VARIATIONS

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New frontiers for ocean surface currents

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Ocean surface currents have a profound influence on human life through their role in horizontal transport and dispersal of pollutants and physical, biological, and chemical properties as well as in air-sea exchange of properties like heat and energy. Surface currents have been poorly observed, particularly within the upper meter of the ocean. Moreover, the vertical structure of currents within the upper ocean is not well understood, making it challenging to relate measurements and model estimates at different depths. While the OceanObs'99 meeting defined requirements for the surface current observing system as one measurement/ month every 5x5 degrees, at 2 cm/s accuracy, the ocean and climate communities have since recognized the need to observe and model the highly energetic ocean variations found at smaller scales (kilometers to tens of kilometer and days to weeks). At the smallest of these scales (the submesoscale), near-surface convergence regimes and areas of horizontal gradients in currents lead to enhanced energy dissipation, vertical transport, and strong coupling between the ocean and the atmosphere. This is an emerging area of observational

Vertical structure of near-surface currents – Importance, state of knowledge, and measurement challenges

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Importance

Near-surface currents are an expression of ocean dynamics within the air-sea transition zone, a key component of the climate system (Cronin et al. 2019). It is within this zone, of spatially and temporally evolving vertical extent, that the ocean and atmosphere constantly exchange kinetic and thermal energies, moisture, and gases including anthropogenic carbon dioxide.

The vertical scales over which ocean currents change speed and orientation from the surface, while still being relevant for air-sea processes, effectively defines the ocean side of the air-sea transition zone, or the oceanic boundary layer. This layer

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and modeling research that is constrained in part by the lack of velocity estimates at these scales. In coastal areas, high-resolution measurements are also a critical gap. Coupling between currents, waves, and wind is essential for air-sea momentum fluxes, particularly at strong winds, but uncertainties in observations and modeling these interactions remain. A number of recent technologies promise new advances in understanding surface currents, their vertical structure, and their interactions with waves and currents. These include drifters and buoys, airborne and satellite-based sensors measuring currents or sea surface height, in addition to other approaches and variables.

This edition of Variations follows the 2020 Surface Currents in the Coupled Ocean-Atmosphere System Workshop organized by US CLIVAR, which brought together 70 US and international participants with expertise in both the research and applications aspects of surface currents, including oceanography and atmospheric science, marine ecosystems and fisheries, and transport of plastics and oil. Contributed articles highlight the state of knowledge of vertical velocity structure and its implications and measurement challenges, wave-wind-current interactions, and the role of surface currents in biological dispersion. In addition, the expected impact of technological and modeling advances on scientific understanding of ocean forecasting is discussed.

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shares many dynamical characteristics with its counterpart, the atmospheric boundary layer, but also differs in important ways due to the different impact of surface gravity waves. As such, observing and characterizing the vertical structure of near-surface currents is a pre-requisite for the fundamental understanding of the mechanics of climate at the air-sea interface. As an example, the flux of momentum into the ocean induced by the atmosphere, or wind stress, is a function of wind speed relative to the surface current speed (Chelton et al. 2004). As a result, estimating wind energy input using any other estimate of ocean current than at the surface will be biased if the vertical structure of these currents is significant (Elipot and Gille 2009b; Liu et al. 2019), yet the meaning of "surface" here, or for other applications, is not always clearly defined.

