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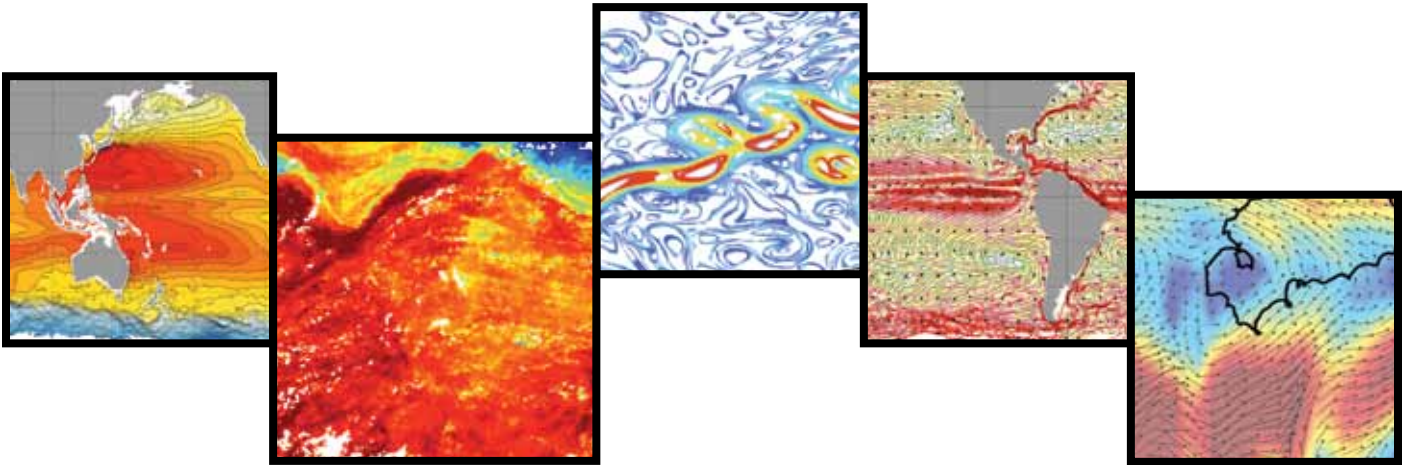
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MONITORING OCEAN CURRENTS WITH SATELLITE SENSORS



ABSTRACT. The interconnected ocean surface current system involves multiple scales, including basin-wide gyres, fast narrow boundary currents, eddies, and turbulence. To understand the full system requires measuring a range of motions, from thousands of kilometers to less than a meter, and time scales from those that are climate related (decades) to daily processes. Presently, satellite systems provide us with global and regional maps of the ocean surface’s mesoscale motion (larger than 100 km). Surface currents are measured indirectly from satellite systems. One method involves using remotely sensed fields of sea surface height, surface winds, and sea surface temperature within a physical model to produce currents. Another involves determining surface velocity from paths of drifting surface buoys transmitted to satellite sensors. Additional methods include tracking of surface features and exploitation of the Doppler shift in radar fields. The challenges for progress include measuring small and fast processes, capturing the vertical variation, and overcoming sensor limitations near coasts. Here, we detail the challenges as well as upcoming missions and advancements in satellite oceanography that will change our understanding of surface currents in the next 10 years.

THE SURFACE CURRENT SYSTEM

The ocean is unimaginable without motion. Breaking waves at its surface, a symbol of the sea, are only one kind of

motion. Other types span the continuous spectra of spatial and temporal scales, from basin-wide motions, to mesoscale eddies (scales greater than 100 km) and fast narrow currents (on the order of

100-km wide), to submesoscale features (1–100 km in scale), to turbulence (less than 1 m). The differences in scale result from differences in the kinds of forcings that induce the motions as well as from differences in the underlying physics that define the motions’ characteristics.

Prevailing global winds, such as the trade winds and the westerlies, together with Earth’s rotation and the restriction of flow by continental boundaries, set up the general ocean surface circulation. These “gyres” have the basic form of a flow around a basin, with an intensified western boundary current and broader eastern boundary current, the theories of which were developed by Sverdrup (1947) and Stommel (1948). This surface motion description is far from complete, however. Large-scale surface motions consist of a complex interconnection of local currents, eddies, and turbulence.

Figure 1 shows a schematic of this surface current hierarchy. Although local currents have been observed for centuries for purposes such as navigation and fishing, the advent of satellite remote sensing has provided us with *regular* and *global* measurements of the complex ocean surface motions.

Western boundary currents (WBC) are often less than 100-km wide. They are also intense, at speeds on the order of 2 m s^{-1} , or 175 km day^{-1} , and are responsible for significant poleward heat transport. For example, the Gulf Stream (the WBC along the eastern coast of North America) transports warm waters toward the western coast of Europe. In addition to heat, these boundary currents transport momentum, chemical components (e.g., CO_2), nutrients, and marine life. WBCs eventually separate from the coasts and extend into the open ocean, forming large meanders that shed large eddies, and creating strong fronts and jets. A full discussion of the global peak in eddy kinetic energy in the areas of the extensions can be found in Fu et al. (2010).

In the Southern Ocean however, the westerlies force a strong current that flows from east to west, called the Antarctic Circumpolar Current (ACC). With no continents to force boundary currents, the motion of this current is similar to that of wind, flowing entirely around Antarctica and inhibiting north-south heat transport. The ACC is the only current that connects the Pacific, Atlantic, and Indian oceans, and thus is crucial for the exchange of properties among basins.

