSCAT observations. A novel aspect of the mission is the 10km (or better) wavelength resolution, which corresponds to a measurement footprint size of about 5km. This resolution allows observations of winds much closer to land, and allows for much more accurate estimation of spatial derivatives of surface winds (curl and divergence) when averaged over larger scales [11].

Doppler information will be used to determine the surface current in the radial direction from the satellite. Observations from multiple directions will be used to determine a vector Doppler motion. The accuracy of the vector components deteriorates rapidly near the swath edge and near nadir due to the lack of diversity in the look angles: one vector component can be very accurately determined, and the other is essentially unmeasured. Therefore, the vector currents are determined over a subset of the swath, excluding the outer 250km and the 50km to each side of nadir. An example retrieval of the currents in the radial direction (fig. 2) shows that the actual currents can differ greatly from the geostrophic component estimated from altimetry.

The scatterometer signal derives from Bragg scattering, therefore the wavelength of ocean surface waves to which the signal (nominal and Doppler) are responding to is clearly defined as a function of the incidence angle and the wavelength of the radar. This situation clearly defines the speed of the surface water waves (which on this scale move in the direction of the stress). Therefore, the vector motion of these water waves can be removed from the Doppler estimate of vector motion to determine the current vector.

The radar frequency needed to achieve this fine resolution with a modestly sized antenna, and to allow for easy and accurate removal of the motion due to waves is Ka-band.

Prior results from scatterometers indicate that biases can be largely removed for most conditions [12]. Estimated random error in wind speeds is $0.6 ms^{-1}$, and the random error in currents are expected to be less than or equal to $0.5 ms^{-1}$. This uncertainty in surface currents is substantial, but with averaging (e.g., over 4 days and spatial smoothing with a half-power filter cutoff wavelength of 50 km) it is adequate for many open-ocean applications. Below is an extreme case, where the vorticity is computed as the curl of the surface ocean velocity based on simulated WaCM sampling with realistic measurement errors.

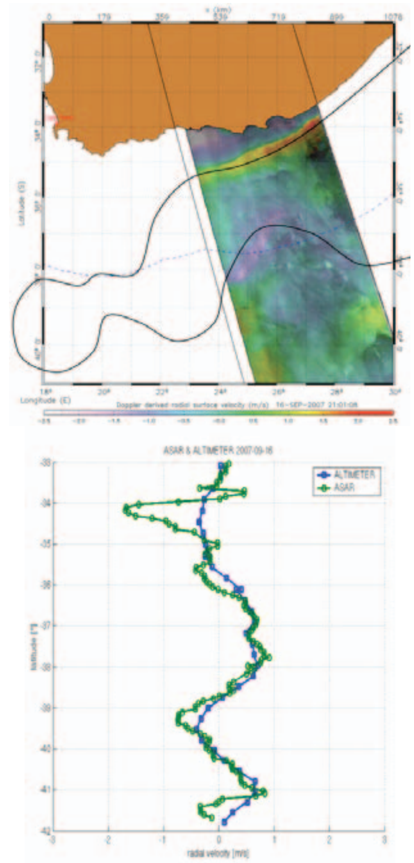

Fig. 2 Surface velocity measurements along the line of sight direction (top) have been demonstrated multiple times from spaceborne SARs. This example from the Aghulas current was observed by ASAR at 10km resolution. The large currents near South Africa are the main Aghulas current, and variability lower in the image is associated with ocean eddies. The lower image shows a comparison of Doppler currents with altimeter radial velocity estimates along the SAR line of sight. Both capture an eddy, but only the high spatial Doppler resolution captures the narrow Agulhas main stream current.

5. OCEAN VORTICITY EXAMPLE

The surface velocity fields from the output of a numerical model are sampled to estimate the accuracy of vorticity, which is a key component of ocean dynamics. The model is for California Current region, calculated with a grid spacing of 0.5km from the ROMS model, courtesy of J. Molemaker. In the following example, the field is smoothed with a Parzen filter to have a 50km wavelength resolution for the curl of the ocean surface current (vorticity) divided by the Coriolis parameter (fig. 3, top). The 'truth' at a 50km spatial scale in a 4-day average is shown in the top panel. This is compared to two estimates (lower panels) based on simulated sampling by WaCM in a QuikSCAT-like orbit. One estimate (lower left) is noise-free, and the other estimate includes realistic measurement noise. It is clear that the WACM mission can estimate the surface vorticity with a temporal resolution of at least 4 days and a wavelength resolution of at least 50km (which corresponds to a feature resolution of about 25 km). This resolution of the surface ocean vorticity would provide unprecedented information about ocean dynamics, including vertical velocity; presently available satellite data have a temporal resolution of about 30 days and a wavelength resolution of about 200 km (Gaube et al., 2015).

10. CONCLUSION

An entirely new dataset and scientific opportunities will result from the global observations of surface currents made by WaCM. At present, global fields of surface currents can only be obtained indirectly, approximated by linking non-current observations to currents through assumed balances of forces, or by analysis of surface drifter observations. Wind stress and currents measured coincidentally are critical for improving our understanding of dynamical ocean forcing. The Winds and Currents Mission will set a new standard for global observations of surface currents coupled with dynamical forcing for the upper ocean.

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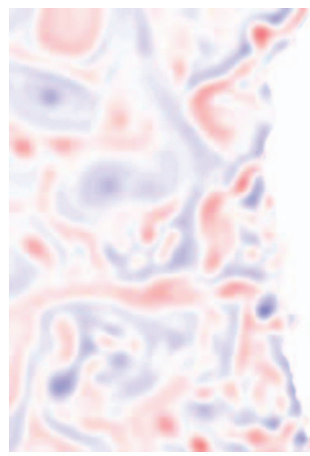

Fig. 3. modeled vorticity divided by Coriolis parameter calculated on the model grid and without noise (top) can be compared to the estimate sampled by the satellite without noice (lower left) and the estimate from the satellite with 0.5 ms-1 noise sampled as by the satellite. Clearly WACM can resolve vorticity on these scales.