Near-surface currents lead to the drift and dispersion of all suspended animate and inanimate matter. From the macro to the micro scales, the temporal and the three-dimensional spatial distribution of marine life is conditioned by the vertical penetration of sunlight and species-specific ranges of depths over which vertically-varying currents and turbulence interact with biogeochemical processes (Lévy et al. 2018). Near-surface currents constitute the most important variable (among for example winds, waves, and sea surface temperature) that needs to be modeled to accurately predict the fate of pollutants that threaten ecosystem and human health such as plastics, oil spills, radioactive isotopes, and chemical compounds (Röhrs et al. 2021). While pollutants typically enter the ocean at the air-sea interface, vertical mixing and current shear determine how far and at which depths they will travel (van Sebille et al. 2018), and accurate prediction requires integration of near-surface currents over the vertical extent of floating and suspended objects (Olascoaga et al. 2020). Knowledge of currents at a single-depth is not sufficient. Even observations close to the surface show significant shear within a few centimeters from the air-sea interface (Laxague et al. 2018). Knowledge of near-surface currents is also an important component of saving lives at sea through search-and-rescue operations, which requires successful modeling of near-surface currents and appropriate depth-dependent observations for validation. Therefore it can be concluded that the knowledge and high modeling skill of the vertical structure of near-surface currents is relevant to achieve appropriate national and international management of marine resources and hazards (Röhrs et al. 2021), and thus contribute to several of the planned outcomes of the ongoing UN Decade of Ocean Science for Sustainable Development that include a productive, predicted, and safe ocean (UNESCO-IOC 2021).

Ekman theory, one of the pillars of dynamical oceanography, provides us with the mechanism by which the oceanic general circulation is forced by the so-called Ekman pumping vertical velocity, which drives changes in sub-surface density fields and pressure gradients. Ekman theory further indicates that details of the vertical distribution of wind-induced stress within the boundary layer are irrelevant for determining Ekman pumping velocities. Yet, these details are critical to the vertical structure of the near-surface Ekman currents, the vertical fluxes of momentum, the dissipation of wind energy within the oceanic boundary layer (Elipot and Gille 2009a,b; Alford 2020), and the associated vertical mixing of upper ocean properties, including the upper ocean heat content distribution and sea surface temperature variability. As such, the vertical structure of Ekman currents remains an active area of research well over a century after its formulation.

Despite their importance, the definition of surface currents, or near-surface currents, and how this definition is related to their vertical structure is not clearly established (Röhrs et al. 2021). This is in contrast to sea surface temperature, another near-surface ocean property whose vertical structure has been the focus of international efforts and coordination by the Group for High Resolution Sea Surface Temperature (Donlon et al. 2009). Under the sponsorship of the World Meteorological Organization and the IOC-UNESCO, the Global Climate Observing System defined surface currents as one of the 54 Essential Climate Variables (ECV) that critically contributes to the characterization of Earth's climate. In parallel, the Global Ocean Observing System (GOOS) and the World Climate Research Program support the Ocean Observations Physics and Climate Panel (2017) which defined surface currents as one of the key physical Essential Ocean Variables (EOV) that are effectively addressing the overall GOOS themes of climate, operational ocean services, and ocean health. For both classifications, as an ECV or an EOV, the relevant specification sheets of surface currents specify that a depth must be stated when dealing with this variable, effectively recognizing the importance of its vertical structure.

In summary, the vertical structure of near-surface currents is of relevance for a wide range of multidisciplinary scientific research and operational applications whose successes can only grow as oceanographers expand their state of knowledge.

State of knowledge

The dynamical processes responsible for near-surface shear include thermal wind flow, wind-driven Ekman currents, surface gravity waves, and ageostrophic flows associated with submesoscale fronts. The conceptual understanding of these processes is grounded in well-developed theories, however major gaps exist in the details. Persistent challenges remain towards determining the temporal variability of shear and rectification across timescales, the detailed structure of shear flow very near the sea-surface, and the interaction between the various dynamical sources of shear-flow (e.g., wave-current interactions, the subject of another article in this issue). Understanding is further complicated by the fact that turbulent momentum fluxes are often both a leading-order term in the dynamics of near-surface shear flows, and are in turn affected by the sheared flow through buoyancy advection and shear production of turbulent kinetic energy. These gaps in the "details" are often not well captured by observations nor represented in numerical models, and they stand as major challenges for operational oceanography, instrument cross-calibration, and model development.

