The geometry, kinematics, and dynamics of the two-way coupling between wind, waves, and currents

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Fundamental and sometimes spectacular exchanges of mass, momentum, heat, and energy occur where the ocean and atmosphere meet. This region, known as the air-sea boundary layer, is of crucial importance for Earth's weather and climate. There, wind, waves, and currents interact in complicated and striking ways. Below is a review of these interactions through the lens of their geometry, kinematics, and dynamics, including an overview of what the community knows, admittedly from a wave-centric point of view, highlights of some important open questions, and a recommendation for future observational campaigns (for more comprehensive reviews see Melville 1996; Sullivan and McWilliams 2010; D'Asaro 2014).

Present observational capabilities

Although the oceanographic and climate communities now recognize that processes happening at the air-sea boundary layer are intrinsically coupled, observational, theoretical, and modeling efforts have traditionally focused on each of these processes independently. There is much that remains unknown about the contribution of the three-way coupling between winds, currents, and waves to the climate system (Villas Bôas et al. 2019). A schematic of this coupling is shown in Figure 1. These interactions are intrinsically multiscale, ranging from millimeters for spray and capillary waves to 100s of kilometers for mesoscale currents, which poses a challenge for observations.

At global scales, spaceborne scatterometers, altimeters, and radiometers have for decades provided a large-scale view of surface winds, sea surface height, and sea surface temperature. More recently, satellites using synthetic aperture radar (SAR) technology have not only increased the resolution of sea surface height measurements but have also made it possible to image the sea surface roughness and capture the signature of boundary-layer processes such as surface waves, submesoscale features, and wind streaks (Kudryavtsev et al. 2017; Wang et al. 2019; Yurovskaya et al. 2019). The launch of the Chinese-French Oceanography Satellite (CFOSAT) in 2018 marked the beginning of a new era for observations of air-sea interactions (Hauser et al. 2019), where for the first time it is possible to measure directional wave information and surface winds simultaneously at global scales. Nonetheless, there are still fundamental gaps in the present observing system that limit the understanding of boundary-layer processes. In particular,

