# WIND WAVES IN THE COUPLED CLIMATE SYSTEM

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Gravity wind-wave–driven processes at the ocean surface—including radiation fluxes and energy, mass, and momentum exchanges—play an important role in the coupled climate system.

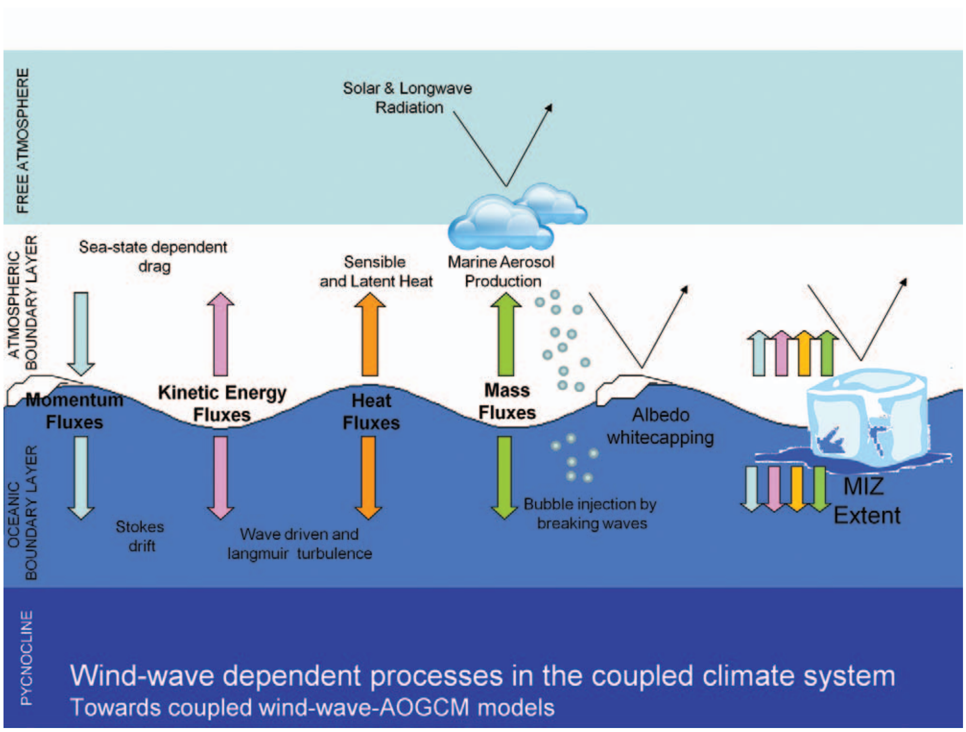


**FIG. 1. A schematic view of the influence of waves on air–sea exchanges.**

**WHERE THE INTERACTION BEGINS.** Erik Mollo-Christensen of Massachusetts Institute of Technology (MIT) and builder of one of the first air–sea interaction buoys used to tell his students: “Meteorologists consider the ocean as a wet surface. Oceanographers consider the atmosphere as a place where wind blows.” Of course things have changed since 1970, and the idea of an active interaction between the liquid and gaseous fluids that surround our planet has progressively tiptoed into the two respective fields. On the one hand, the meteorologists have acknowledged ▶

the role of the ocean as a strong absorber/provider of heat, gas, and physical quantities crucial for seasonal and longer forecasts. On the other hand, oceanographers now recognize multiple coupled interactions. Ocean modelers now say that the appropriate upper boundary condition for an ocean model is not restoring or having fixed fluxes—it is a full atmospheric model. Extending the range of interaction has benefited both communities.

In the 1980s, wave modelers were simply users of meteorological output products—in practice, surface wind fields. However, it was quickly realized that waves imply a feedback to the atmosphere, capable of directly affecting the evolution of weather systems. This led, at least in some institutions, to two-way coupling of wave and meteorological modeling, with information flowing in both directions. The modern view is that the atmosphere and ocean are continuously exchanging "information," this flux being actively modulated by the dynamics of the separation surface: waves. Observations demonstrate that waves influence the transfer of momentum, heat, and mass across the surface, affecting the fluids above and below. Quantifying the importance of these effects is relevant, and perhaps crucial, for the required climate modeling advances.

