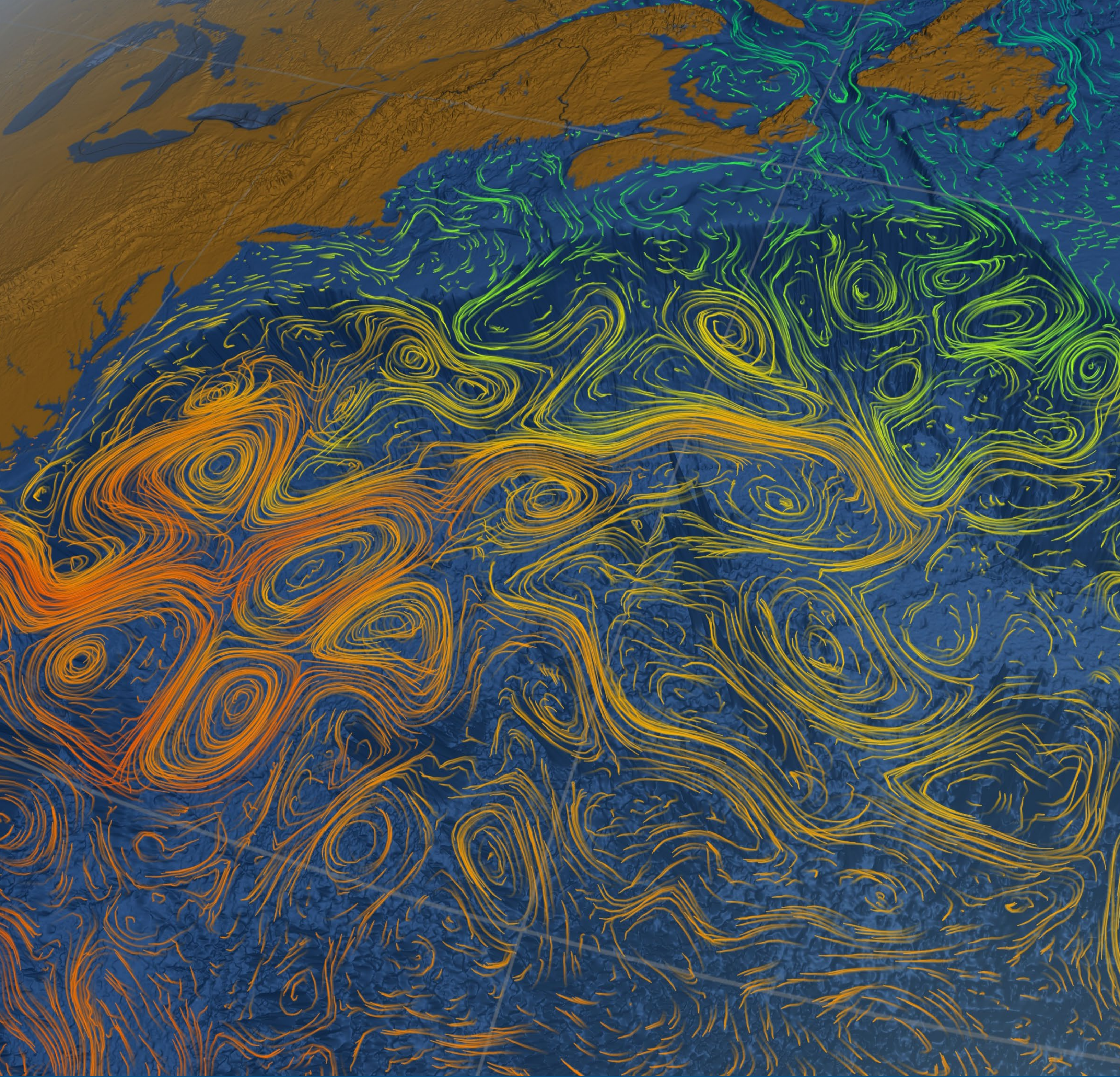

SURFACE CURRENTS IN THE COUPLED OCEAN-ATMOSPHERE SYSTEM

A US CLIVAR Workshop
February 22 – 23, 2020
La Jolla, California

SURFACE CURRENTS IN THE COUPLED OCEAN-ATMOSPHERE SYSTEM

Workshop Report

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FRONT COVER IMAGE

Gulf SST visualization produced using model output from the ECCO2 project (Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio)

BACK COVER IMAGES

Group photo of workshop participants (Credit: Jennie Zhu, US CLIVAR)

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EXECUTIVE SUMMARY

The workshop included 81 participants, with four sessions covering surface-current-related needs, gap analysis, and suggestions for resolving these gaps. Each session had four breakout groups. There were also two poster sessions with a total of 36 presentations. The presentations and discussions brought forth the wide range of applications for surface currents, including improved air-sea coupling in models, transport of pollutants and water properties, upwelling of nutrients, coastal management, and safety at sea. It was previously demonstrated that surface currents could be assimilated in numerical ocean models, with great benefit to the placement of eddies; the value of these observations for assimilation was strongly restated.

The workshop discussions revealed that there are many wave-related complications to understanding current profiles in the upper several meters of water, making it challenging to develop conversions between the definitions preferred by various user communities (e.g., geostrophic currents, layer-averaged currents, or the net horizontal motion at the surface). For observational studies, these conversions appear to be relatively straightforward applications of Stokes drift (assuming sea state is known) in the absence of wave breaking (Clarke and Van Gorder 2018). However, they are very uncertain if there is sufficient wave breaking and in the absence of sea state information, and Stokes drift is challenging to include in the high-resolution models desired for surface current applications. This complication and the wide range of applications contribute to the lack of a formal definition of a surface current. The OceanObs'99 meeting two decades ago defined requirements for the surface current observing system as one measurement every month every 5x5 degrees in space, at 2 cm/s accuracy. However, the need for much greater sampling in both space and time was a repeated theme in each session, with coastal applications requiring at least ten times the spatial sampling as open ocean applications.

Enhanced dissipation rates occur in the near-surface convergence regimes and areas of horizontal gradients in currents. These are also areas of enhanced vertical transport, which can upwell nutrients, gases, and cool water. This motion also contributes to much stronger coupling between the ocean and the atmosphere than is typical of scales >25 km, which provides some indication of the scales that must be observed. Wind/wave/current coupling is essential to momentum flux under high winds, but the uncertainty in modeling wind stress and the coupling processes increases as the wind speeds increase to hurricane-force winds. Thus a better understanding of wave-current interaction is expected to be important for modeling key processes in the ocean surface boundary layer, as well as for accurate conversion between the different definitions of upper ocean currents.

Recent applications of surface currents support the need for a better understanding of the current profile in the upper few meters, as well as a better understanding of how different processes contribute to currents (e.g., processes related to wind forcing, ocean topography, and waves). Applications also emphasized the importance of currents on basin scales down to scales of tens of meters for very near-shore processes, and the need to better observe currents on the scale of 10 km or finer.