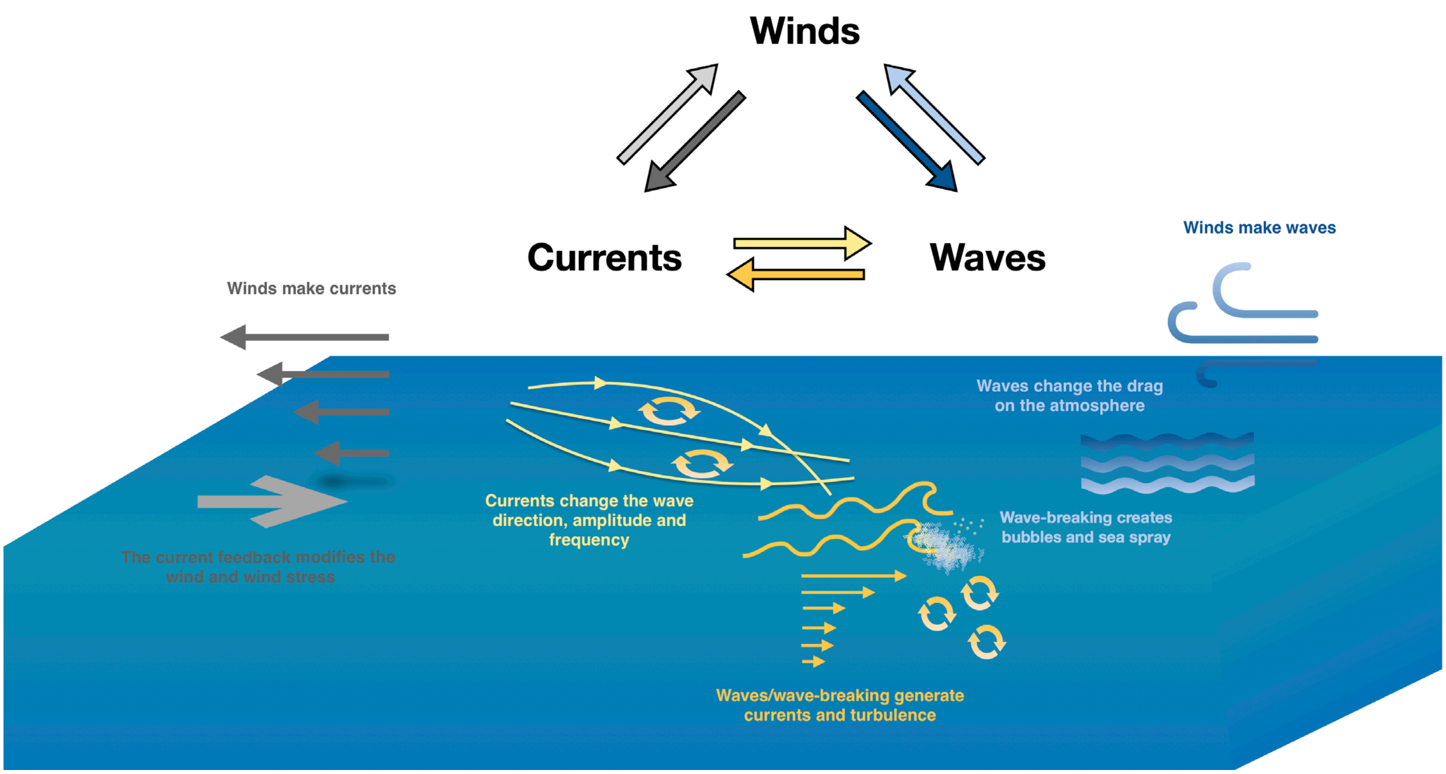

Figure 1. A schematic of the full two-way coupling between wind, waves, and currents considered in this paper. Examples of these interactions are indicated, with the color corresponding to the direction of interaction indicated by the prism

these phenomena are strongly coupled, so there is a need for simultaneous co-located observations of winds, currents, waves, temperature, and humidity over a broad range of scales and environmental conditions in order to test existing theories and refine (or redefine altogether) present model parameterizations.

Sea-surface geometry

One of the first things people notice when going out to sea, particularly if they have a sensitive stomach, is that the ocean surface is not flat. This has important implications for fluxes between the air and sea, which are by definition a function of the surface area separating the two fluids. For example, the transfer of carbon dioxide (CO2) and other gases between the atmosphere and ocean is greatly increased by the surface area of spray and bubbles created by wave breaking (Veron 2015; Deike et al. 2017b). Additionally, the geometry of the waves changes how momentum is fluxed from the wind to the water. That is, while it is somewhat intuitive that winds affect surface waves, waves can also affect the wind stress by modulating the sea surface roughness (Edson et al. 2013).

Waves are strongly affected by currents, which can modulate their frequency, direction, and amplitude (Phillips 1977). Thus, wave-current interactions play a fundamental role in the geometry of the sea surface. Although surface waves are often regarded as noise in most remote sensing measurements, the signature of currents on waves encodes important information that can be used to infer properties of the underlying current field. This is an idea that has been around for decades (e.g., Stewart and Joy 1974; Phillips 1984). However, despite the maturity of some of these theoretical ideas, there is currently no systematic way of using wave measurements to infer information about the currents. This inverse problem remains very much at the forefront of the field.

As new remote sensing technologies to measure ocean surface emerge, there is an increasing need to better understand and characterize the impact of waves on radar and lidar measurements. Jules Charney once remarked that the ocean surface does not really "look the same upside-down," which is due to the fact that ocean waves have pointier crests and flatter troughs (Laughton et al. 2010). This implies that for nadir altimeters more radar power is reflected back from the trough of waves than the crests, giving rise to the so-called electromagnetic (EM) bias (Fu and Glazman 1991; Melville et al. 1991). Theoretical models of this bias predict a linear relationship between the EM bias and the significant wave height. However, other characteristics of the sea state, such as the degree of wave development (wave age), the wind speed, and the direction of the waves, also contribute to the EM bias (Melville et al. 2004). Thus, as satellite altimeters evolve towards resolving finer spatial scales, precise knowledge of the wave field will be key to understanding how surface waves contribute to the error budget of sea surface height measurements.

In the context of the upcoming Surface Water and Ocean Topography mission (SWOT, Morrow et al. 2019), other errors related to the sea surface geometry will also be important. SWOT will be equipped with a wide swath SAR altimeter that will measure the sea surface height at an order of magnitude higher spatial resolution than present altimeters. Because the footprint of SWOT will be comparable to the wavelength of surface waves, non-linear effects can result from multiple points at the sea surface that are within the same radar range mapping into a single point, a phenomenon known as the surfboard effect (Peral et al. 2015).