Climate models should include well-understood, ubiquitous processes with a level of complexity commensurate with their climate impact, our degree of understanding, and their predictability. With the current need to provide estimates of future climate, despite our wide and deep ignorance of many processes, the obvious solution has been to ignore or parameterize what is less than obvious or properly known. A little physics, logical intuition, measured data, and practical experience suggest parameterizations that lead to sensible results. However, we propose that the surface wave problem is significant, sufficiently understood, measured, and predictable enough to warrant a more detailed representation in climate models. The processes affected by wave motion include momentum and energy fluxes, the turbulence in the upper layers and the consequent vertical mixing, the fluxes of gases at the interface, the production of spray to be then diffused in the atmosphere, Earth albedo, and its influence on the overall radiation budget. The purpose of this paper is to give a qualitative description of the above processes and, wherever available, at least an order of magnitude of their role in climate. We conclude with suggestions for immediate progress.

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**WAVY PROCESSES.** We qualitatively describe what are potentially the most relevant processes at the interface between ocean and atmosphere (see Fig. 1). We will deal with surface wind waves, and their influence on fluxes of momentum and energy, heat, mass, and radiation. The influence on sea ice, as a modulator of all of these processes, is also raised. For each process we give a short description of the physics and the state of the art in its modeling, and discuss its potential role in the coupled climate system in general and the atmospheric and oceanic boundary layers in particular.

For the sake of clarity, we split the exposition into various subsections, each dealing with a dominant process (see Fig. 1). However, processes affect each other, so that there will be frequent connections between the different parts. To help explain the overall view, the highlights of the basic concepts that are to be discussed are listed at the beginning of each subsection.

*Wind causes surface gravity waves.*
Basic ideas:

- Wind generates waves.
- Wave breaking affects exchanges between sea and atmosphere.
- Traditional parameterizations using wind can be improved using wave information.

Wind blowing on a water surface generates waves. This daily observation is as old as humanity, but the mechanism of wave generation is not completely obvious. Wind blowing across a fully flat surface couples the two fluids by a thin viscous layer and leads to a two-fluid shear instability similar to the Kelvin–Helmholtz instability. The growing undulations steer the wind over the waves, resulting in differential surface pressures that increase the transfer of energy and momentum from wind to waves. Waves grow and evolve in height and length (hence speed and period), and are modulated via breaking and nonlinear interactions. Breaking, or whitecapping in the open ocean, is a key element of many of the processes discussed here. At all stages wave energy is distributed across a range of frequencies and directions (the wave spectrum). Although some details remain unknown, the generation of waves by wind is largely understood; see, among others, Janssen (1989, 1991, 2004).

Several processes across the air–sea interface depend on wave breaking—the surface extent of the whitecap, how long they persist on the surface, how many bubbles are formed and forced through the upper water, the spray in the air—are all important. Video and photographic techniques have been used to estimate the percentage of sea covered by whitecapping, most recently by Holthuijsen et al. (2012). Figures vary from less than 4% in mild storms to a slightly higher percentage at higher wind speeds (but streaks can be much more extended). The actual percentage depends on the duration of an active breaker (about one wave period), the depth of penetration (roughly one wave height), and the persistence of the bubble cloud. A promising technique using satellite microwave radar recently proposed by Anguelova and Webster (2006) is capable of providing, still with some difficulties, whitecap coverage day and night independently of the weather.

