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Special Section:
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Key Points:

- Ocean surface currents strongly influence human activity
- The OSCAR project develops ocean surface currents from satellite-sensed fields
- Satellite data are used to study the momentum transfer between the atmosphere and ocean

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Ocean surface currents from satellite data

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Abstract The atmosphere drives entire ocean motions, and yet the exchange of momentum between the atmosphere and ocean occurs in the thin layer where they meet, involving the smallest scales of turbulence. The Ocean Surface Current Analyses Real-time (OSCAR) project attempts to better understand this exchange using satellite observations with simplified physics to calculate global ocean currents. The goal is to continually improve the physics in OSCAR and more accurately model the currents. The theoretical study will help coupled ocean-atmosphere modeling efforts whereas the societal benefits of measuring ocean currents are broad, e.g., fish larval dispersion, heat transport, commercial shipping, and search and rescue.

1. How Do Ocean Currents Impact Our Lives?

The ocean is constantly in motion. It is at the surface where much of human activity in the ocean occurs. Ocean currents affect boating, fishing, and commercial shipping where knowledge of surface currents can not only aid in navigation but also significantly impact fuel consumption [*Bialystocki and Konovessis*, 2016]. Seasonal and interannual variability of currents has a significant impact on fish larval dispersion [*Qian et al.*, 2015]. Tracking methods utilizing the surface currents [*Parker*, 2014] can be used for to track marine debris, for search and rescue, to map the spread of pollutants, or to backtrack paths to the original source such as with pieces of the Malaysian Airlines Flight 370 airplane. Heat and salt transports can be calculated using currents, sea surface temperature (SST), and sea surface salinity. Ocean eddies are an important source of upwelling, a process that brings nutrient-rich deep waters to the surface to supply the food chain [*McGillicuddy et al.*, 2003].

Surface currents play a crucial role in El Nino Southern Oscillation (ENSO) dynamics. In the equatorial Pacific, the trade winds generate currents that carry the warm surface waters to the west, pulling up cold deep waters in the east. Occasionally (every 3–7 years), the trade winds relax, reversing the currents and creating an El Nino event. When the trade winds resume, westward currents restore conditions to normal. Unusually strong trade winds and currents create a La Nina event. The changes in the Pacific equatorial currents typically lead the more commonly used SST observations by 2–3 months. This can be seen in the surface current-based ENSO index (http://www.esr.org/enso_index.html) [*Lumpkin et al.*, 2016]. In this way, surface currents are a valuable early indicator of ENSO events. Monthly maps of currents and their anomalies are used routinely to monitor ENSO in the Climate Diagnostic Bulletin (Climate Prediction Center, NOAA).

We now have 24 years of satellite currents allowing us to track long-term changes and help us to redefine our present state and to better predict the future. This provides the context to better understand the role that circulation plays in drastically changing conditions such as the recent massive oyster die-off along the U.S. West Coast [*Cheng et al.*, 2016] and to guide recovery efforts. Flooding, droughts, super storms, frequencies and intensities of hurricanes, etc. are all connected to oceanic conditions. They affect us today and they will continue to affect us tomorrow.

2. How Do the Atmosphere and Oceans Interact?

Ocean currents contain a vast range of interacting scales and a variety of dynamical regions. Alternating bands of planetary-scale winds such as the jet stream and the trade winds drive large-scale water circulation in the oceans. Because most oceans are bounded by the continents and because of the dynamics on a rotating Earth, the result is water circulations within ocean basins, with intensified currents along the western boundaries, such as the Gulf Stream along the east coast of the United States. These western boundary currents (WBC) are fast and narrow, with speeds typically around 2 m/s (about 100 mi/d), and widths on the order of 100 km (62 mi). The WBCs eventually separate from the continental shelf and join the basin circulation, meandering and breaking into a train of eddies. The Southern Ocean is the only place where the ocean is able to flow without a continental boundary, resulting in the Antarctic Circumpolar Current (ACC), an east-west flowing train of eddies. The nature of the currents depends on latitude as well. Scales of eddies are generally smaller with higher latitudes (see Rossby radius) [*Gill*, 1982], whereas the equatorial region, which is the location of ENSO events [*Philander*, 1990], requires a separate treatment from the rest of the ocean.