Developing this understanding will require rigorous model validation against measurements. However, the necessary observations are limited at small scales, hampering our capacity to improve model representation of wind/wave/current interaction in the coupled ocean-atmosphere system. The observational problems are two-fold. First, the theory behind 3-D structures of currents and wave breaking at smaller mesoscale and submesoscales are not well constrained by data and models. Second, currents observed with Eulerian and Lagrangian platforms have been shown to have different vertical structures: all near-surface velocity measurements that are not purely Lagrangian or Eulerian are contaminated to some degree by surface wave effects, including flow distortion, aliasing, and tilting/heaving of instrumentations that correlated with the flow. Recent developments of near-surface drifters, drones, and satellite-based sensors point to paths forward that could provide both the increased spatial and temporal sampling of current (and waves) as well as the understanding of the processes key to making the most use of these observations.

1 INTRODUCTION

1.1 Workshop motivations

Ocean surface currents are poorly observed, but they have a profound influence on human life in two major ways: (1) they are critical in horizontal transport and dispersal of pollutants and physical, biological, and chemical properties; and (2) they are an important factor in air-sea exchange of properties like energy and momentum, and hence in subseasonal-to-seasonal prediction. Surface currents have been poorly observed, particularly within the upper meters of the ocean.

Prior work has shown that currents can exhibit a large vertical gradient within the upper few meters, and that different parameterizations represent this vertical gradient differently in numerical models. Most ocean models do not represent the near-surface vertical shear in the currents, and instead provide information about the “layer-averaged” velocity, which can be very different from the surface currents. For applications such as transport of oil or buoyant plastic particles, it is often the very-near-surface currents that are important. The presence of surface waves further complicates the dynamics: in the absence of wave breaking, Stokes drift can modify the current profile (Clarke and van Gorder 2018). However, in association with breaking waves, observations show that the current profile departs significantly from Stokes drift (Morey et al. 2018; Streßer et al. 2017). Wave breaking is a relatively common occurrence during high winds, when air-sea coupling is strong. However, there are few observations and parameterizations to characterize the vertical current profile under these conditions. Furthermore, horizontal shear in currents has been shown to strongly modify air-sea coupling (Stern 1965; Gaube et al. 2015; Shi and Bourassa 2019) and particularly vertical and horizontal transport of energy and materials, which is of great importance for marine ecosystems and fisheries. Assimilation of observed currents has also been demonstrated to improve model representation of ocean eddies. Temperature anomalies associated with these eddies impact tropical storm strength, and hence impact forecasting and coastal flooding.

In short, ocean currents in the upper meters can have substantial impacts on air-sea coupling and on biogeochemical and biological transport. They can also be assimilated in operational models to improve forecasts (Carrier et al. 2014; Muscarella et al. 2015; Domingues et al. 2019). However, there are large gaps in understanding of these currents and in the observational capability to address this problem. This workshop addressed these applications, gaps in knowledge and observations needed to move forward.

1.2 Workshop objectives

The overarching objective of the workshop was to improve the interdisciplinary collaboration between the physical oceanography, atmospheric science, and biological and chemical oceanography communities, as well as the communities who use surface currents in various "applications," such as transport (e.g., of pollutants and biota), navigation, and forecasting.

A major objective was to develop a practical definition for "surface current." Many communities would benefit from such a definition, which would be useful in converting between the average current in an ocean model's upper layer and a true surface current, and in relating velocity measurements from platforms sampling at different depths. Specifically, we aimed to determine measurement/model depths and accuracies needed for different applications.

Additionally, we aimed to quantify uncertainties in estimates of mass transport (for storm surge), pollutants, particles, sea ice, etc., resulting from misrepresentation of surface currents in the models/observations, and how new measurement strategies (e.g., from satellites) can help reduce errors in these applications. Specific physics-related goals of the workshop included summarizing the current knowledge of the role of currents in: air-sea fluxes of heat and momentum; the generation of turbulent kinetic energy; horizontal and vertical transport and mixing in the upper ocean; sea ice formation and transport; coupling to chemical and biological processes; mixed layer energy budgets and surface temperatures; and feedbacks with the atmosphere.

Specific application-related goals included summarizing the measurement and modeling requirements of surface currents for: reduction of recently identified inconsistencies in surface stress parameterizations and satellite observations; improved uncertainty estimates on observational products; developing a route to improving parameterization of sub-grid-scale air-sea interaction processes; improving ship routing and hurricane forecasting through improved placement of ocean eddies; and how better current profile can improve modeling of transports of microplastics transport, larval dispersal, and oil spill modeling. A major objective of this workshop was to develop plans for improved modeling and observations with the goal of understanding the above processes.

2 CURRENT STATE OF KNOWLEDGE

2.1 Progress and lessons learned from prior research

Surface currents have been defined in different ways across different scientific communities. Some of the definitions of surface currents summarized from a survey of the workshop participants include the daily averaged current at the top of the ocean, average current in the top layer of an ocean model, and currents at a particular depth (e.g., 3, 10, 15 m or on the surface). These differences in the definition of an ocean surface current emphasize the need to understand the profile of the near-surface currents and develop definitions that would translate across a broad range of communities.

The Ocean Observations Physics and Climate panel (OOPC) is responsible for the definition of the physical essential ocean variables (EOVs), and has responsibility for the ocean-related topics relevant to climate for the Global Ocean Observing System (GOOS). Ocean surface currents are classified as an essential climate variable. OOPC has a lot of good reference material on currents in its EOV specification sheet. For instance, one of the references to ocean surface currents and circulation is as follows:

> “The surface ocean general circulation is responsible for significant surface transport of heat, salt, passive tracers, and ocean pollutants. On basin scales, surface currents and their variations are a major player in climate to weather fluctuations. Parameterized wind stress and heat flux depend upon the speed of the near-surface wind relative to the moving ocean surface, which can be significantly affected at large scales by surface currents such as the western boundary currents and Antarctic Circumpolar Current, and at smaller scales by mesoscale variability. Convergences/divergences, spiraling eddies, and filaments all contribute to vertical motions and mass exchange. Surface currents impact the steepness of surface waves and are thus important for generating accurate marine sea state forecasts. Because of their significance in advecting passive particles, knowledge of surface currents is also important for applications such as oil spill and marine debris response, search and rescue operations, and ship routing. Currents, particularly tidal currents, can also modify storm surge impacts and sea-level changes.“

The OOPC definition of surface currents meets some of the community needs for surface current definitions but it does not encompass all the definitions needed for the use of surface currents in different fields. There is no standardized meaning of surface currents when used across different scientific communities. The OceanObs’99 meeting a couple of decades ago defined requirements for the surface currents observing system as one measurement every month every 5x5 degrees in space, at 2 cm/s accuracy. This need has been met by today's observing system yet is not sufficient for our present-day observational and modeling needs.