Earth's rotation causes motions to be deflected to the right (left) in the Northern (Southern) Hemisphere, due

to the Coriolis force. The extent of the rotation depends on length scales and speed of motion, as well as on latitude, with large scales being more affected than small. The Coriolis force is zero at the equator and strongest at the poles. Equatorial dynamics are, therefore, qualitatively different than the rest of the ocean, with predominantly zonal flows (east-west) and large meridional (north-south) temperature gradients. Large-scale waves (1000–2000-km wavelength) propagate along these temperature fronts. They play a crucial role in tropical dynamics, in particular El Niño and

La Niña (Philander, 1990).

Finally, the small scales (less than 100 km) and fast processes (less than a day to evolve), for example, small eddies, filaments, turbulence, and surface waves, are also important to the surface current system, not only for stirring and mixing, but also for strong associated vertical motions.

Because of the complexity of behavior, the range of temporal and spatial scales, and the dependence on local conditions for ocean surface currents, satellite remote sensing is an ideal tool for studying ocean surface dynamics.

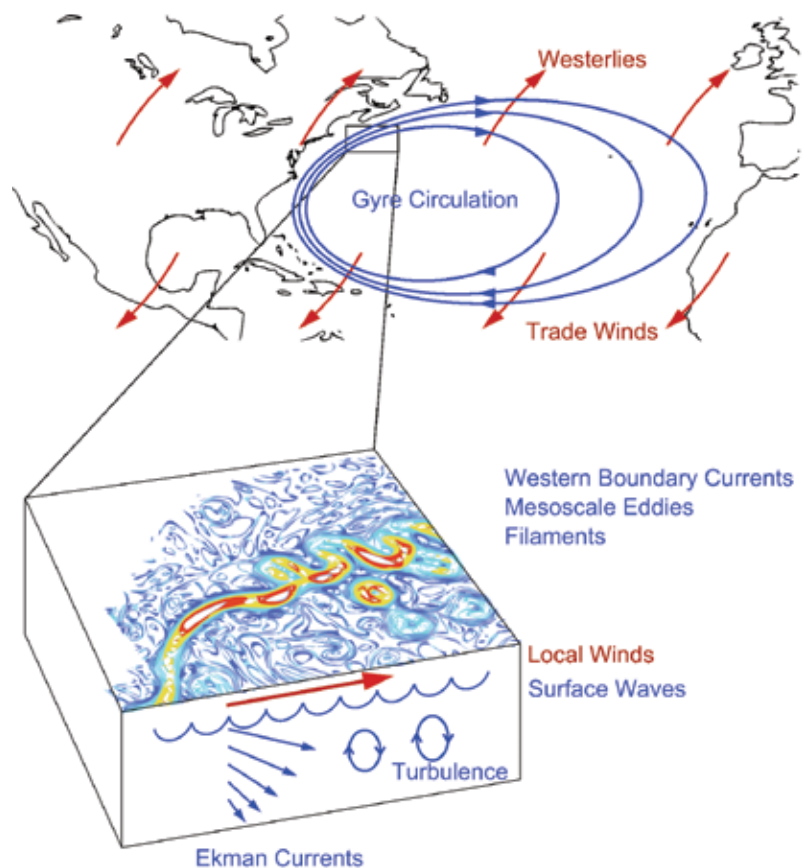


Figure 1. Schematic of the hierarchy of near-surface currents focused on the Gulf Stream region in the North Atlantic Ocean. The gyre circulation consists of a broad eastern component and a narrow, fast, western boundary current (WBC). The WBC is enlarged to highlight the mesoscale (100 km and larger) features and the submesoscale eddies, filaments, and turbulence. Global winds drive basin circulation, while local winds force local Ekman currents, surface waves, and turbulence.

The regular, repeated coverage offered through satellite systems is unachievable through in situ measurements. However, the ability to capture the desired features of the global surface current system becomes increasingly challenging for satellite systems as the spatial scales become smaller or the processes take place on faster time scales.

MEASURING OCEAN CURRENTS USING SATELLITE SENSORS

Today's satellite sensors are not capable of measuring ocean currents directly.

However, remotely sensed data are used to assess current velocity with a variety of methods. The most direct method uses satellite altimetry and ocean vector winds to estimate surface currents.

Currents from Satellite Altimetry and Vector Winds

Geostrophic Currents

On scales of tens of kilometers and larger, horizontal motions are much larger than vertical motions, and the ocean is approximately hydrostatic (pressure is determined by the height and density of the water column). At these scales, for approximately steady motions, and away from boundaries, the primary balance of forces is between horizontal pressure differences and the Coriolis force, which drives currents that follow lines of constant pressure, known as geostrophic currents. Because pressure is related to sea surface height (SSH), geostrophic currents can be calculated using horizontal gradients in SSH.

Satellite altimeters measure the height of the sea surface. One compromise that is made during the design of a satellite orbit is between the temporal and spatial resolution, that is, between the frequency the satellite passes over an area and the distance between its track lines. Having a constellation of satellites solves this compromise. The field of satellite altimetry thus benefits from 18 years of international cooperation, when there have been at least two altimeters in orbit at any given time. The system of altimeters today captures the mesoscale, with real-time estimation (less than a day) of global SSH. More details on the satellite missions and the SSH data produced can be found through the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) data distribution site (<http://www.aviso.oceanobs.com>).