The atmospheric winds drive these motions, but the connection between the atmosphere and ocean is through a relatively thin air/sea interface. This surface layer of the ocean is a high-energy part of the ocean where the action of the winds on the ocean produces waves and turbulence. Heat and fresh water fluxes occur through this layer. All of these processes interact with the background currents and eddies. These upper ocean processes involve the micrometer scales in turbulence but are part of currents on a global scale.

3. How Are These Motions Measured?

Satellite sensors provide us with an amazing near-real-time global view of properties of both the atmosphere and ocean. The Ocean Surface Current Analyses Real-time (OSCAR) project is a NASA Earth Science funded research project to use satellite fields to create global surface currents (www.esr.org/oscar_index.html) [*Dohan and Maximenko*, 2010]. Surface currents are provided on global 1/3° grid every 5 days, dating from 1993 to present day. The data are freely available through the NASA Physical Oceanography data center, PO.DAAC (http://podaac.jpl.nasa.gov). Later in 2017, a daily 0.25° grid product will be available. A sample snapshot of OSCAR current speeds is shown in Figure 1a. The WBCs, ACC, and the equatorial waves are the dominant features in global maps but the oceans are full of evolving currents, jets, eddies, and wind motions.

Also shown in Figure 1b is a sample highlighted region, showing the progression of the Loop Current in the Gulf of Mexico. The Loop Current flows from the south into the Gulf, then out into the Atlantic along Florida, forming the southern branch of the Gulf Stream. In 2016, the loop meandered deep into the Gulf in March and pinched off into an eddy in June which then traveled westward in the second half of the year. These events are important since the Loop Current carries warm water, which is a source of energy for hurricanes. Knowledge of their position is important for hurricane prediction. In addition, this area was the site of the Deep Water Horizon spill and remains an important location for oil and gas drilling. The Loop Current and the eddies it sheds are strong enough to halt operations of offshore drilling [*Almeida*, 2014] and can carry particles hundreds of miles in a week in the event of a disaster.

OSCAR ocean surface mixed layer velocities are calculated from satellite-sensed sea surface height (SSH) gradients, ocean vector winds, and sea surface temperature (SST) fields. Over the years, the OSCAR project has evolved from a tropical study [*Lagerloef et al.*, 1999] to a global near-real-time product. The physics in OSCAR are based on three factors: geostrophy, Ekman dynamics, and thermal wind. A fluid is in geostrophic balance when pressure forces balance momentum in steady state. Flow follows lines of constant pressure: clockwise around highs (deflect to the right) in the northern hemisphere, counterclockwise around lows. From satellite measurements of depressions and elevations (SSH fields), geostrophic flow can be calculated. Ekman balance assumes wind-forced motions are in steady state. Wind-driven stress at the surface is transferred to the layers below the surface, spiraling with depth due to rotational effects. Horizontal differences in density also give rise to vertically varying currents, the thermal wind. OSCAR uses SST to indicate density fronts. OSCAR uses SSH from AVISO (www.aviso.altimetry.fr/duacs/), a combination of QuikSCAT (coaps.fsu.edu/scatterometry), ERA Interim winds (www.ecmwf.int/en/research/climate-reanalysis/era-interim), and NCEP vector winds (nomads.ncep.noaa.gov/dods/NCEP_GFS), and Reynolds OI SST (www.ncdc.noaa.gov/oisst).

4. What Can This Satellite Data Tell Us About the Science?

The wind-driven component of the surface current results from the momentum exchange between the atmosphere and the ocean within the planetary boundary layer interface. A main research objective of the OSCAR project is to further our understanding of the mechanisms behind the transfer of momentum