Another aspect of surface waves that deserves particular attention is that the wave field is highly directional and anisotropic (Longuet-Higgins 1962; Lenain and Melville 2017; Romero 2019). Measurements from narrow-swath instruments effectively take a 1D slice through the 2D wave field which can alias wave energy onto lower wavenumbers and frequencies. Recently, Yu et al. (2020) investigated this effect on sea surface height measurements from the Ice, Cloud and land Elevation Satellite (ICESat-2) and emphasized the importance of directional wave information to interpret the sea surface height signal at scales shorter than the mesoscale. Many of the implications that waves have for remote sensing depend on details of the sea surface geometry that are more complex than what is captured by bulk low order parameters such as significant wave height.

What we do not know. Physically, there is still much to learn about the volume of air entrained due to wave breaking (see, for example, Brumer et al. 2017) and how this modulates gas transfer at the ocean surface. Additionally, modern research on wave generation by wind has moved away from drag law parameterizations and has instead focused on elucidating particular mechanisms of wave generation (Janssen 2004; Grare et al. 2013; Buckley and Veron 2016). However, there is still considerable uncertainty for momentum and gas transfer at the ocean surface, while the two-way coupling between wind and waves remains an open question. More practically, it remains unclear how the sea state (beyond the bulk parameters), and in particular wave breaking, affects the free surface geometry and how this modifies measurements from remote sensing instruments, such as radar and lidar.

Kinematics

Wave effects on currents. The particle trajectories of irrotational surface waves are not closed, but slightly open, leading to a net transport in the direction of wave propagation known as Stokes drift. This, together with wave breaking (Deike et al. 2017a; Pizzo et al. 2019), forms the wave-induced mass transport at the ocean surface. The current induced by waves can often exceed Ekman currents and is an important component of the total surface current velocity, which is essential for transporting jetsam, flotsam, plastics, pollutants, algae, and ice (van Sebille et al. 2020).

Current effects on waves. Surface waves not only generate currents but also interact with existing currents.

For slowly-varying currents, the kinematics of this interaction are well-known and can be described by geometrical optics. Perhaps the most intuitive effect that currents have on waves is through their Doppler shift in the wave dispersion relationship. In the presence of currents, the wave energy is no longer conserved due to the exchanges of energy between currents and waves. Instead, the wave action, the ratio between the wave energy and the intrinsic frequency of the waves, is conserved. Waves propagating over an opposing current will experience an increase in frequency, which leads to a corresponding increase in wave energy in order for action to be conserved (the opposite is true for co-flowing current and waves). This modulation of the wave frequency and wavenumber by currents shows up in radar and optical imagery as a deviation from the linear dispersion relationship, and it can be used to estimate current magnitude and direction. This technique has been applied to field and airborne measurements as well as sparse images from optical satellites (e.g., Sentinel-2), but the technology necessary to measure surface currents globally has yet to be implemented. A step in this direction was taken with the conceptualization of the ocean Surface TRansport, kinetic Energy, Air-sea fluxes and Mixing (STREAM) mission. However, there are no current plans to fly such a mission.

Figure 2. Photograph taken from an airplane off the coast of California showing an area of enhanced wave breaking in the upper right corner due to wave-current interaction. The horizontal length scale of the image is on the order of a kilometer. Photograph courtesy of Nick Statom, Scripps Institution of Oceanography.

In the same way that gradients in the water depth cause waves approaching the shore to change direction (refract), horizontal current gradients can change the wavenumber and direction of waves. These changes in wave direction ultimately result in convergences and divergences of wave action that can lead to spatial gradients in wave height, slope, and breaking statistics (Figure 2). Descriptions of the relationship between vertical vorticity and the curvature of individual ocean wave rays date back to Kenyon (1971). Yet, it is only recently that studies based on numerical modeling and remote sensing observations have shown that the spatial variability of the surface wave field at mesoscales is dominated by the spatial variability of currents. More specifically, theoretical (e.g., Villas Bôas and Young 2020), numerical (e.g., Romero et al. 2020; Villas Bôas et al. 2020; Marechal and Ardhuin 2021), and observational (Quilfen et al. 2018; Quilfen and Chapron 2019) studies focusing on swell-type waves have found that surface wave properties are most sensitive to current vorticity and that refraction is the main mechanism controlling the spatial variability of wave heights. Meanwhile, models suggest that short wind-waves (O(1) m), which are the main contributor to the mean square slope and sea surface roughness, may be more influenced by current divergence and strain (Rascle et al. 2014, 2016; Lenain and Pizzo 2021). Despite this compelling evidence for the strong effects of currents on waves across various scales, operational wave models are still routinely run without current forcing.