To calculate SSH, several measurements and calculations are required along with altimetry data, including precise determination of the orbit and highly accurate tide models. In addition, because satellite altimeters measure SSH relative to the geoid (the sea surface at resting state), accurate knowledge of the geoid is required. Gravity Recovery and Climate Experiment (GRACE) satellites (<http://www.csr.utexas.edu/grace>) flying since 2002 have greatly improved accuracy of the gravity model, enhanced spatial resolution of the geoid to some hundred kilometers, and measured for the first time long-term gravity changes due to redistribution of ocean mass.

The Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite, launched in 2009 (<http://www.esa.int/esaLP/LPgoce.html>), is expected to finally improve resolution to 100 km. Until that happens, various ocean observations and techniques are used to characterize ocean dynamics. Rio and Hernandez (2004) and Maximenko et al. (2009) combine (in two different techniques) surface drifter trajectories and satellite sea level anomalies to compensate for the effect of eddies on the ocean's mean level. Their mean dynamic topographies (e.g., in Figure 2a) reveal a complex structure of main oceanic frontal systems, such as the Gulf Stream and the Kuroshio Extension, improving SSH calculations.

Ekman Currents

Geostrophic motions dominate the mesoscale signal in many regions, but not all motions are geostrophic. Winds exert a stress on the ocean's surface, transferring momentum between the atmosphere and ocean, driving surface currents. In the classical Ekman balance (Ekman, 1905), the Coriolis force is balanced by the vertical divergence of wind stress and has the shape of a spiral decaying with depth. The Ekman velocity in the Northern (Southern) Hemisphere is 45° to the right (left) from the wind direction, and the angle increases with depth.

Wind stress can be estimated from winds using empirical relations. Ekman currents can then be derived from vector wind measurements (winds with both direction and speed). The assumptions are steady winds, a well-mixed surface layer, and a constant eddy viscosity. The eddy viscosity is the simplest

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parameterization of turbulent processes. It is based on the concept that turbulent eddies act on the large-scale flow like a viscosity.

There are several classes of instruments that measure vector winds: scatterometers, passive polarimetric sensors, and synthetic aperture radar (SAR). Each instrument has its own advantages and disadvantages, such as performance in high winds, in rain, or close to land. Bourassa et al. (2010) provide an overview of ocean vector wind sensors.

Surface Current Products

Ocean Surface Current Analyses Real-time (OSCAR; Bonjean and Lagerloef, 2002; <http://www.oscar.noaa.gov>, <http://podaac.jpl.nasa.gov>), Mercator/SURCOUF (Larnicol et al., 2006; <http://www.mercator-ocean.fr>), and the Centre de Topographie des Océans et de l'Hydrosphère (CTOH; Sudre and Morrow, 2008; <http://ctoh.legos.obs-mip.fr>) all provide global surface current products directly calculated from satellite altimetry and ocean vector winds. The variations between the methods are most notably in the treatment of geostrophic currents at the equator (where geostrophy becomes invalid), treatment of wind-driven turbulence, and inclusion of an adjustment to the currents due to gradients in sea surface temperature. Although missing more complex physics, such as nonlinearities, the advantage of these methods is in their lack of assumptions, producing as close to a direct satellite measurement of surface currents on a fixed global grid at regular intervals as possible.

These models have shown great success in capturing currents in areas strongly influenced by geostrophy,

such as in the WBCs. Figure 3 shows a comparison between OSCAR's currents and those measured from the trajectories of "drifters" (drifting buoys, see next section) for two months for two months in the Agulhas region (the WBC along the south tip of Africa). The figure shows comparisons between one-day binned drifter velocities and OSCAR velocities linearly interpolated to each drifter time/space point. OSCAR velocities are systematically lower than those of the drifters, although with high correlation. The underestimation of amplitude is

partly due to the ability to resolve sharp gradients in SSH. The correlation is particularly high when considering that the drifters will follow the small features and fast motions that are not captured by the satellites.

Global Drifting Buoy Array

Satellite technology has also revolutionized measurements taken directly within the ocean. For example, drifters are buoys that drift on the ocean's surface. These buoys measure surface properties (e.g., temperature), but they