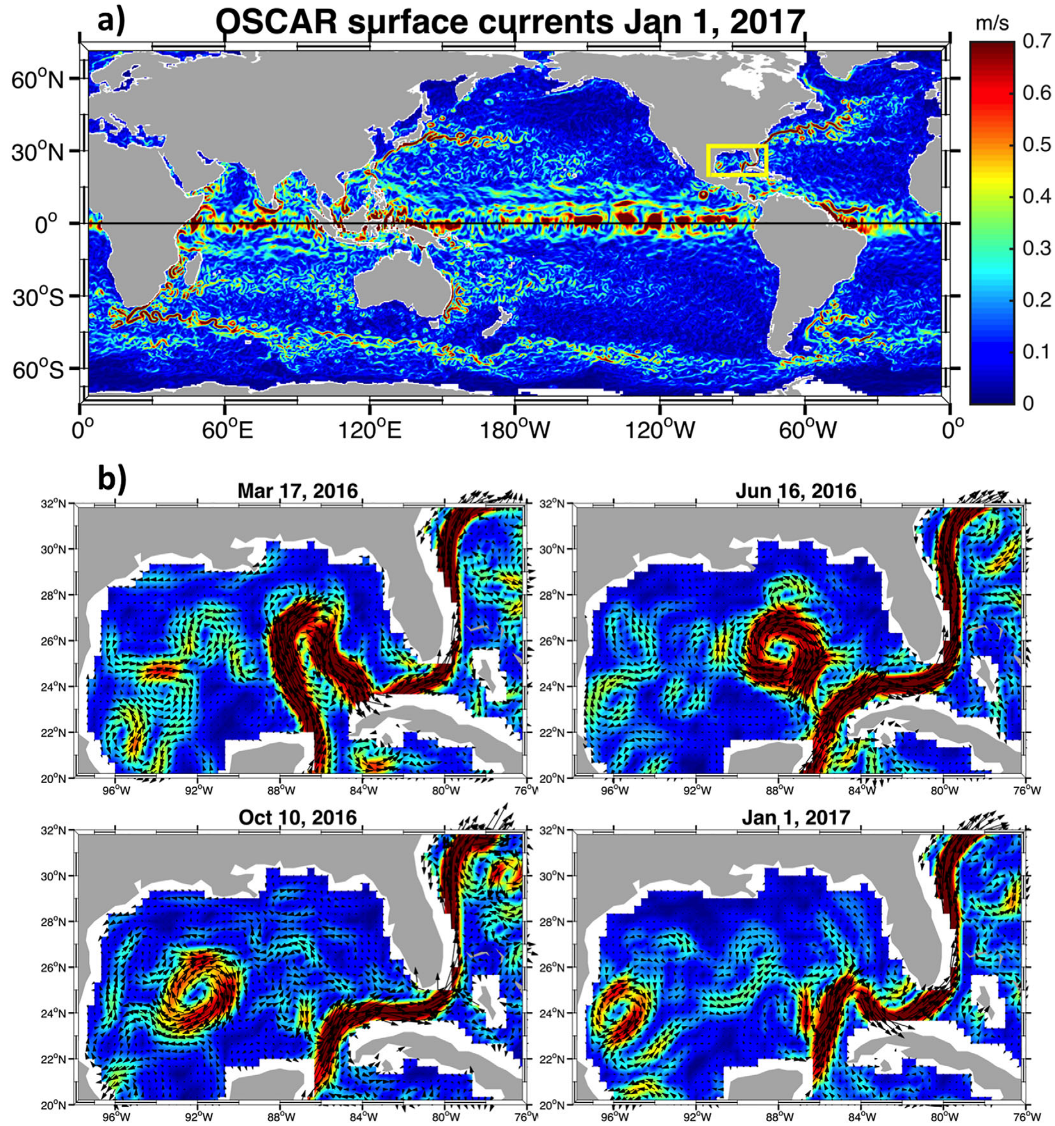

Figure 1. (a) Snapshot of global OSCAR surface current speeds for 1 January 2017. OSCAR currents are calculated from satellite fields of SSH, vector winds, and SST. Although the largest currents are in the western boundary currents, equatorial waves, and the Antarctic Circumpolar Current, the ocean is full of eddies and wind motions. (b) Vector plot of some of the details in the map, highlighting the Gulf of Mexico. The Loop Current enters from the south then exits to form the bottom branch of the Gulf Stream along the Florida coast. A deep meander of the loop into the Gulf in 2016 pinched off to form an eddy in June that traveled westward throughout the year. These currents and eddies carry warm water which can fuel tropical storms and are strong enough to affect drilling operations in the Gulf. The colors are speed in meters per second (1 m/s = 54 mi/d).

between the atmosphere and the ocean and thereby improve the calculation of surface currents from ocean vector winds, in both quality and spatial-temporal resolution. OSCAR performs well in most parts of the ocean, but there still remain some areas that need more model development.