Many advances in observation technology over the last three decades have helped us improve our understanding of the surface currents and different processes that influence the surface currents. For example, the Stokes drifter (Morey et al. 2018) is a Lagrangian observation platform that measures the Stokes drift ~ 5 cm below the surface. The CARTHE drifter (Novelli et al. 2017) can measure currents 50 cm below the surface. Eulerian measurement platforms, such as moorings, with Acoustic Doppler Current Profilers (ADCPs) can measure vertical profiles of currents below the surface. Similarly, ships and autonomous vehicles carry ADCPs to measure currents below the surface. HF Radar is used to measure near-shore currents from land-based stations along the coast. Very recently, high resolution imagery from drones has been used to infer near surface current profiles from observed short waves (Streßer et al. 2017), which could prove invaluable in understanding the differences between the wide range of current observations mentioned above.

2.2 Key gaps in observations, modeling, and understanding

Our ocean observing system does not measure surface currents directly. We attempt to infer surface currents from measurements of quantities that are affected by ocean surface currents; for example, some remote sensing techniques measure the motion of scatterers moving in the currents and even more direct measurements from surface drifters are affected by factors like waves, wind, and vertical shear. The current shear at and near the surface have not been widely measured and must be considered for interpreting the signals from the observing system. Air-sea interaction occurs at the interface of the ocean and atmosphere, but there are very few observations of the "true" ocean surface that can constrain air-sea interaction with observations alone. Coarse resolution models and many oceanographic applications mainly produce currents 10–15 m below the surface, and high resolution regional models often have an upper layer within the top meter of the water column. In both cases, their resolutions are too coarse to resolve the "true" surface because of strong near-surface changes in current.

2.3 New technological tools for making progress

Remote sensing techniques can be used to measure currents near the ocean surface. The two main principles used for remote sensing of currents are: (1) measure the space-time spectrum of optical imagery to infer the surface current from the Doppler shifting of short surface waves (Young et al. 1985); and (2) measure surface wave radial Doppler shift with instruments such as coastal HF radar or Doppler Scatterometry (including SARs). Rodriguez et al. (2019) described one concept for a satellite Doppler scatterometer, which is referred to as the Wind and Currents Mission (WaCM) mission concept. It has a large swath (with ~daily global coverage from space) and low data rate (for easy on board processing); it measures the Ka-band, which minimizes wave contamination; and it can be mounted on planes or on space platforms (Figure 1). A disadvantage is that longer gravity waves and winds contribute to total signal: this contribution must be removed using a mixture of theory and experiment to extract surface currents. The Doppler Scatterometer can also be used to measure winds (at incidence angles > 20 deg: WaCM) or gravity waves (SKIM; Ardhuin et al. 2017).

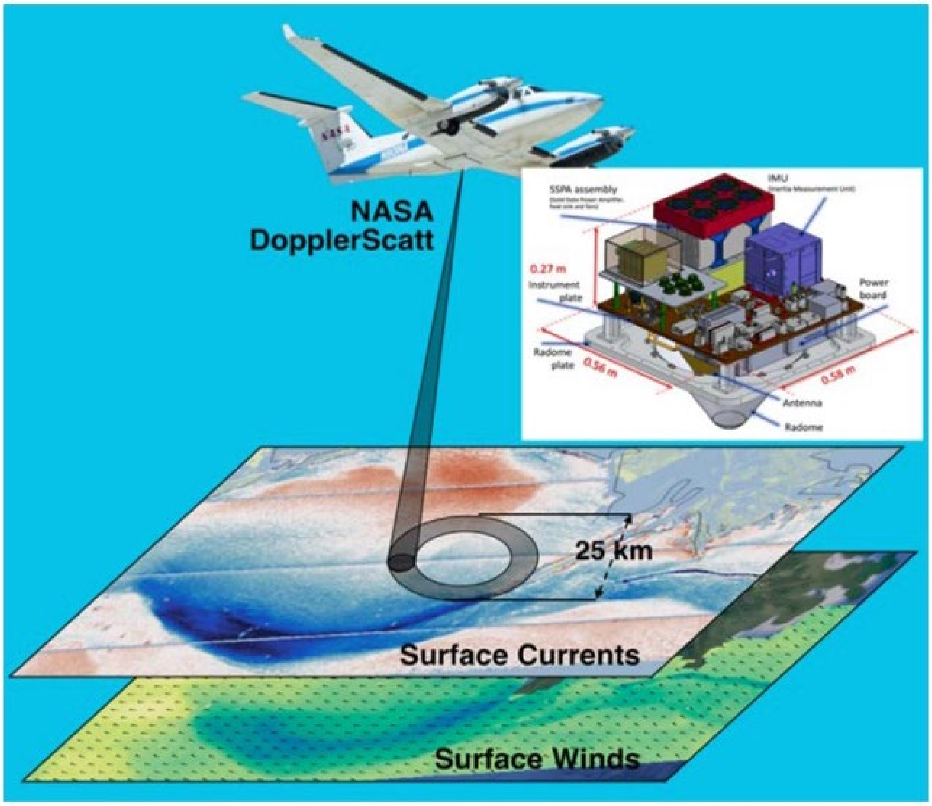

Figure 1. NASA DopplerScatt (airborne Doppler scatterometer) has a small rotated antenna that can observe surface currents over large swaths (Rodriguez et al. 2018). A satellite version of this instrument could provide nearly global, daily measurements of surface currents (Rodriguez et al. 2019).

2.4 Leveraging existing activities and coordinating new activities to address challenges

SKIM and WaCM can have global coverage. SKIM would have global coverage every 4 days (as per its present design plans). WaCM would have the same coverage as QuikScat, with 90% of the globe covered every day. SKIM was recommended but not funded by the European Space Agency in 2019. The US Decadal survey recommended that these measurements be considered in the next decade via the “Earth Explorer Line” (NASEM 2018). Yet, at present, there is no budget allocated for SKIM or WaCM. Hence, funding for these missions must leverage community support as well as these organizational recommendations. During the workshop, Dr. Meghan Cronin presented specific goals derived from the OceanObs’19 white paper (Cronin et al. 2019) and discussions on the formation of an integrated surface ocean observing system (ISOOS). We need many EOVs to measure the surface fluxes as part of this ISOOS. Some of the requirements to achieve these goals are not yet met, including observing the skin surface currents. The community recommendation for this effort was to launch a satellite to measure these EOVs in addition to deploying many in-situ reference sites in different regimes. The proposed Tropical Pacific Observing System (TPOS) array will have many more surface current observations than the current array. These observation systems in the Tropical Pacific will be phased in over the next few years. Hence, the surface currents observation community should recommend and engage with the TPOS community to coordinate needs and efforts.