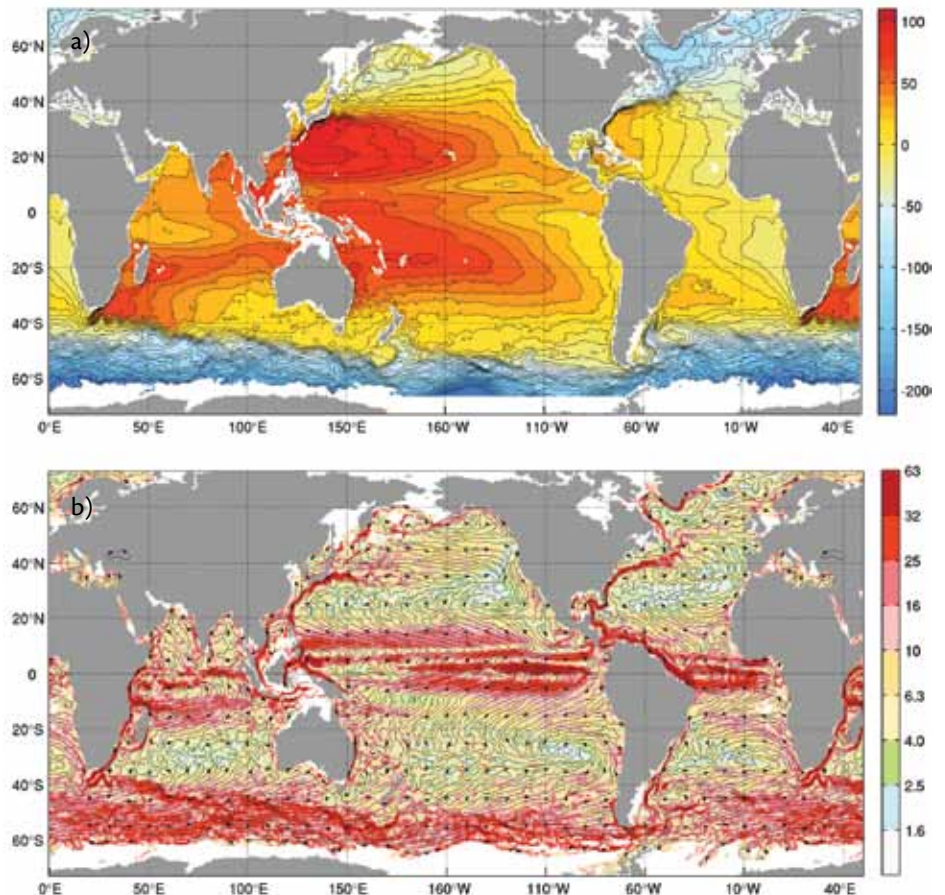


Figure 2. (a) 1993–2002 mean dynamic topography consisting of fronts and eddies. Note the strong signal from high-eddy WBCs such as the Gulf Stream (60°W, 30°N), the Kuroshio (140°E, 30°N), and the Agulhas (30°E, 40°S). (b) Velocities are calculated during the computation of (a) from simple relations among drifter velocities, local winds, and sea level anomaly gradients. Mean streamlines shown here are calculated from 0.25° ensemble-mean velocities between February 15, 1979, and May 1, 2007, smoothed to 1°. Colors are magnitudes of mean drifter velocity and units are cm/s. From Maximenko et al. (2009). Data are available at <http://apdr.csoest.hawaii.edu/projects/DOT>

are attached to subsurface anchors (drogues) designed so that buoy motion is dominated by water motion at drogue depth. The data collected by the buoy are transmitted to passing satellites. Satellite

sensors detect instantaneous positions of the drifters, and changes in the coordinates can be converted into velocities. The buoys of the Global Drifter Program (<http://www.aoml.noaa.gov/>

[phod/dac/gdp_drifter.php](http://www.aoml.noaa.gov/phod/dac/gdp_drifter.php)) have global coverage with more than 1350 drifters launched as of the fall of 2010. The drifters are drogued at 15-m depth, although the currents may vary with depth, and drifters suffer from some slip in high winds, which may affect actual drifter trajectories.

The advantage of drifters is their high frequency of information transmitted (six hourly or better velocities) and their direct measurement of water properties. However, the data follow an irregular trajectory, resulting in irregular sampling of the ocean's surface.

Combining Drifters with Satellite Derived Currents

Simple relations among drifter velocities, local winds, and sea level anomaly gradients recognized during computations of the mean dynamic topography (e.g., Figure 2b; Maximenko et al., 2009) can be used to assess time-varying velocities. The Surface Currents from Diagnostic model (SCUD) data set is produced (Maximenko and Hafner, 2010) at the International Pacific Research Center (<http://apdrc.soest.hawaii.edu/projects/SCUD>). The data set uses satellite wind and altimetry, regressed locally to scarce drifter data, to expand the latter onto a global, 1/4-degree, daily grid. This product is particularly useful for studies of marine debris and other tracers with properties close to the ones of Lagrangian surface drifters.