Even before the contribution of wave modelers, it was evident that many air–sea interactions depend on the wave conditions at the interface. The obvious solution was to parameterize waves on the basis of local wind or, even more, to relate the processes directly to local wind. While there is an obvious correlation between wind and waves at given time and position, their relationship is not unique. Rather, waves are also present where wind is not blowing, and for a given wind speed the local wave conditions vary by an order of magnitude (Hanley et al. 2010). While remarkable results have been achieved using wind-only dependent parameterizations, if a process depends on the wave conditions, then a better agreement can be found using the wave information (Fairall et al. 2011). In the absence of wave observations, a wave model may be used to supply the needed wave variables. Wave models are increasingly reliable, being just a few percent away from observations in some variables, while others (e.g., Stokes drift) are more difficult to estimate (Webb and Fox-Kemper 2011).

*Affecting momentum budget aloft.*
Basic ideas:

- Taking wave-induced drag into account leads to substantial modifications of the synoptic pressure and wind patterns in the Southern Ocean.
- This, in turn, affects the local estimates of heat and $CO_2$ fluxes across the surface.
- Swell implies an equatorward flux of atmospheric momentum from the storm belts.
- Swell also affects the local dynamics of the oceanic boundary layer.

The influence of drag due to the wavy surface and the transfer of energy and momentum from wind to waves have consequences on the atmospheric boundary layer. Together, these have the effect of an enhanced surface drag that leads to a reduction of the surface wind speed, which is greater in regions of growing (young) seas (see Janssen 1989, 1991). This interaction was first implemented operationally at the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, United Kingdom) in the mid-1990s, and is an early example of two-way coupling between atmospheric and wave models. In a way it marked the official acceptance of the wave modeling community into meteorology. ECMWF studies show that the sea-state-dependent momentum transfer impacts climate across the troposphere in both hemispheres. In the Southern Hemisphere, the wave influence weakens pressure minima and lowers surface wind speeds, and shifts the Southern Ocean storm track equatorward by 10°. As surface winds over the Southern Ocean, typically poorly represented in climate models, drive large components of the present and future ocean uptake of heat and $CO_2$, a wind bias in this region degrades GCM simulations of future climate. The recently updated sea surface roughness parameterizations in the Goddard Earth Observing System, version 5 (GEOS-5) GCM, effectively increasing surface friction over the ocean to more closely match recent observations, lead to significant improvements in the GCM from the surface to the stratosphere (Garfinkel et al. 2011).

The interaction between waves and the lowest atmospheric layers is stronger in an actively growing, especially young, sea, in practice in the storm belts. Here waves are steep, leading to a higher drag. Breaking in particular can enhance drag up to 30 times (Sullivan et al. 2004). On the contrary, in the tropical and extratropical zones, with the exception of cyclones and hurricanes, the sea is swell dominated. Swell, the long smooth waves propagating from distant storms, has a double effect. On one hand, albeit limited, there is a transfer of momentum from waves to the atmosphere, leading to the so-called swell wind (e.g., Hanley et al. 2010). The net result is a transfer of atmospheric momentum from the storm belts toward the tropics. On the other hand, swell has implications for the dynamics of the oceanic boundary layer (McWilliams and Restrepo 1999; more on this in the next subsection). Given that swell is independent of the local wind conditions, its effects cannot be predicted with parameterizations based on local wind.

*Wave-induced currents.*
Basic ideas:

- The so-called wind-driven currents are mainly driven by wave breaking.
- Another important source of currents is the Stokes drift.

The classical turn of phrase "wind-driven currents" expresses the wrong conceptual approach to the problem. While it is true that surface wind stress leads to some current (we have seen above this to be the trigger of wind-wave generation), most of the wind energy and momentum are transferred to waves, and are then indirectly passed to the ocean, predominantly by whitecapping, possibly at a different location. Energy is transferred mostly to turbulence that mixes the surface ocean stratification (see the next subsection), and momentum is transferred to current. The traditional wind-to-current momentum transfer often works satisfactorily because about 90% of the wind momentum input to waves is immediately passed to the ocean—only the remainder is spent on wave growth. Indeed, if the wind and waves were always in equilibrium, with consequently constant wave conditions, then it would be entirely acceptable to overlook waves in this transfer of energy and momentum. However, this is hardly the case, and input by wind and loss by breaking are two well-defined different quantities. Sullivan et al. (2004) demonstrate this transfer in a field of randomly distributed modeled breakers. With active breakers covering only 1.6% of the area, a full working system of currents arises without any direct momentum input from wind to currents.