In ocean general circulation models where surface gravity waves are not included and submesoscale fronts are generally not resolved, the broad spatial pattern of surface shear is dominated by the response to the surface wind forcing (Figure 1). Time-varying winds generate shear near the surface over a vertical scale that is dependent on the forcing frequency (Gonella 1971; Elipot and Gille 2009a; Lilly and Elipot 2021), and with vertical structure that depends on the profile of turbulent momentum flux (Madsen 1977; Miles 1994; Wenegrat and McPhaden 2016a), a challenging quantity to resolve in observations. Surface gravity waves further complicate the basic conceptual picture of wind-driven shear, both as an additional source of near-surface shear (which often dominates the directly wind-forced shear flow) (Belcher et al. 2012) and through new terms in the Eulerian wave-averaged momentum equations. This includes the Stokes-Coriolis term, which can be a leading-

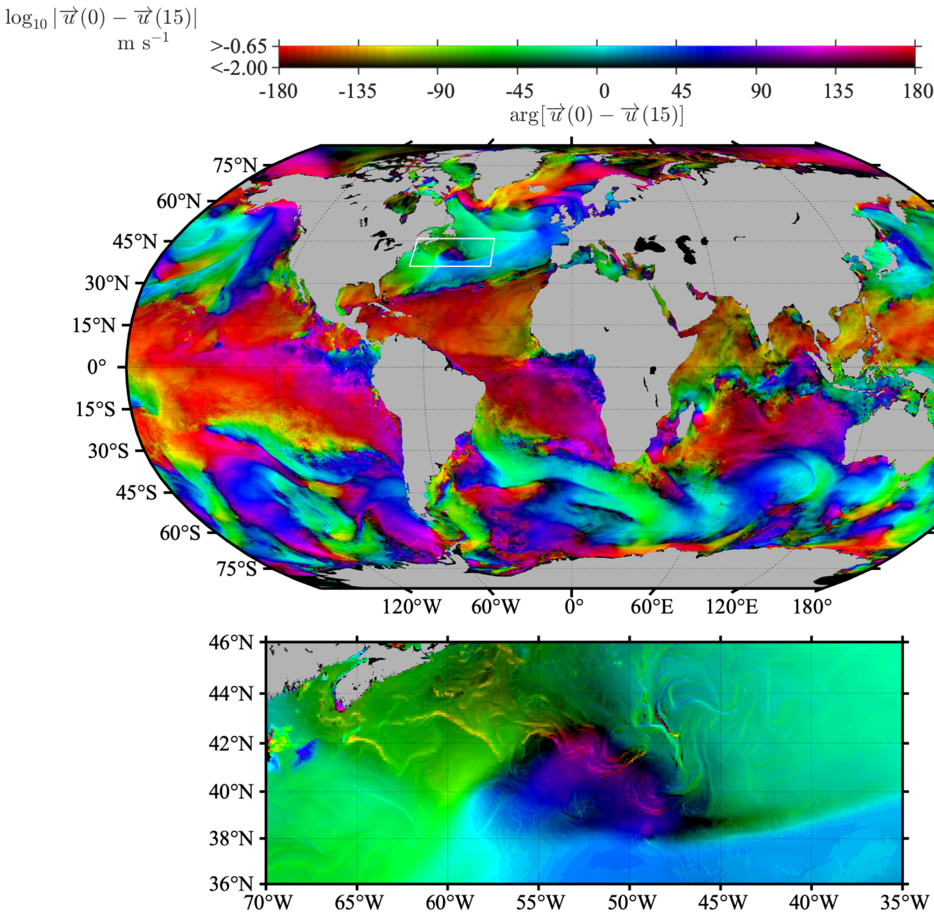

Figure 1. Snapshot of near-surface currents shear in the HYbrid Coordinate Ocean Model (HYCOM). This figure displays the velocity at 0 m minus the velocity at 15 m in a run of HYCOM at approximately 1/25 degree resolution on January 1, 2014 (Arbic et al. 2010). The outputs from the model were first regridded on a regular 2/25 degree uniform grid. The lower panel is a zoom on the region delineated in the upper panel by a white rectangle in the North Atlantic. The velocity difference is indicated using a Hue-Saturation-Value (HSV) color model with a constant color saturation of one as indicated by the colorbar. The color hue indicates the angle difference (positive counterclockwise), and the color value indicates the decimal logarithm of the absolute value of the difference from less than 0.01 m s-1 (black) to more than 0.22 m s-1 (full value).