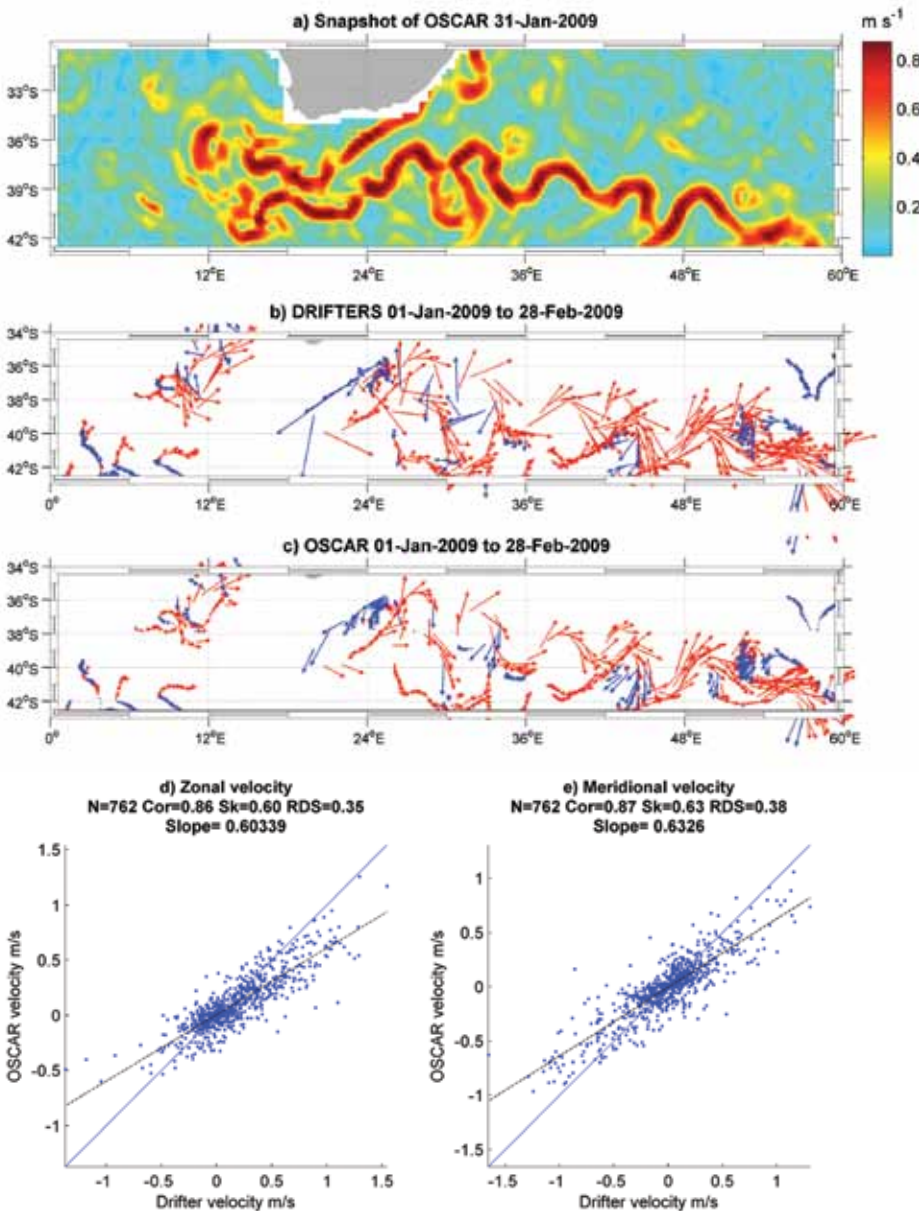


Figure 3. Comparison of velocity fields between drifting buoys and Ocean Surface Current Analyses Real-time (OSCAR) surface currents. (a) Snapshot of OSCAR currents in the Agulhas Current region. (b) One-day binned drifter velocities over two months. Red and blue vectors denote zonal direction. (c) OSCAR currents interpolated onto the drifter time and space position. Scales of vectors are set to be the same as in (b). Comparison statistics between the two are given in the scatter plots of (d) and (e), with N = number of points, Cor = correlation coefficient, Sk = $1 - \text{std}(D-O)/\text{std}(D)$, RDS = $(\text{std}(D) - \text{std}(O))/\text{std}(D)$, Slope = slope of the best-fit line, and where D = drifter and O = OSCAR signal. While overall the comparison is high between the two fields, the smoothed nature of OSCAR compared to drifters is apparent in the vector fields.

Velocities Through Feature Tracking

An alternative method for measuring surface currents is to track features on the ocean surface. The Maximum

Cross-Correlation (MCC) technique tracks the displacements of small-scale features on high-resolution satellite SST images and attributes them to advection by ocean currents (Emery et al., 2003). With great possible potential, MCC today is limited to areas free of clouds for periods long enough to identify the displacements. In addition, the accuracy of the velocity estimate is impacted by the ability to distinguish “material” features from those associated with waves or processes such as heterogeneous mixing and local forcing, which change the shape of the tracked feature. A strong advantage of a feature-tracking technique is that it can be used on a variety of surface imaged fields. For example, a similar technique has been used to track mesoscale features in the surface height field measured with radar altimetry (Fu, 2006). Similarly, SAR images (Liu, 2009) have been used to map the surface drift.

General Circulation Models

Some features of the mean circulation are harder to diagnose exclusively from surface observations. For example, rather than being constant, the Antarctic Circumpolar Current is a circumpolarly flowing sea of eddies, continually focused and defocused into jets, and interacting with the bottom, all of which modify the mean circulation (e.g., Karsten et al., 2002; Williams et al., 2007). Ocean general circulation models (GCMs) and coupled atmosphere-ocean GCMs have greatly benefitted from global satellite measurements through assimilation of the satellite data to improve model performance. For an overview of ocean state estimation from models, see Lee et al. (2010). In return,

data assimilation models are able to model the scales that remote sensing cannot capture, with insights into three-dimensional dynamics, thus aiding the understanding of physical processes and guiding scientific requirements for future satellite missions.

Doppler-Based Surface Velocities from SAR

An alternative method for calculating surface currents is through the exploitation of the Doppler shift in synthetic aperture radar data (Chapron, 2005). This method has promise in particular for coastal zones, although there are many technical challenges, including isolating the surface currents from signals such as wave orbital motion or tides.

IMPORTANCE OF SURFACE CURRENTS

At all scales, currents are responsible for water exchange between different parts of the ocean. The overall ocean circulation compensates for the effect of differential solar heating and air-sea fluxes by redistributing heat, momentum, and salt between the equator and the polar regions, and between the surface and the deep ocean. The surface branch of the circulation is a dominant term in heat transport (Boccaletti et al., 2005). Surface currents play a particularly important role in the dynamics of such large-scale phenomena as the El Niño Southern Oscillation and the Pacific Decadal Oscillation (Lee et al., 2010).