3 VERTICAL STRUCTURE OF NEAR-SURFACE VELOCITY (AND IMPACTS ON APPLICATIONS)

Understanding the vertical structure of surface currents in the ocean is challenging in terms of both acquiring and interpreting the necessary measurements. Yet, that understanding is crucial, notably for relating the ocean velocity at one depth to that at another depth. For instance, remote sensing of surface currents provides an estimate of currents at a depth level typically much shallower than the in situ observations used for validation so that a bias may exist between the two observations. Theoretical bulk estimates of air-sea momentum fluxes need to be estimated using surface currents, yet only deeper current estimates are typically available, suggesting again that biases may occur. Quantifying the downward momentum transfer from the surface into the ocean interior beneath diurnal warm layers or fresh layers requires knowledge of the vertical structure of surface currents, yet with only one depth estimate that flux cannot be estimated (e.g., Figure 2).

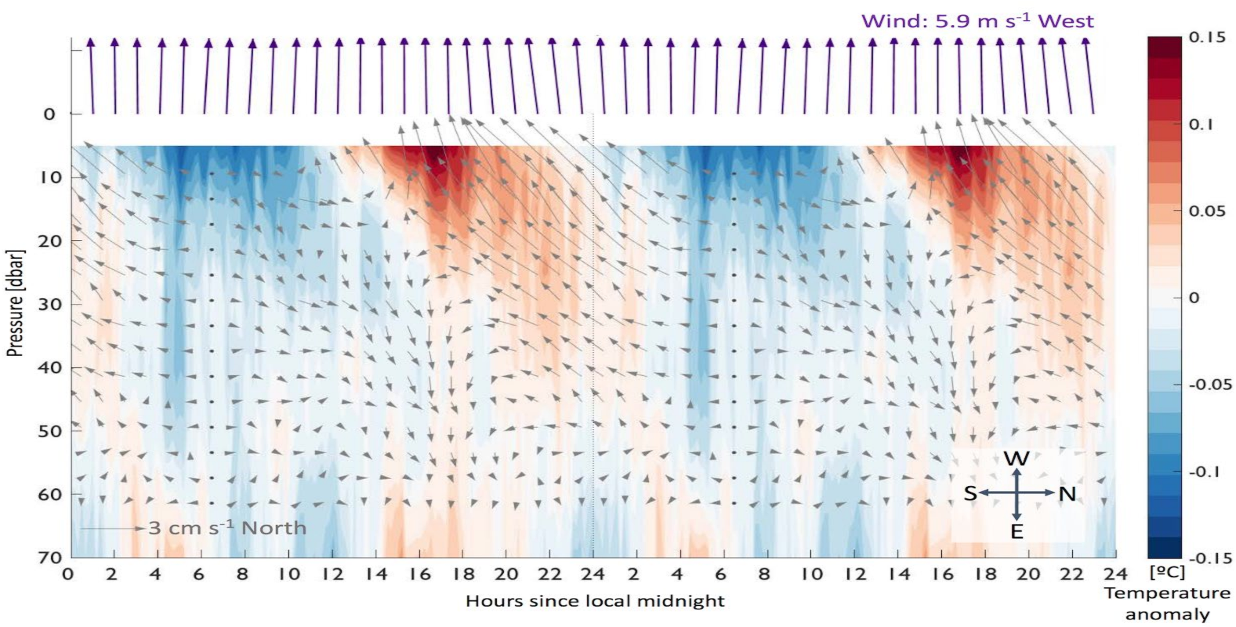

Figure 2. Wind (m s $^{-1}$), current anomaly (cm s^{-1}) w.r.t. current at 68 m, and temperature anomaly (°C) at 0° 155°W. Diurnal temperature (color) and velocity (gray arrows) and wind (purple arrows) anomalies in the equatorial Pacific Ocean from enhanced Tropical Pacific Observing System (TPOS) mooring, showing a strong increase in vertical shear that descends through the water column through the day (Masich et al. 2020).

The upper ocean velocity structure is currently observed using moorings (typically instrumented with point current meters or Acoustic Doppler Current Profilers [ADCPs]), drifting buoys anchored at various depths, autonomous or freely drifting surface or underwater vehicles carrying ADCPs, profilers, ADCPs mounted on ships, and remote sensing platforms (aircraft, land-based). Observations have revealed that currents within the ocean surface boundary layer (OSBL) are strongly sheared and turbulent on a broad range of time and space scales, and are forced by multiple drivers. One of the most critical drivers of vertical velocity structure—and the uncertainty in measuring it—is surface gravity waves. Stokes drift can transport significant amounts of mass, as can wave breaking. While the mass transport by linear waves is fairly well constrained, the impact of nonlinear waves remains a challenge.

Measuring the vertical structure of ocean currents is still challenging from a technological standpoint because it requires accurate measurements at multiple depths in the turbulent and wavy OSBL. In addition, integrating measurements from different platforms can be difficult. For instance, currents observed with Eulerian and Langrangian platforms have been shown to have different vertical structures (e.g., Figure 3). Moreover, all near-surface velocity measurements that are not purely Lagrangian or Eulerian are contaminated to some degree by surface wave effects, including flow distortion, aliasing, and tilting/heaving of instrumentations that correlated with the flow. Estimates of these effects using an observing system simulation experiment (OSSE) method suggests that wave motion can bias current measurements by O(0.01-0.1) m/s depending on wave conditions, averaging period, etc. (Farrar and Zippel 2020).

Throughout the workshop, the topic of wave-current interaction emerged as one of the most pressing gaps in our understanding of vertical velocity structure in the upper ocean. Efforts are needed to understand this issue through measurements and modeling. More generally, we lack measurements (and models) with sufficient vertical resolution to capture vertical shears in the upper ocean, hampering our ability to quantify and understand the vertical current structure as well as its forcing and eventual impacts. We particularly lack accurate velocity measurements in the upper 1–2 m, where surface reflections confound ADCP measurements and flow distortion is problematic for buoys. Evidently, observation and model developments need to work in synergy as measurements are needed to validate models with increasing complexity and resolution. In addition, measuring near-surface currents is not sufficient, as coupled ocean-atmosphere assimilation efforts require concurrent observations of both winds and currents.

Several new and emerging tools should allow us to make progress on the aforementioned knowledge gaps. A satellite-based Doppler scatterometer would be transformative, providing near-global measurements of surface currents on an unprecedented space and time scale, and paired with existing measurements at other depths (e.g., from drifters and moorings), such satellite-based measurements would produce information about the vertical structure of ocean velocity on a global scale.