Waves induce currents also via the Stokes drift. Although rapidly attenuated with depth, McWilliams and Restrepo (1999) show that the global circulation based on Stokes drift rivals that of the wind-driven Ekman current in the surface ocean. A full calculation of the Stokes drift requires knowledge of the directional wave spectrum; information is available from wave modeling but not from satellite or most of the many, but still relatively few, scattered buoys. Webb and Fox-Kemper (2011) find the relation between wave spectral moments and the derived Stokes drift based on a number of empirical spectral shapes and wave models. Thereby, the significant errors involved in inferring the Stokes drift from typical wave data can be comparatively assessed. Errors can be greatly reduced by saving the third frequency moment of the spectrum when measuring waves and forgoing the assumption that waves and winds are equilibrated.

*Wave-induced mixing in the upper ocean layers.*
Basic ideas:

- Wave breaking injects turbulence in the upper layers of the ocean.
- Wave orbital motion induces turbulence (still debated).
- Wave-induced Langmuir circulation leads to a vigorous mixing of the oceanic boundary layer.

Wind waves are a primary source of turbulent energy into the surface ocean, and thereby aid in mixing heat, mass, and other tracers throughout the boundary layer. Three wave-related mechanisms are noted (Babanin et al. 2009): the injection of turbulence in the course of wave breaking, the direct generation of turbulence due to the spatial gradients of the wave orbital velocity, and the vertical circulation of the mixed layer turbulence within Langmuir cells. We will briefly discuss them in sequence.

Injection of turbulence. While the momentum lost by waves with whitecapping goes into ocean currents (see the previous subsection), the corresponding lost energy is injected as turbulence into the upper ocean. Indeed, the whitecapping imbues a vigorous mixing of the surface layers, with up- and downwelling patterns. The kinetic energy anomaly associated with the single breaker asymptotically approaches an inverse proportionality with time, and the mechanism leads to the spawning of a vortex beneath the breaker. The localized energy anomaly of the vortex has been tracked in models and laboratory experiments for over 50 wave periods.

Orbital velocities. Babanin (2006) proposed that the velocity spatial gradients associated with wave orbital motion could induce a substantial mixing in the affected ocean layer (depth about half a wavelength). The evidence derived from the experiments is hardly reproducible in the oceans, and there is still a debate in the community about the physical basis of the approach. If definitely proven to be true, the implications would be relevant. Parameterized into a global circulation model on the base of wave model information (Shu et al. 2011; Song et al. 2012), the turbulence thought to emanate from orbital velocities leads to a substantial deepening of the ocean mixed layer with a strong reduction of a long-standing climate model bias.

LANGMUIR CIRCULATION. Probably one of the most prominent effects of waves on the circulation of the oceans is the setup of Langmuir circulation (Langmuir 1938) and their disordered form, Langmuir turbulence (McWilliams et al. 1997; Sullivan and McWilliams 2010). Langmuir cells may arise from the Craik–Leibovich (1976) mechanism CL2, which is a form of shear instability that draws energy from both the Stokes drift shear and the mean (Eulerian) shear from the wind and whitecaps. Langmuir cells, typically between 10 and 100 times longer than wide and deep, often have a profound effect on the energy in boundary layer turbulence (D'Asaro 2001). While the cells are sometimes limited to the upper layers, a change in wind may rapidly lead to downwelling jets beneath the Langmuir cell convergence locations (windrows). These jets are limited horizontally but deeply penetrate through the boundary layer to entrain water from the pycnocline below.