Wind variations create convergences and divergences of surface currents, which in turn force vertical motion (downwelling and upwelling, respectively). Strong winds along coasts, if

oriented in the right direction, push waters off the coast (due to the Coriolis force), forcing colder, nutrient-rich bottom waters to the surface. Much of the biological production in the upper ocean depends on the supply of nutrients from deep layers (Yoder et al., 2010).

Surface current trajectories also impact marine life. Surface current patterns define marine migration (e.g., the migration of larvae), and knowledge of these paths is important for efficient management of resources. Shipping, commercial fishing, recreational boating, search and rescue, and pollutant dispersal (e.g., oil spills) all rely on surface current patterns. The “Great Garbage Patch,” a huge cluster of floating plastic debris formed in the middle of the subtropical North Pacific Ocean by converging Ekman currents, has the potential to damage marine life and alter the biological environment. Figure 4 shows these convergent zones for surface tracers.

The surface branch of the ocean general circulation is the location of all air-sea exchange. Although it is a crucial component of the atmosphere/ocean system, the range of scales necessary to measure the complete system is an insurmountable challenge for in situ sampling. Frequent global satellite measurements provide invaluable information that greatly increases our understanding of surface circulation (see <http://oceanmotion.org> for a comprehensive overview of the surface system).

KEY CHALLENGES AND FUTURE DEVELOPMENTS

Satellite systems can now capture the mesoscale global eddy field and western boundary currents, and with more

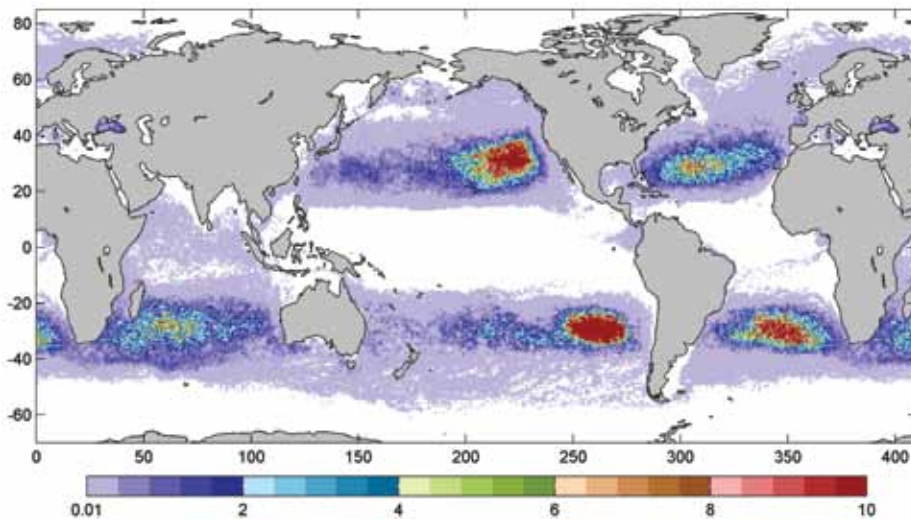


Figure 4. Tracer density distribution after 10 years of advection by surface currents, consistent with statistics from drifters, starting from a uniform initial condition of unity.

than 18 years of altimetry data, we can now begin to observe changes at time scales relevant to climate. However, many important physical processes remain elusive to satellite remote sensing because of their faster time scales, smaller spatial scales, and vertical variation (see Figure 5).

Coastal Regions

Because the majority of recreational and commercial ocean use is along the coasts, it is of interest to understand coastal circulation patterns. Knowledge of these patterns is also important for tracking land pollutants, river exchange, and ecological components such as larval migration. Coastal altimetry (applying satellite altimetry to coastal regions) is an emerging field with a relatively recent history because of limitations in the accuracy of the satellite system's signals near land, which are only reliable at distances of 25–100 km offshore. These limitations are due to several factors: size of the altimeter footprint, atmospheric effects (wet tropospheric correction), modulation of the altimeter waveform

near land, and strong tidal signals. In addition, coastal processes are often high frequency, small scale, and controlled by the shape of the seafloor, which would be missed by gaps between nadir satellite tracks. For example, storm surges can drastically affect coastal communities, with potential increases in severity with climate change. These surges occur too quickly to be consistently captured by conventional altimetry.

Recent advances in coastal surface current calculations have occurred through several approaches. One area of research is in waveform retracking—reprocessing individual satellite track signals to recover the distorted waveform as it reaches land (Deng and Featherstone, 2006). Another area of development is application of regional coastal physics to signal-processing algorithms, such as customized atmospheric physics or local tides (Volkov et al., 2007). A different approach is to combine satellite data with in situ measurements, such as tide gauges (Saraceno et al., 2008), and to use statistics to predict storm surges

(Madsen et al., 2007). These types of methods have been shown to accurately calculate circulation up to 5 km from land. All involve regional treatment of the problem, so that developing any complete global system of coastal currents will involve combining the results of all regional studies.