order modification to the classic Ekman solutions (Huang 1979; Polton et al. 2005), and a Stokes-vortex force term, central to the generation of Langmuir circulation. Velocity shear can be further modified by surface wave effects on turbulence through the Stokes shear production and enhanced downward transport of turbulent kinetic energy (McWilliams et al. 1997; D'Asaro 2014; Li and Fox-Kemper 2017). Despite recent developments of turbulence parameterizations that aim to include the effects of surface waves on turbulence (Li et al. 2019; Chor et al. 2021), the Stokes drift and wave effects on currents are still absent from many ocean simulations, limiting their applicability to problems in Lagrangian dispersal (Fraser et al. 2018; van Sebille et al. 2020).

Interactions between dynamics and the buoyancy field are also critical to the wind-driven response. Stratification inhibits the vertical transport of momentum, thus generating strong inertial shear across the mixed-layer base. Time-varying stratification near the surface leads to the formation of thin shear layers, such as the afternoon diurnal jet (Price et al. 1986; Cronin and Kessler 2009),

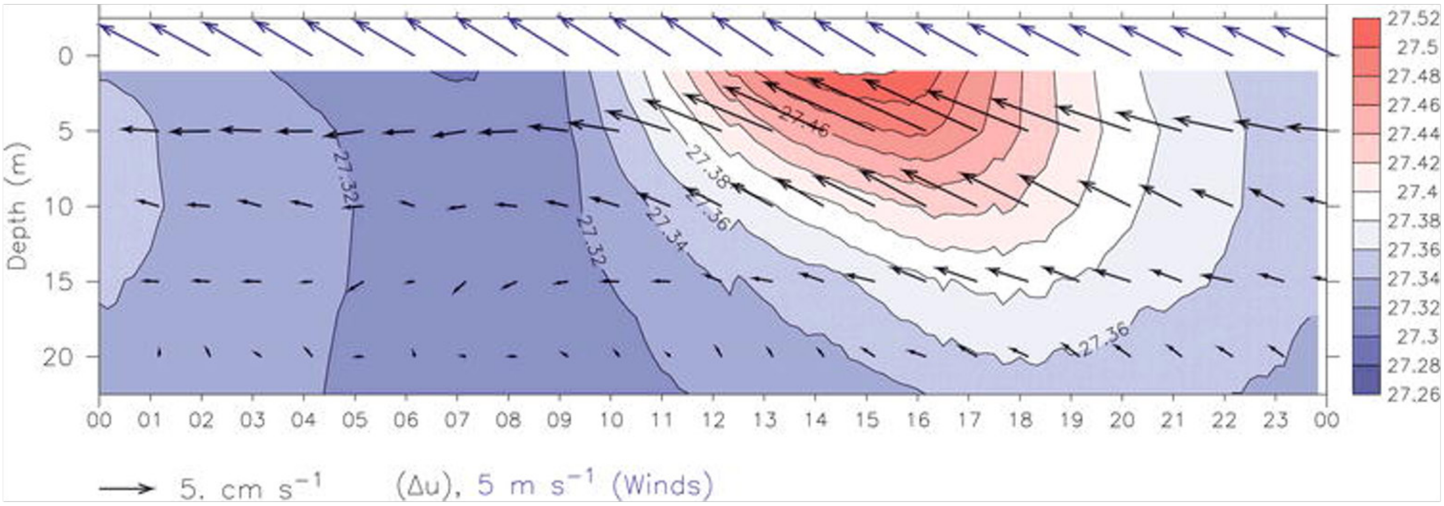

Figure 2. A composite diurnal cycle of shear flow from approximately 4 months of moored observations at 2°N, 140°W in the tropical Pacific. Observed currents are shown (black vectors) referenced to 25 m depth, oriented such that northward vectors point up, eastward vectors point right. The surface wind is also shown (blue vectors). Afternoon near-surface warming (temperature, colorscale) leads to the development of stratification that inhibits the downward transport of momentum from the surface, accelerating a sheared diurnal jet in the downwind direction. Figure from Cronin and Kessler 2009.