Current effects on winds. Surface currents modify work done by the winds on the ocean, as it is the relative velocity of the wind that enters the wind-work formulation, not its absolute value. The wind work is key for the kinetic energy (KE) budget of the ocean, having implications for near-inertial oscillations, mesoscale eddies, and the mean ocean circulation. Results based on coupled numerical models and remote sensing observations (Renault et al. 2017; Julien et al. 2020) have shown that this current feedback represents a sink of eddy KE (EKE) from the ocean to the atmosphere, acting as an "eddy-killer," and there are suggestions that the two-way coupling between ocean and atmosphere affects this EKE sink (Renault et al. 2016; Flexas et al. 2019). These results underline the importance of considering the relative wind in numerical models, including in wave models (Rapizo et al. 2018), and show a need for simultaneous measurements of ocean vector winds and total surface current in order to better constrain the ocean KE budget. Although we have decades of global ocean surface vector wind measurements, the currents used to compute the wind work are often geostrophic currents estimated from satellite altimetry, which cannot be estimated near the equator, are fairly limited in spatial resolution (100s of kilometers), and only account for part of the total surface current.

What we do not know. An important practical and physical problem for understanding the kinematics of these interactions involves the current shear profile. Information about the current's vertical structure would, for example, allow one to map surface measurements of the current to its behavior at depth. There is indication that wave measurements help better understand this inverse problem, but considerable practical barriers exist, including quantifying the uncertainty in the inversion process (Campana et al. 2017) and the interesting question of whether or not critical layers (i.e., areas of the flow with speeds equal to the phase velocity of a surface gravity wave) exist in the water for very short waves. Additionally, there are theoretical features of wave-current interaction that are only now being constrained, including their two-way coupling (Phillips 2002; McWilliams et al. 2004; McWilliams 2016; Suzuki 2019; Pizzo and Salmon 2021). In order to validate these problems, concurrent measurements of the wind, waves, and currents, and in particular, the current depth profiles, must be conducted – a primary aim of the NASA S-MODE Earth Venture Suborbital-3 (Farrar et al. 2020). There is excitement that a fleet of uncrewed platforms, together with state-of-the-art in-situ and airborne measurements of surface wind, currents, and waves, might be a first step in making progress on this important problem.

Dynamics

Heat is a form of energy and, together with CO_2, is among the most relevant variables to track in our warming planet. The ocean acts as a massive solar panel, absorbing around 90% of the heat imbalance in the Earth system. The ocean also takes up ~30% of the CO2 that is released in the atmosphere, through both the physical and the biological carbon pump (Sarmiento and Gruber 2006). The dynamical budget of heat and carbon is strongly mediated by fluxes that happen at the air-sea boundary layer and are controlled by processes that mix these properties from the upper ocean down to the ocean interior. Thus, processes that contribute to vertical transport and mixing are of crucial importance for Earth's climate.

Most of the energy that is transmitted to the wave field by the wind is locally converted into turbulent mixing and heat and sound generation, predominantly accomplished by wave breaking (Melville 1996). Some of this energy generates the so-called "wind-driven" currents. Wave breaking directly affects dissipation in the upper layer of the ocean (D'Asaro 2014). This is parameterized by an eddy viscosity, which implies that waves could affect larger-scale processes like Ekman flow. The direct effects of surface waves on larger-scale flow are still an open question, but there is theoretical (McWilliams and Restrepo 1999; Shrira and Almelah 2020) and numerical (Lewis and Belcher 2004; Sullivan et al. 2007; Sullivan and McWilliams 2010) evidence that surface waves can affect currents at much larger scale than the waves themselves.