Capturing Small-Scale Features

As resolution increases, both in numerical models and in satellite observations, the ocean looks more like a sea of interacting eddies than a system of gyres and currents. Blended satellite products, such as those produced by AVISO, are showing great success at capturing mesoscale eddies, as in the rings of Figures 3 and 5a. These mesoscale eddies are an important mechanism for drawing nutrients up into the euphotic zone. Approximately 20–30% of vertical nutrient transport in the upper ocean is estimated to occur within these eddies (McGillicuddy et al., 2003). The planned Surface Water and Ocean Topography (SWOT) mission will provide an unprecedented global characterization of fine-scale features and fronts, with $O(10\text{ km})$ resolution, with much closer coastal coverage. Fu et al. (2010, in this issue) include a detailed description of the SWOT mission and existing success at capturing near-real-time mesoscale eddies.

Between these eddies are submesoscale features, such as small eddies and high potential vorticity filaments that are stretched and pulled by the eddies in ocean turbulence. Filament scales are kilometers thick and hundreds of kilometers long, with rapid changes on the order of a day, making them difficult to observe by satellite. At wavelengths shorter than 100 km, however,

measurement noise masks submeso-scales (Fu and Ferrari, 2008). This is somewhat improved with multiple satellites, but filament structure has yet to be observed globally. Filaments are ubiquitous features of the ocean that are consistently seen in high-resolution SST images (Figure 5b, for example) but they have been studied mostly numerically and theoretically in the context of geophysical turbulence.

Modeling studies that account for filaments are beginning to show that motions at these small scales are responsible for as much vertical transport as the large eddies (Klein and Lapeyre, 2009). Winds can also play a significant role in vertical transport, adding to the challenge of capturing these scales by satellite. Numerical studies suggest that fronts, the interface between water masses of different density, are also responsible for much of the vertical transport in the upper ocean (Mahadevan and Tandon, 2006). Using the principles behind the creation of tracer filaments from the stirring caused by mesoscale eddies, advances are being made in diagnosing submeso-scale statistics from existing altimetry (d'Ovidio et al., 2009).

Use of surface quasi-geostrophic theory (SQG) has also been successful (Held, 1995) in extracting three-dimensional dynamics from surface fields (Isern-Fontanet, 2008). This method requires high-resolution fields, and thus has relied to date more on SST fields, which have a much higher resolution than SSH fields.

The high-resolution SWOT mission will provide an unprecedented map of the *global* submesoscale field, providing the information needed for estimates on

previously missed dynamics, validation of both regional and global numerical models, and validation for analytical methods such as SQG and Lyapunov exponents, as well as new insights into the physics of surface circulation.

Vertical Shear

Satellite sensors measure surface properties: SSH, winds at the ocean surface, and SST (the only exception is the GRACE satellite pair, which measures ocean mass, or ocean bottom pressure). The models that calculate surface currents

from these fields use assumptions about the vertical structure of currents in order to define a vertically averaged current. Vertical shear modifies calculations of the transport of properties such as heat, momentum, and salt. The trajectories of suspended pollutants (e.g., the Great Garbage Patch) depend on vertical shear. Additionally, shear affects biological processes. For example, if a species moves vertically in the water column during the course of the day according to the percentage of sunlight, it will be carried on a path that will rely heavily