The importance of full knowledge of the wave spectrum for Langmuir evaluation has been stressed by Harcourt and D'Asaro (2008) and Van Roekel et al. (2011). They pointed out that a realistic wave spectrum is required to get the correct Stokes drift shear, and thus the energy source for Langmuir turbulence. Even more, if wind and waves are not aligned, then Langmuir cells extend along an intermediate direction with an asymmetric structure of the upcoming and downgoing flow, and a degree of mixing of the oceanic boundary layer that depends on the projection of waves and wind stress into that intermediate direction (Van Roekel et al. 2011).

Babanin et al. (2009) investigated the influence of each of the wave-induced upper-ocean mixing processes within a climate model of intermediate complexity (using wind-based parameterizations) and concluded with notable changes in the consequent climate. Webb et al. (2010) have provided a worldwide climatology of the Langmuir circulation consistent with simulations using the National Oceanic and Atmospheric Administration (NOAA)'s WaveWatch III model, the 40-yr ECMWF Re-Analysis (ERA-40), and satellite altimetry. Initial tests of Langmuir mixing sensitivity based on parameterization by McWilliams and Sullivan (2000) and Li and Garrett (1997) show the potential for much improved results, particularly by deepening the too shallow mixed layer in the Southern Ocean (Belcher et al. 2012).

*Heat fluxes.*
Basic ideas:

- A wavy surface is larger than a flat one—this enhances the heat exchange between ocean and atmosphere.
- The presence of spray and bubbles in a breaker increases enormously the surface of contact.
- Latent heat exchange is greatly enhanced by the evaporation of water droplets in the air.

Latent and sensible heat fluxes are crucial links between ocean and atmosphere for long-term meteorological forecasting and climate modeling. While often parameterized on the basis of wind speed and air–sea temperature difference, their detailed physics is much more complicated.

The wave water surface per unit area is greater than that of a flat surface. As fluxes (of heat or mass) are a function of the extent of the interface between atmosphere and ocean, an obvious implication is a wave-modulated flux across the sea surface, particularly in the case of wavelets, droplets, and bubbles. The discussed wave-induced turbulence of the upper-ocean layers leads to a continuous renewal of the contact layer at the surface. This, in turn, implies a steady supply of warmer or colder (whichever the case) water with a continuous enhancement of the transmission. With warmer water this may imply a surface cooling of several tenths of a degree. Direct measurements by Veron et al. (2008, 2011) in the open ocean (no whitecapping) have provided an estimate of the wave-modulated flux up to 15% of the total one, rivaling the perturbation of longwave radiation flux attributed to greenhouse gases. A similar estimate has been reached by Sullivan and McWilliams (2002).

The observations and scalings above rely on a relatively calm surface, with surface undulations not roughened to breaking or by wind. If breaking occurs, then things change completely. We will talk more about bubbles and spray in the next subsection. Whitecapping is white because of the surface foam and the cloud of submerged air bubbles that follow the breaking. Both spray and bubbles imply a tremendous increase of the contact surface between air and water. On heavy sea conditions, the surface begins to lose its physical significance as the two means, air and water, begin to mix. In extreme conditions, for example, hurricanes, a surface can hardly be identified. Even in more common conditions, given the obvious turbulence in both air and water, the heat flux is increased possibly one or more orders of magnitude. This is true particularly with the spray because of the quick transfer of latent heat. At its release a water droplet has the water temperature. It rapidly cools by evaporation and latent heat release to the vapor, reducing the droplet radius to half of its original size. The latent heat release cools down both the droplet and the surrounding air with a frequent enhancement of the air-to-sea temperature difference. Full evaporation of the droplet water further reduces its radius to one-quarter of the original one.