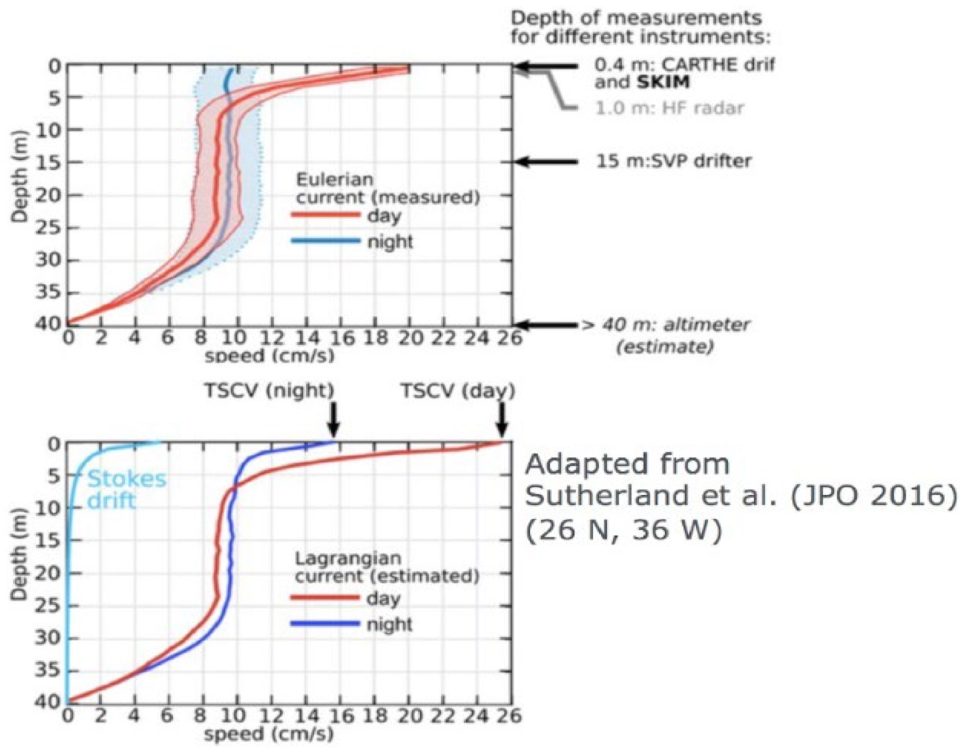

Figure 3. Daytime and nighttime ocean currents measured in the upper 40 m in an Eulerian (top) or Lagrangian (bottom) framework (Arduin 2020; adapted from Sutherland et al. 2016).

The topic of wave-current interactions and their impact on vertical current structure could be addressed through in situ and modeling process studies, as well as by revisiting existing datasets in the light of most recent research. High-frequency ADCP measurements of the upper ocean boundary layer have been shown to be valuable for understanding velocity structure, and should therefore be deployed on an increasing range of platforms (e.g., profilers, floats, AUVs, or ASVs). More use could be made of the Global Drifter Program (GDP) measurements, including utilizing the undrogued drifters to infer surface currents (see Lumpkin presentation). Developing climatologies of currents at multiple depths (e.g., surface and 15 m) would be valuable.

Modeling efforts must be sustained and expanded. Valuable improvements should include: parameterization of wave-current interactions (including Stokes drift, wave breaking, etc.), validated by high-resolution observations and ultimately integrated into coupled models; Large Eddy Simulations (LES) focusing on understanding current structure and how it is affected by waves; and OSSE experiments to identify strategic locations for observational studies, as an example to determine where Stokes drift significantly influences atmosphere-ocean coupling.

Finally, it appears that bringing together the surface gravity wave and surface current communities would offer substantial mutual benefits. A working group or a series of workshops to that effect are possible ways forward.

4 WIND-WAVE-CURRENT INTERACTION (AND IMPACT ON APPLICATIONS)

There remain many challenges in measuring and accurately modeling wave-wind-current (WWC) interaction processes, especially at small spatial scales. In situ observations, for example, have shown that enhanced dissipation rates occur in the near-surface convergence regimes associated with windrows. Because of their inherently short spatio-temporal scales, however, sparse measurements hinder reliable estimates of balances among shear production, buoyancy production, and dissipation in turbulent kinetic energy (TKE) budgets. This observational challenge translates directly into difficulty in validating model performance and improving parameterizations. Wave modeling studies demonstrate that submesoscale gradients of flow fields (e.g., vorticity or divergence), for example, significantly influence simulated surface wave properties. Yet, rigorous model validation against measurements is limited at small scales, hampering our capacity to improve model representation of WWC interaction in the coupled ocean-atmosphere system.

Ocean waves also modulate marine atmospheric boundary layer (MABL) turbulence and surface wind, with a notable impact at sea surface temperature (SST) fronts. Wind-wave coupling is essential to momentum flux under high winds, but the uncertainty in estimated wind stress also increases with wind speed, indicating missing dynamics (e.g., wave breaking) in bulk formulae and models. Wind-stress dependence on waves is sensitive to the turbulence profile in the MABL and to the strength of surface currents. There is a clear need for accurate and simultaneous measurements and modeling of WWC.

Further, surface currents, which are particularly strong in western boundary currents and mesoscale eddies, influence wind stress by creating velocity shear across the air-sea interface. Results from recent high-resolution coupled modeling studies have indicated that the relative wind effect could remedy long-standing biases in climate models (Figure 4) by generating negative eddy wind work and thereby damping the eddy kinetic energy of western boundary currents. That the wind work becomes negative implies that energy is injected from the ocean to the atmosphere, which partially re-energizes the near-surface wind. These effects are parameterized to optimally force ocean-only models.

Thus, improved understanding and representation of air-sea interactions demand a combined cross-boundary approach through integrated observations and modeling of ocean winds, surface currents, and ocean surface waves (Figure 5).