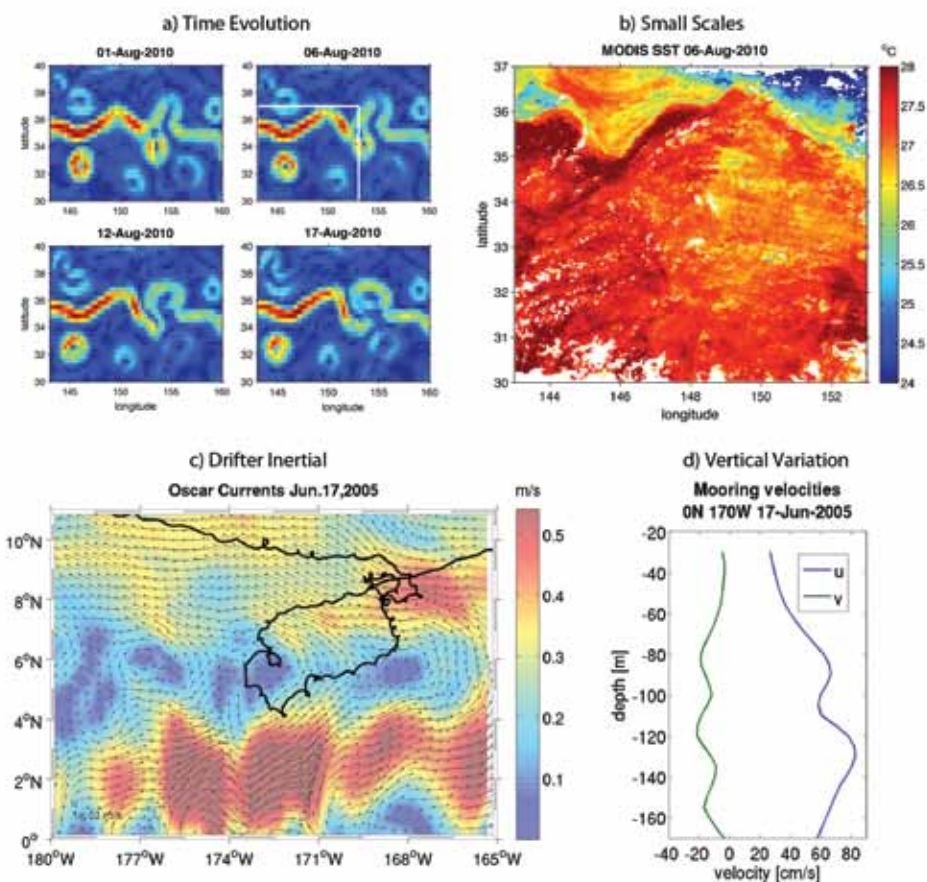


Figure 5. Issues in surface current measurements. (a) Time evolution of the breakdown of the Kuroshio western boundary current into eddies, shown over 17 days on the OSCAR time spacing capability. (b) MODIS gridded SST at 4.63-km spacing, zoomed into the white box region in (a) (MODIS Terra Global Level 3 Mapped Thermal IR SST from podaac.jpl.nasa.gov). (c) Drifter track overlaid on an OSCAR snapshot in the equatorial Pacific. Along with small-scale motions, near-inertial oscillations are prevalent in the drifter signal. (d) Vertical variation of currents seen in mooring data (courtesy of TAO Project Office of NOAA/PMEL <http://www.pmel.noaa.gov/tao>) on the same day as the OSCAR snapshot shown in (c).

on the vertical structure of the currents, both in strength and direction.

Many processes affect the vertical structure of the upper ocean. Diurnal fluctuations in solar radiation cause daily fluctuations in temperature structure, which in turn cause daily fluctuations in mixed-layer depth. Particularly in equatorial regions, the temperature difference can be large enough to limit wind-driven motions to the shallowest surface layer, funneling motions into a shallow jet for a few hours over the day. Equatorial regions also exhibit large subsurface jets. An example of the vertical variations in upper ocean currents is given in the Tropical Atmosphere Ocean (TAO) mooring current plotted in Figure 5d. In addition, wind-driven waves and currents are intensified at the surface. Ekman currents have an exponential decay in depth on the order of tens of meters. The penetration depth of turbulence and momentum transfer from breaking surface waves depends on, among other factors, wind intensity, with a qualitatively different regime depending on whether conditions are mild or stormy (Gargett, 1989). Surface waves carry an associated “Stokes drift,” known to surfers, which decays within the top few meters.

Surface current calculations, such as those from SSH and winds, will need to include a vertical component for progress to be made. The notion of a surface mixed layer with homogeneous turbulence and constant density will need to be modified as applications demand more accurate and complete physics. These enhanced models will need in situ ocean mixed layer measurements in a variety of dynamical locations for validation and development.

Wind-driven Fast Time Scales

The Ekman spiral is the response of the ocean surface to a steady wind. In general, however, winds are far from steady in either time or space. Variations from the mean wind have an additional wave response, known as inertial waves, trapped within the surface ocean mixed layer. Inertial motions can be clearly seen as the spiral modulation to the drifter trajectory plotted in Figure 5c. These waves are an energy source for motions that mix the ocean interior, comparable to the energy from tides (Wunsch and Ferrari, 2004), and they consequently play a significant role in establishing the density structure of the ocean interior and hence the global overturning circulation. However, estimates of this transfer, and its subsequent propagation into the ocean interior, rely on accuracy of wind-field measurements that capture both steady features and fast storms. Storm systems generally have scales of hundreds of kilometers, large enough to be captured by satellite systems. Whether a storm turns clockwise or counterclockwise, though, can make an order of magnitude difference in wave amplitude (Dohan and Davis, in press), thereby requiring wind measurements that include both speed and direction. To capture these motions requires more than twice-daily measurements and therefore several vector wind measuring satellites.

Connecting Global Satellite Data to the Deep


The behavior of surface currents is a combination of short-term surface forcing and long-term climatic changes. The ocean’s subsurface properties are both affected by and affect the surface.

As we advance our understanding of ocean circulation, it is necessary to connect the surface to the subsurface. To this end, the Argo array of profiling floats (<http://www.argo.ucsd.edu>) has been providing a continuous global map of subsurface pressure, salinity, temperature, and velocity measurements. Deployment of Argo floats began in 2000, and over 3000 floats are operating at present, providing full global coverage. The floats range in depth of measurement, typically down to either 2000 m or 1000 m. The floats descend to depth and then ascend to the surface, collecting data that are transmitted to satellites at the surface. Subsurface current plots from Argo data are produced by the YoMaHa project (<http://apdrc.soest.hawaii.edu/projects/yomaha>).

Ultimately, for a full understanding of surface ocean circulation and its role in thermohaline circulation, information from long-term extensive in situ measurement campaigns in key locations of strong exchange between surface and deep waters will also need to be coupled to the global surface arrays.

SUMMARY

The view of the ocean’s surface movement has progressed far beyond the concept of its being simply the surface branch of the thermohaline circulation that redistributes heat and salinity between the tropics and the poles. Multiple satellite systems, measuring SSH, SST, winds, and gravity, along with the in situ global drifting buoy array, have provided us with a comprehensive view of open-ocean surface motion, resolving scales on the order of hundreds of kilometers, and in nearly real time. Unprecedented understanding of upper

ocean boundary layer physics and its connection with the deep will emerge in the next decade with the advent of more satellite systems, including those for salinity (Lagerloef et al., 2010); more extensive processing of near-coast satellite data; higher-resolution satellites (SWOT); and combining satellite surface and in situ subsurface data sets. 

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