The Navier Stokes equations to describe viscous fluid flow were developed in the nineteenth century but there is no analytical solution to these equations (indeed turbulence is one of the great unsolved problems in classical physics). Also, the range of interacting scales is too large to practically solve by computational methods, particularly on a global three-dimensional scale. It is therefore necessary to parameterize or empirically model the effects of the smallest scales in the equations. Turbulence parameterization has a long history, with different approaches depending on the field of study and application. The two main approaches in atmosphere ocean models are based on a nonlocal parameterization with some variables set by observations (KPP) [*Large et al.*, 1994] and a turbulence closure technique [*Mellor and Yamada*, 1982].

Both involve a complicated set of equations and require surface flux measurements. The OSCAR approach is to pare down the equations to as simple of a treatment of the turbulence as possible while still capturing the momentum transfer necessary to calculate wind-driven currents.

The Ekman formulation in the version of OSCAR being produced today is based on simple dynamics [*Bonjean and Lagerloef*, 2002]. Wind stress is calculated from vector winds using empirical relations. This stress is transferred through the water column using a simplistic parameterization for turbulence, an eddy viscosity, which essentially treats the effects of turbulent eddies as if they act like viscosity. The research component of OSCAR involves extending beyond a vertically constant eddy viscosity and steady state equations. Adding vertical variation and higher-order turbulence parameterizations into the OSCAR equations adds a complexity and a large variability between model solutions, with no one solution ideal for a global application. Meanwhile, adding time dependence to the OSCAR equations introduces inertial waves. This is problematic because the timing of the waves requires vector wind measurements every 1–6 h depending on latitude, which is beyond the capabilities of our present satellite constellation, and the exact nature of the evolution of inertial waves in the mixed layer is unknown. The various experimental versions of OSCAR models are evaluated by comparison with velocities obtained by the global drifter program (http://www.aoml.noaa.gov/phod/dac), a global array of satellite-tracked drifting buoys. The performance of the different models tells us where and when each parameterization works best and therefore which physical processes are dominant. Not only will the accuracy of ocean current calculations increase, but an improved understanding of the effects parameterizations have on ocean currents will also benefit the development and interpretation of large ocean-atmosphere models.

5. At What Scales Are We Able To Understand These Processes?

In addition to the main research goal of understanding the air/sea momentum exchange, research in the OSCAR project also involves a better understanding of the small scales. The finer scale we measure, the more we can see that much of the ocean is a sea of interacting travelling eddies and filaments. Satellites observe pieces of the ocean as they pass over, and it is only with multiple passes and with multiple satellite systems that images of the entire global can be collected at frequent intervals. Regular gridded products such as the AVISO SSH fields, which blend multiple satellite systems (an extremely challenging task in itself), provide us with accurate input SSH fields but at the expense of smoothing over the small details in the original sensed signals during the gridding and merging. The size of detectable eddies in the final product ranges from 100 to 300 km (62–186 mi), depending on location. By investigating currents calculated directly from the satellite signals before gridding, we can start to understand more about the role of the small scales and question just how far can we apply balances like geostrophy to small scales. This type of study is an important precursor to the upcoming planned Surface Water & Ocean Topography (SWOT) mission (swot.jpl.nasa.gov), which will measure very high resolution SSH. Much of the mixing, exchange, and vertical processes of the ocean circulation occur at scales less than 100 km, which SWOT will be able to measure.

6. Theory and Observations Working Together

The OSCAR surface current project is a combination of pure theoretical mixed layer physics research together with technical analysis of satellite-sensed fields. Progression of our knowledge requires state of the art satellite systems and continued commitment to the ongoing satellite sensing of SSH, vector winds, and SST. Production of reliable surface currents has direct benefits ranging from commercial shipping to management of marine life. The ultimate research goal is a better understanding of air/sea momentum exchange and the effects that upper ocean turbulence parameterizations have on this exchange and wind-driven currents. The oceans are dynamic and change on hourly, daily, seasonal, multiyear, and multidecade times. Physical oceanography research using satellite observations is a powerful tool to understand the ever-evolving ocean circulation.

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