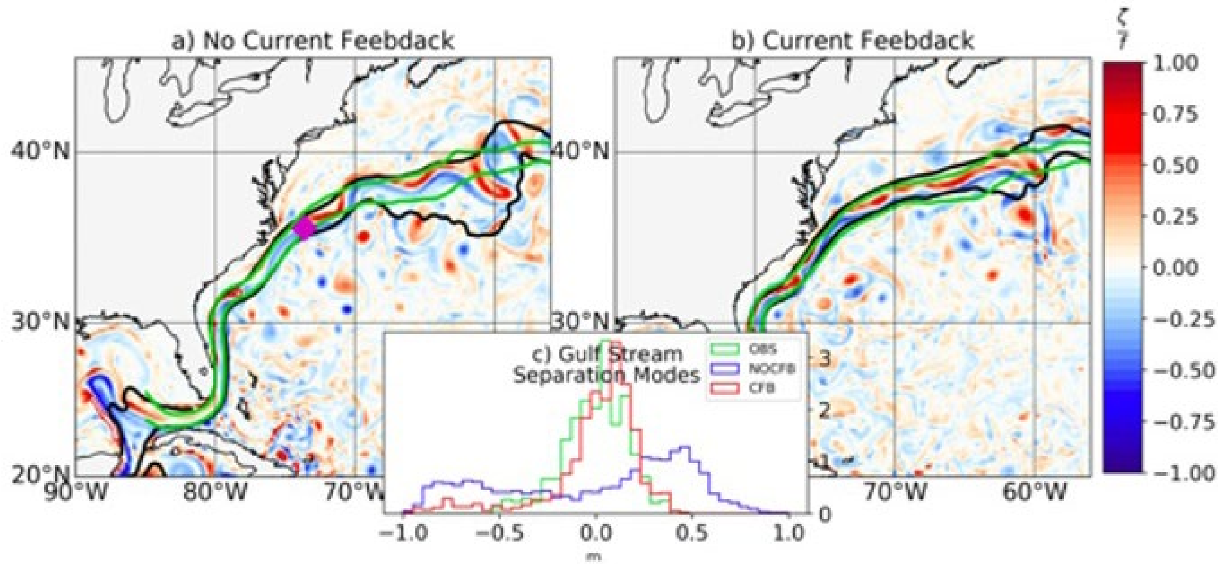

Figure 4. Eddy killing improves the Gulf Stream (GS) position in simulations. The color field presents a typical snapshot of surface relative vorticity from (a) coupled simulations without current feedback to the wind (NOCFB) and (b) coupled simulations with current feedback (CFB). Black contour lines represent the simulated long-term mean GS path (contour of 0.6 m/s). The green contour lines show the observed GS path (contour of 0.6 m/s). (c) Probability density function of sea level anomaly around the magenta diamond box (indicated in panel a) from AVISO (green), NOCFB (blue), and CFB (red). The eddy-resolving coupled model with CFB rectifies long-standing biases in oceanic models of bimodal and unsteady GS separation. Adapted from Renault et al. (2019).

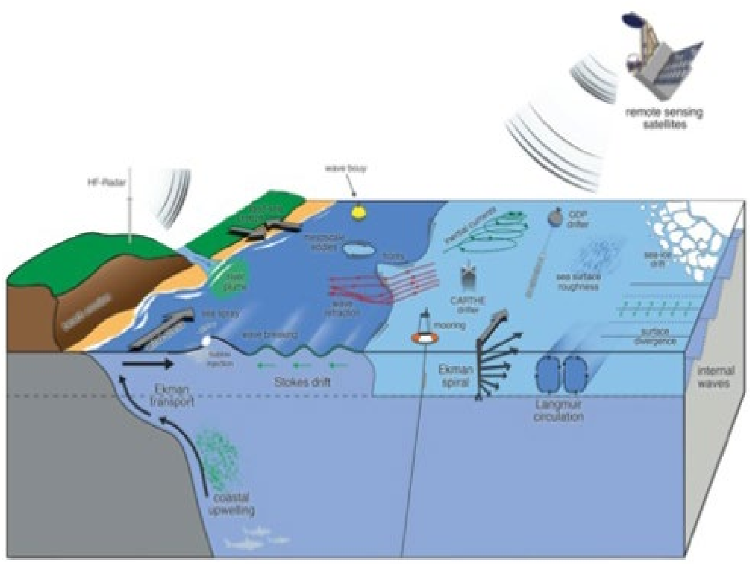

Figure 5. Schematic representation of upper-ocean processes that are coupled through the interaction between surface winds, currents, and waves. Processes that are driven by these interactions range from regional to global scales and happen in coastal areas (e.g., coastal upwelling and land-sea breeze), open ocean (e.g., inertial currents and mesoscale eddies), and marginal ice-zones (e.g., sea ice drift). Multiple components of the observing system including in situ (e.g., surface drifters, wave buoys, and moorings) and remote sensing (e.g., HF-radar and satellites) platforms are also illustrated (Villa Bôas et al. 2020).

4.1 Key gaps in observations, modeling, and understanding

Presentations and discussion during the breakout sessions highlighted a number of gaps, as well as identifying strategies for addressing these gaps.

1. **Gap in observations: Coincidental and co-located observations**
   There is a clear need for coincidental and co-located observations of WWC with short waves on oceanic mesoscales and submesoscales and/or under high-wind and large-flux conditions. The spatial gradients of wind, waves, current, and stress on both sides of the interface need to be measured, especially when and where winds and currents are not aligned, or where short waves introduce a non-locality and nonequilibrium conditions at small scales.

2. **Gap in knowledge: How does wind, wave, and current interaction influence vertical and horizontal fluxes?**
   We need to understand better how WWC interactions affect vertical motions, turbulent mixing, bubbles, and tracer fluxes, all of which are essential for air-sea fluxes and biogeochemical processes. Currently, sparse measurements of dissipation in the wave-enhanced layer hinder a reliable estimate of TKE budgets, making it challenging to parameterize the circulation and dissipation in large-scale models.

3. **Gap in knowledge: Parameterization of wind, wave, and current interaction**
   We need to identify and improve deficiencies in theoretical frameworks for the WWC interactions to better guide observations and parameterizations. A technology that has been effective for field observations is the current copter (Streßer et al. 2017) which uses imagery of short waves to determine the near surface current profile. Laboratory experiments can be important to study processes in a controlled environment in order to build frameworks for making and interpreting observations. However, the wave fields under such conditions might not be sufficiently similar to open ocean conditions. Such laboratory studies have been very effective for low and modest wind speeds, but suffer from unrealistic sea state for extreme winds (Troitskaya et al. 2017).

4. **Application gap: Wind, wave, and current coupling in climate models**
   Climate models incompletely represent WWC interactions. The stochasticity and 3-D structures of currents and wave breaking at smaller mesoscale and submesoscales are not well constrained by data and models.

4.2 New technological tools for making progress

Existing and emerging observational platforms can be used to measure WWC. These platforms include: Saildrones (though they do not make wave observations yet; ADCPs can be mounted to measure subsurface current profiles); drifting SWIFT buoys (wind, waves, and currents); and moored buoys with wave measurements (e.g., Ocean Station Papa). Use of multiple, complementary platforms is also recommended (SPARS+drifters or SAR+X-band radar + drifters as examples). These observations should be made over various conditions. Adaptable and mobile network capabilities that resemble Atmospheric Radiation Measurement (ARM) Research Facility would be useful observational tools. For the coastal environment, high-frequency radars are proving useful. The Tropical Pacific Observing System's (TPOS) multiple platforms would be valuable in combination with satellite observations for coupled data assimilation and prediction experiments, and similar instrumental configurations in other oceanic regimes will allow a broader exploration of WWC processes.

Satellite observations also have enormous potential to advance understanding of WWC processes. A number of options have been explored including systems that combine wind and wave measurements (the Chinese French Oceanography Satellite, CFOSAT), wind and current measurements (the proposed Wind and Current Mission, WACM), or winds and currents (Sea surface KInematics Multiscale monitoring, SKIM). Each of these has the potential to enormously enhance understanding, and a constellation of systems that obtained all three measurements would address scientific objectives for WWC processes on a global scale.