where afternoon surface heating leads to the development of near-surface stratification, a concomitant reduction in turbulent momentum transfer away from the surface, and the acceleration of a sheared jet in the downwind direction (Figure 2). The presence of these fast-timescale shear flows is known to drive turbulent mixing in the tropics (Moum and Caldwell 1985; Lien et al. 1995; Smyth et al. 2013; Wenegrat and McPhaden 2015), to rectify to affect the vertical structure of low-frequency shear flows (McWilliams et al. 2009; Wenegrat and McPhaden 2016b), and to affect climate variability on intraseasonal and longer timescales (Shinoda 2005; Danabasoglu et al. 2006; Bernie et al. 2007, 2008). Current generation models are capable of capturing these processes and interactions if run with sufficiently high vertical resolution and when considering regions of relative spatial homogeneity (where turbulence parameterizations are well-vetted). These conditions are not always met because they are computationally expensive and because much of the world's oceans contain significant horizontal variability.

Horizontal buoyancy gradients, or fronts, are regions of strong shear flow, both through the well-known thermal wind balance and through other ageostrophic frontal dynamics at the submesoscale, which are not as completely understood (McWilliams 2016). For example, the Gulf Stream region in Figure 1 shows stripes of high-shear regions associated with both persistent large-scale fronts, such as the western boundary current, and transient mesoscale eddies present in this 1/25° HYCOM simulation. Observations indicate the surface buoyancy power spectrum has an approximately k-2 horizontal wavenumber slope down to much smaller scales (Ferrari and Rudnick 2000) with strong thermal wind shear present through the submesoscale (below the resolution of this simulation). At these small scales, loss of balance occurs through a variety of frontal processes (McWilliams 2016), and sharp fronts are sites of both strong thermal wind and ageostrophic shear. Processes at this scale tend to evolve quickly (on the order of hours) and are sensitive to the time-varying surface forcing (Thomas et al. 2016; Duahajre et al. 2018; Sun et al. 2020). At the same time, boundary layer turbulence is also strongly modulated at fronts by the advection of buoyancy and the extraction of kinetic energy from the balanced flow by the geostrophic shear production (Taylor and Ferrari

2010; D'Asaro et al. 2011; Thomas et al. 2016; Smith et al. 2016). Sharp fronts in the surface boundary layer thus lead to coupled interactions between frontal dynamics, turbulence, and the wind-driven flow, which modify the near-surface shear flow through a variety of pathways that have not yet been fully explored. For example, the Ekman transport is modified by the vertical relative vorticity (Niiler 1969; Wenegrat and Thomas 2017), and inertial oscillations at fronts can have significant ellipticity and vertical shear (Whitt and Thomas 2015; Skyllingstad and Samelson 2020). This is in contrast to the predictions of classic slab-layer conceptual models, and has been shown to increase horizontal tracer dispersion (Wenegrat et al. 2020). Determining to what extent these intense, but spatially localized, sources of frontal shear flow matter to larger-scale circulation, tracer dispersion, and climate remains an important priority for improved modeling and prediction.

Measurement challenges and future outlook

Complete observations of the vertical structure of near-surface currents requires continuous sampling of the water column downward from the oscillating air-sea interface. Fully understanding these observations further requires apprehending environmental conditions such as density stratification and atmospheric forcings. Eulerian observations from moorings form an important basis of our observations of near-surface velocity and are well-suited to simultaneous collection of velocity, temperature, salinity, and meteorological data. Current meters deployed at fixed depths on mooring lines or surface buoys can capture both spatial and temporal structure of near-surface currents (Weller and Pluddemann 1996; Farrar and Weller 2006). However, these observations are often limited in vertical resolution and when made close to the surface, can suffer from biases due to mooring motions induced by surface gravity waves (Pollard 1973; Rascle and Ardhuin 2009). Acoustic Doppler Current Profilers (ADCPs) can also be mounted on moorings, either in a subsurface upward-facing configuration or in a downward facing configuration attached to surface moorings, providing well-resolved vertical profiles. Both configurations can, however, suffer from signal contamination from various sources, including surface gravity waves, such that the upper few meters of the water column are often not resolved, and fish, which aggregate under surface moorings, causing low biases in ADCP velocity magnitudes.