Wave breaking also introduces vorticity into the ocean. This vorticity then interacts with the Stokes drift, generating Langmuir circulation and Langmuir turbulence, which mixes the upper ocean and deepens the mixed layer. Note, the vertical shear of the Stokes drift shows up in the turbulent kinetic energy budget, not the Stokes drift itself. This upper-ocean mixing sets the temperature difference between the air and sea – a crucial value for coupled air-sea models. However, numerical models represent unresolved processes that control vertical mixing through parametrization schemes that often do not explicitly take into account the effects of surface waves. Observed biases in the mixed-layer depth in a number of climate models (Verdy et al. 2014; Li et al. 2016) suggest that there could be processes relevant for turbulent mixing that have been ignored in most parameterizations of the mixed layer. Despite the obvious importance of these processes, the details of these phenomena remain poorly understood, as discussed below.

Finally, the characteristics of winds, waves, and currents vary strongly geographically and seasonally. Local changes in winds modulate the wave field, which may, in turn, affect mixed layer depths through enhanced mixing due to the Langmuir turbulence mentioned above. This can, for example, lead to deeper mixed layers and stronger submesoscale activity, whereas in the absence of wave-induced turbulence, shallower mixed-layers with strong stratification at their base may encourage internal wave generation and inhibit the vertical motions associated with (horizontally divergent) submesoscale currents. Hence, to better understand processes such as internal waves and submesoscale fronts, we must better constrain the impact of wave-driven mixing to upper ocean dynamics.

What we do not know. The so-called Craik-Leibovich (CL) equations governing Langmuir circulations/turbulence have not been validated against laboratory/field data in a meaningful way, leaving their applicability uncertain. In general, they are found to reduce the bias between modeled mixed-layer depths and observations, but the detailed comparisons between model output and observations from a controlled environment remain scarce. This is because there are only a very small number of observations of mixed layer deepening on the space and time scales necessary to resolve the genesis and evolution of the process (Smith 1992; Grare et al. 2021). Additionally, these limited observations exist for just a few environmental conditions. This represents a major gap in our knowledge, particularly as the CL equations are being more commonly employed in coupled air-sea boundary layer models of weather and climate.

A vision for future observations

Although the study of wind, waves, and currents is mature, there are still fundamental open questions regarding the two-way coupling between these complex phenomena. Researchers are optimistic that progress will be made to tackle these questions. First and foremost, it is currently the golden age of observational and computational oceanography. Existing, soon to be launched, and future satellite missions will provide unprecedented coverage of global winds, waves, and currents, despite the caveats discussed above. The *Earth system response to air-sea interactions* has been identified as a priority in the National Academy of Sciences Decadal Survey for Earth Science and Applications from Space. In response to that, mission concepts for satellites targeting the air-sea boundary layer have been developed and have the potential to be selected by NASA in the upcoming decade (e.g., Rodriguez et al. 2019; Gentemann et al. 2020). Crucially, the geometry, kinematics, and dynamics of wind, waves, and currents need to be *simultaneously* measured across a broad range of scales and environmental conditions for progress to be made.

Interactions between wind, waves, and currents play a major role in the exchange of momentum, heat, energy, and gases between the ocean and the atmosphere. To push the envelope of weather forecasting, climate predictions and projections, and designing of mitigation and adaptation strategies in response to climate change, requires understanding the physical processes that control air-sea exchanges in order to properly parametrize them in numerical models. Dedicated process studies in the fashion of the upcoming Submesocale Ocean Dynamics Experiment (S-MODE) will be pivotal to fostering the development of coupled atmosphere-wave-ocean models and to better constrain the parameter space for validation and development of new model parametrizations. The wealth of data that will become available in the upcoming decades will also provide a unique opportunity to explore physically constrained, data-driven solutions that can help to disentangle some of the complexities of these boundary layer processes. At the oceanographic and atmospheric community level, there is a need to entrain theoretical (Emanuel 2020), numerical, laboratory, and field scientists into the task. Central to this collaborative approach will be open-science based around open-source software, reproducibility, data availability, and transparent discussions of theoretical, numerical, and observational limitations (Wilkinson et al. 2016). Significant progress in Earth sciences will come from a cultural change that pushes the community in this direction. Finally, there is a need for a more diverse community in the Earth sciences field (Goldberg 2019). Hopefully current and future endeavors to understand wind, waves, and currents will place a high priority on building a broader community that reflects the population of the United States and the world to tackle these problems of global importance.

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