4.3 Leveraging existing and coordinating new activities to address challenges

Some field experiments, such as S-MODE (a pilot for WACM-like satellites) and ROAM-MIZ, could provide valuable observations for modeling efforts at submesoscales. After the launch of the SWOT altimeter in 2022, there will be three months of daily observations at a limited number of "cross-over" sites where the satellite tracks intersect (d'Ovidio et al. 2019). A reference site could be co-located at a SWOT cross-over site to leverage high-resolution SWOT measurements. It may be possible to estimate surface currents from wave properties using existing or these forthcoming satellite observations. The air-sea flux and MABL data from the 2020 ATOMIC/EUREC4A experiment (Tropical Northwest Atlantic) over different eddy regimes (divergence and vorticity) can be examined. A series of pilot field/modeling studies in regions of persistent ocean fronts, high winds, and waves (e.g., western boundary currents or Southern Oceans) is needed to improve model deficiencies and to guide the design of a global observing system.

5 APPLICATIONS

5.1 Progress and lessons learned from prior research

There are numerous and diverse applications for surface current measurements, many of which consider different temporal and spatial scales and require different resolution and accuracy. Applications include: search-and-rescue; air-sea gas exchange; numerical weather prediction; improved models; larval connectivity and dispersal for diverse taxa; oil spill transport; ship routing applications; waste water dispersal; biogeochemical transports (e.g., Figure 6); field campaign designs; offshore and wind energy; glacial melt; divergence/convergence and importance for plankton; planning of marine protected areas; satellite calibration; carbon tracking; and heat transport.

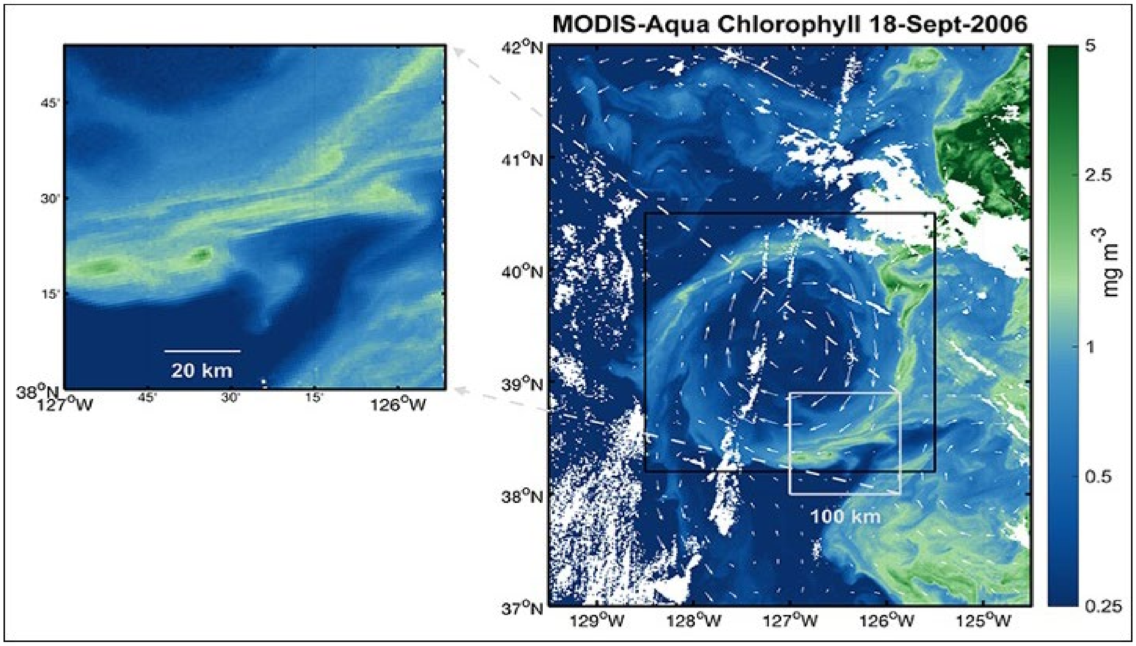

Figure 6. Chlorophyll a concentration in a mesoscale eddy offshore of central California on September 18, 2006, as observed by NASA's MODIS instrument on the Aqua satellite along with geostrophic ocean current vectors estimated from sea level anomaly data. White patches indicate clouds. The logarithmic color scale represents chlorophyll a concentrations in milligrams per cubic meter (Fassbender et al. 2018).

Some of the applications discussed in detail at the meeting ranged from large-scale global applications to near-shore applications requiring accurate current and wave data with fine resolution. Talks highlighted several topics including the importance of small-scale (kilometers) variability in the coastline on local patterns of beach erosion and nourishment. Very high spatial resolution current/wave measurements near the coast are key to applications for coastline change, beach replenishment plans, and flood predictions.

On meso- and basin-scales, current patterns must be considered for investigating marine top predators. For example, Elephant Seal foraging patterns can be characterized as quasi-planktonic periods of passive transport with the currents interrupted by periods of directional swimming. “Passive” behavior has been shown to occur when seals are entrained within coherent (sub)mesoscale structures. Identifying the movements (passive and active) of top predators will inform the development of marine protected areas and other management actions.

At the global scale, surface currents and Lagrangian modeling are used to simulate the transport of marine litter including microplastics. There are multiple scales and different processes that affect marine litter transport. Simulations conducted including only Stokes drift, Ekman currents, geostrophic currents, or Ekman currents, geostrophic currents highlight the different roles these processes play in, for instance, general transport and retention/accumulation in specific regions. Lagrangian models can predict the locations that marine litter will accumulate, but may have less utility in determining the source of litter in accumulation zones, because trajectories mix in these regions.

5.2 Key gaps in observations, modeling, and understanding

Gaps and needs are highly variable for the different applications. For instance, estimating coastal flooding and cliff erosion requires very high resolution current and wave measurements in a narrow band along the coast. Heat transport may not need such high resolution measurements, but requires global coverage with a particular emphasis on better measurements near the equator. Accurate predictions for marine litter transport and search-and-rescue applications may require careful incorporation of Stokes drift. Organism dispersal and planning of marine protected areas will need spatial coverage and resolution that vary based on the behavior and habitat of different species as well as observation of the vertical structure of currents as organisms reside in various positions in the water column. A hierarchy of different spatial resolutions and accuracy tolerances is likely necessary as we move from the land-sea boundary region (high resolution required: 10s of meters) to the open ocean (lower resolution is tolerable: 1–10 km). It is likely that different products will be better suited to specific applications. Rapid progress may be possible if communities of users can be informed of the benefits and limitations of different measurement products. These gaps in observations and modeling can be addressed through the same approaches that have been recommended in the previous sections.

5.3 Leveraging existing and coordinating new activities to address challenges

A publication or review targeted at users that documents the merits and limitations of the different current products could be impactful. Ideally, such a document could serve as a road map for end users, pointing them towards tools that are optimally suited for the applications outlined above, by taking into account the special requirements (e.g, coastal/high resolution only, Stokes drift required, waves necessary, real-time crucial) that are important for each application. This publication could also be presented as a Town Hall at, for example, Ocean Sciences Meeting. Ideally it would also point toward well-documented example use cases for different products and links to software and tools.