The overall transfer is parameterized in the Coupled Ocean–Atmosphere Response Experiment, version 3.0 (COARE3.0) algorithm that in more recent papers is based on a sea roughness expression dependent on wind speed and wave age (Fairall et al. 2011). However, the complexities of breaking and roughness of a full wave spectrum cannot be captured with so few parameters. The uncertainty of the results is estimated at about 20%, with more problems in the low and high wind speed range. It is obvious that more physical and accurate estimates based on specific wave situations are badly needed.

*Mass flux.*

Basic ideas:

- A wavy surface is larger than a flat one.
- Wave-induced turbulence, bubbles, and spray strongly increase (by orders of magnitude) the contact surface, hence the possibility and intensity of gas exchange.
- Spray derives from bubble bursting and wave crest tearing by wind.
- Aerosol forms the base for cloud condensation nuclei and partly reflects incoming solar radiation.
- Overall sea-spray aerosol production is still uncertain within two orders of magnitude.

GAS. The ocean is a vastly larger sink of carbon than the atmosphere, containing roughly 50 times as much carbon. The carbon exchange between atmosphere and ocean is nearly 15 times as much as the carbon emitted by fossil fuel burning. Much of the carbon arrives in the ocean as dissolved carbon dioxide gas, fueling an acid–base reaction chain to form carbonate and bicarbonate ions as well as supplying carbon for biology. Accurate modeling of the air–sea carbon exchange is a crucial part of global climate modeling.

The exchange of gas at the air–sea interface is controlled by a 20–200-$\mu$m boundary layer (see, e.g., Jähne and Hauβecker 1998), where the transmission is mainly molecular. In this layer the transfer of gas is 1,000 times slower than for the transmission of momentum. Upward from this layer, the transmission is dominated by turbulence, which is typically considered to be driven by wind, and gas transfer velocities are parameterized in terms of wind speed. However, there is not a unique relationship between gas transfer and wind speed due to a number of effects, including a dependence on sea state (Woolf 2005).

As for heat transfer, the increased surface of contact due to (nonbreaking) waves and the turbulence-induced steady supply of nonequilibrium layers at the surface imply an increased transfer of gas. Note that the various characteristics of the various gases, including their possible solubility in water, imply different consequences from the wave motion. So, $CO_2$ transfer may increase up to fivefold due to waves, while other gases differ.

Two distinct mechanisms of gas transfer are associated with large-scale wave breaking and air entrainment (Woolf 2005). The first is associated with plumes of turbulence in the upper layer generated by breaking waves that mix the gas deeper into the water column. Breaking renews the air–sea interface, which was contaminated by surface active impurities, and results in a rapid increase in gas transfer. The second is transfer mediated by bubbles, where gas is captured in a bubble during a particular interval of its exchange between atmosphere and ocean. These processes enhance the rate of transfer one order of magnitude or more. Lamarre and Melville (1991) estimated that between 30% and 50% of the dissipated wave energy by whitecapping is converted in bubble cloud buoyancy potential energy. Tkalich and Chan (2002) estimated that the bubble radii are distributed as $r^{-2.5}$ for $r < 1$ mm and $r^{-4.5}$ for larger ones. The peak of the size spectra is usually at 30–50 $\mu$m, with a substantial variability depending on wind and wave conditions. The dependence of gas transfer on wave conditions has been clearly proved with the wave tank experiments by Ocampo-Torres et al. (1994) and Ocampo-Torres and Donelan (1995), showing, among other things, that in these conditions the mass transfer of water vapor is two orders of magnitude faster than for $CO_2$. Certainly, there is also a role in gas exchange for sea spray.

As a result of the wave dependence, several authors have suggested new parameterizations of the gas transfer velocity that consider wave state (or surface roughness measured by altimeter-derived mean-square slope estimates). The COARE3.0 algorithm, recently extended to the gas-specific version COARE3.1 (Fairall et al. 2011), provides a reasonable estimate of the single gas transfers. The formulas depend on several parameters, including wave age and wave slope, implicitly a proxy for whitecapping. Algorithm performance varies over an ample range, so future improvement is likely.