Alternate measurement techniques focus on near-surface Lagrangian currents, traditionally achieved by observing the drift of floating objects that are advected by total currents, that is the currents that are the result of all geophysical processes and their interactions (Rörhs et al. 2021; Marié et al. 2020). The water-following characteristics of a floating object are a function of the object's combined geometry and buoyancy, impacted by the direct force applied by near-surface winds if the object is partially exposed to air and the vertical structure of near-surface currents over the vertical extent of the object (Olascoaga et al. 2020). Drift measurements are now relatively abundant thanks to the drifting buoys, or drifters, of the NOAA Global Drifter Program (GDP, Lumpkin and Pazos 2007), which are initially drogued to follow currents at 15 m depth. GDP observations have allowed the characterization of near-surface currents arising from both the low-frequency and large-scale oceanic global circulation (Laurindo et al. 2018) and high-frequency and small scales processes including internal waves (Elipot and Lumpkin 2008; Elipot et al. 2016; Poulain and Centurioni 2015; Yu et al. 2019; Zaron and Elipot 2020). The preponderance of near-surface current observations from the GDP has had a large influence on our view of what constitutes the near-surface oceanic circulation. The majority of GDP ocean current observations actually originate from "undrogued drifters'' that have lost their anchor, the water-following capabilities of which are not completely known (Laurindo et al. 2018). Systematic comparisons between drogued and undrogued drifter data may be an underutilized source of information on near-surface shear. Drifters with designs that differ from those of the GDP have also been deployed for a number of dedicated process studies (Poje et al. 2014). However, combining drifters of different designs introduces uncertainty due to differing water-following capabilities and biases (Lumpkin et al. 2017). The influence of various geophysical processes on comparisons between drifter types is not yet fully understood, and comparisons between simulated drogued and undrogued surface drifters using a tide-simulating run of the MITgcm indicate average differences that depend on both frequency and latitude (Yu et al. 2019).

The spatial variability of near-surface currents can also be measured by remote sensing observations, but capturing remotely the current shear is more difficult. For example, the geostrophic component of near-surface currents is regularly obtained from satellite-borne altimetric radar instruments measuring sea surface height, but the thermal wind shear component can only be obtained from ancillary in situ data. Along coastal areas, high frequency radars provide estimates of the velocity of that upper layer of the ocean that interacts with small surface gravity waves. Yet, the nature of the surface currents estimated in this way (Eulerian or Langrangian) and the depth scale that they represent, are still a topic of active discussion (Isern-Fontanet et al. 2017). Comparisons with other current measurements lead to results that appear to depend on environmental conditions (Röhrs and Christensen 2015).

The distinct capabilities, as well as limitations, of the various instrumental platforms mentioned above altogether suggest that a successful strategy to measure the vertical structure of near-surface currents will need to include integrations and syntheses of different types of observations in parallel with theory advancements and numerical modeling to aid interpretations. Examples of such successes that have managed to obtained shear measurements extremely close to the surface include the combination of microstructure profiler, ADCPs, and surface gravity wave measurements (Sutherland et al. 2016), and the combination of various drifters, imaging techniques, and ADCPs (Laxague et al. 2018). There is currently a range of proposed satellite missions aiming at measuring simultaneously a mixture of surface currents, atmospheric winds, and surface gravity waves (Ardhuin et al. 2018; Rodriguez et al. 2018; Ardhuin et al. 2019; Chelton et al. 2019; Rodriguez et al. 2019; Villas Bôas et al. 2019) for which calibration and validation efforts will be of the utmost importance; not only to acquire accurate estimates of currents at the surface but also potentially to understand how these relate to currents just below the surface. Combining observations necessitates understanding both the potential uncertainties associated with individual measurements and how the spatial heterogeneity and non-stationarity of oceanic processes near the surface may conflate the horizontal and vertical shears of near-surface currents.

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