There was also discussion of “hackathons” or “bake-offs” to compare the utility of different products for specific applications. This might be done in coordination with future meetings. Finally, it is important to work toward better and more consistent practices for metadata, data sharing, and uncertainty quantification.

6 RECOMMENDATIONS

There is a strong need to understand the processes that contribute to surface currents and to current shear in the upper few meters of the ocean. Without such understanding, it will be difficult to convert from the definition of currents preferred by one user community to another, which is critical for wide use of current observations and for assimilation into ocean models. Therefore, we strongly recommend targeted field and laboratory experiments to improve this understanding. Such experiments will need to be conducted in regions with different wind/wave/current regimes to model the spectrum of commonly occurring parameter space, and these observations should include winds, waves and currents. In some or all cases, there are non-physics communities that could benefit from the physical observations. Obvious opportunities include studies of the fate of nutrients and carbon that are transported out of upwelling regions (and the corresponding impact on biology), the transport of microplastics and pollutants, examination of spatial variability in the partial pressure of carbon dioxide, and coastal erosion. Atmospheric studies involving modification of the atmospheric boundary layer would likely be highly informative regarding the impacts on available heat and energy to influence weather, the stability of the boundary layer, and perhaps on mixing between the boundary layer and free atmosphere. We recommend that all such experiments include subsurface observations of currents, temperature and salinity, as well as atmospheric variables such as air temperature, humidity, and surface pressure. There was considerable discussion of how autonomous underwater vehicles and drones could contribute to such field studies, with drones being one of several approaches to obtaining information about fields of waves and currents, as well as some information about winds.

Global coverage of surface current observations is extremely poor, and should be improved through remote sensing from coastal radars and satellites. Very recently, several mission concepts have been developed to provide vector currents (and coincident winds or waves for the lower cost missions). A satellite-based Doppler scatterometer would be transformative, providing near-global measurements of surface currents on an unprecedented space and time scale, and paired with existing measurements at other depths (e.g., from drifters and moorings), such satellite-based measurements would produce information about the vertical structure of ocean velocity on a global scale. Similarly, other satellite missions will provide the currents related to specific ocean processes (e.g., surface topography, wind, or waves), and observed differences from these currents will provide insights into currents related to the other processes. The results of the above mentioned fields and modeling studies can be used to make such observations useful to the widest range of user communities.

Finally, it appears that bringing together the surface gravity wave and surface current communities would offer substantial mutual benefits. While this appears to be useful for almost all wind/wave/current applications, it appears to be necessary to make progress for extreme wind and wave conditions. A working group or a series of workshops to that effect are possible ways forward.

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APPENDIX C: AGENDA

Saturday, February 22, 2020		
Time (PST)	**Agenda**	**Presenter**
7:30 AM	Registration and continental breakfast	
8:30 AM	Welcome, opening remarks, and workshop goals	Sarah Gille, UCSD-Scripps Mark Bourassa, Florida State University Mike Patterson, US CLIVAR
8:50 AM	**Session 1: Current State of Knowledge** Chairs: Sarah Gille and Larry O'Neill	
8:50 AM	Definition of surface currents for integrating observations and modeling	Shane Elipot, University of Miami
9:10 AM	(Invited) The state of the art in surface current estimation from remote sensing and in situ observations	Ernesto Rodriguez, NASA JPL
9:30 AM	(Invited) Challenges of forecasting surface currents	Sergey Frolov, NOAA ESRL
9:50 AM	A big idea from OceanObs'19: Formation of an integrated surface ocean observing system	Meghan Cronin, NOAA PMEL
10:10 AM	Intro to breakout session on current knowledge	Sarah Gille, UCSD-Scripps
10:15 AM	Break	
10:45 AM	Breakout session on current knowledge	
12:00 PM	Lunch	
1:00 PM	**Session 2: Vertical Structure of Near-Surface Velocity (and Impacts on Applications)** Chairs: Kyla Drushka and Renellys Perez	
1:00 PM	Challenges in measuring the vertical structure of near-surface currents	Tom Farrar, WHOI
1:20 PM	Improving slip removal from undrogued drifters	Rick Lumpkin, NOAA AOML
1:40 PM	Diurnal cycles of near-surface ocean velocities at five moorings across the tropical Pacific	Jessica Masich, NOAA PMEL

2:00 PM	Stokes drift and vertical shear at the ocean surface: Evidence and implications for upper ocean transport and mixing and remote sensing	Fabrice Ardhuin, UCSD-Scripps
2:20 PM	Sustained Lagrangian observations of upper-ocean currents, stratification, and turbulence	Andrey Shcherbina, University of Washington
2:40 PM	Intro to breakout session on vertical structure of near-surface velocity	Kyla Drushka, University of Washington
2:45 PM	Break	
3:15 PM	Breakout session on vertical structure of near-surface velocity	
4:30 PM	Report from day 1 breakout sessions	
5:00 PM	Early career scientist poster lightning talk for poster session 1	
5:30 PM	Poster session and reception	
7:00 PM	End day 1	

Sunday, February 23, 2020		
Time (PST)	**Agenda**	**Presenter**
7:00 AM	Continental breakfast	
8:00 AM	**Session 3: Wind-Wave-Current Interaction (and Impact on Applications)** Chairs: Hyodae Seo and Amelie Meyer	
8:00 AM	(Invited) Wind, wave, and current interactions	Bia Villas Bôas, UCSD-Scripps
8:20 AM	The circulation, geometry, and turbulence of windrows: Measurements from the St. Lawrence Estuary	Seth Zippel, WHOI
8:40 AM	Atmospheric response to changes in sea-surface temperature: Insights from an analytical model	Alex Ayet, LOPS (IFREMER) / LMD(ENS)
9:00 AM	The current feedback to the atmosphere: Implications for the ocean dynamic, air-sea interactions, and how to best force an ocean model	Lionel Renault, IRD
9:20 AM	Intro to breakout session on wind-wave-current interaction	Hyodae Seo, WHOI
9:25 AM	Break	
9:55 AM	Breakout session on wind-wave-current interaction	
11:10 AM	Early career scientist poster lightning talk for poster session 2	

11:30 AM	Lunch and poster session 2	
1:00 PM	**Session 4: Applications** Chairs: Mike Stukel and Angela Kuhn	
1:00 PM	(Invited) Simulating the transport of floating marine litter across scales	Erik van Sebille, Utrecht University, Netherlands
1:20 PM	Quasi-planktonic behavior of foraging top marine predators	Alice Della-Penna, University of Washington
1:40 PM	(Invited) Beach change, cliff erosion, and flooding	Bonnie Ludka, UCSD-Scripps
2:00 PM	Intro to breakout session on applications	Mike Stukel, Florida State University
2:05 PM	Breakout session on applications	
3:20 PM	Break	
3:50 PM	Report from day 2 breakout sessions	
4:20 PM	Final discussion and wrap-up	Co-chairs: Kyla Drushka and Mark Bourassa
5:00 PM	End of workshop	

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