Application of these updated parameterizations have so far shown little change in globally averaged transfer velocities, but global and regional fluxes have differed by up to 100%. While dedicated ground-truth data are lacking, consequent higher gas transfer velocities in storm belt regions (Southern Ocean and North Atlantic) demonstrate that bubble-mediated gas transfer is likely to play a major part in some of the main global sink regions for $CO_2$ (Fangohr and Woolf 2007).

Sea spray. Spray is the natural consequence of the breaking of a wave crest. Tiny droplets of water are thrown in the air and carried away by wind. Some of these particles are so tiny (aerosols) that they can remain in the air for a very long time, forming condensation nuclei for clouds and affecting incoming solar radiation.

Two main sources of spray exist. The most common source is the bursting at the sea surface of the air bubbles entrained in water after breaking. Bubbles vary in size, which controls the way they burst. Each burst ejects into the atmosphere a very large number, $O(10^3)$, of droplets of water, each one with its load of water, salt, gas, and heat. Its lifetime depends on chance and size. The second source, not always present and of growing importance with growing wind speed, is the tearing of the wave crests by wind with the production of foam both in the air and on the sea surface. These droplets are usually larger than the ones from bubble bursting.

Of the overall droplets flying in the air, the largest ones fall quickly back to the water; the intermediate ones are carried ahead, strongly accelerated by wind, with some of them hitting the back face of the previous wave and increasing air–sea momentum transfer. A large component of the smallest droplets stays in the air.

Soon after its release, quick evaporation and latent heat release reduce the droplets to one-quarter of its original size, leaving a tiny salt particle that becomes part of the atmosphere as sea salt aerosol (SSA). De Leeuw et al. (2011) point out that there may be a substantial amount of organic material in the spray, with this too becoming part of aerosol. For this reason they suggest a different reading of SSA as sea spray aerosol.

Aerosols have different implications. Besides being the base for cloud condensation nuclei, they scatter electromagnetic radiation and reflect incoming solar radiation. Aerosol cooling action has been estimated at 0.08–6.0 W $m^{-2}$ (Lewis and Schwartz 2004), which is both large and uncertain when compared to the longwave radiation perturbation due to greenhouse gases, including water vapor (roughly 1.5 W $m^{-2}$).

There is strong uncertainty about the actual global production of sea-spray aerosols. The present estimates (see de Leeuw et al. 2011) span two orders of magnitude, between 0.02 and $1 \times 10^{14}$ kg $yr^{-1}$, of whose small range (<1 $\mu$m), 20% or more, is expected to be organic matter. As breaking waves are especially abundant in the surf zone, Monahan (1995) speculated that many more sea-spray aerosols per unit area and time would be generated over the surf zone than in the open ocean, and these have been observed to be transported over tens of kilometers. The uncertainty in global production derives from both limited knowledge of the physics of the processes involved and of the estimate of the forcing function. Until recently, the parameterization of spray production has been based solely on wind speed. Clearly, wave modeling, in particular whitecapping and wave energy dissipation in the surf zone, may improve these estimates. Some new recent parameterizations take into account the energy lost by whitecapping and the expected height of the crest (e.g., in the climate model of the Canadian Community; see Gong et al. 2002). The first results indicate a deepening of the atmospheric lows and higher wind speeds. Independently of being quantitatively exact, the role of spray in the general climate is potentially very large.

*Albedo.*
Basic ideas:

- The sea surface has a low albedo, and it absorbs much of the incoming radiation.
- A stormy sea may double the surface albedo.
- The overall effect is comparable to the effect of some greenhouse gases.
- It is also 3 times the radiation forcing of contrails and cirri.

Much of the direct and diffuse solar shortwave electromagnetic radiation that reaches the sea surface penetrates the ocean, differentially heating the surface ocean boundary layer that is continually remixed by turbulent mixing. This radiation is absorbed because of the ocean's generally low albedo. However, oceanic whitecaps have the potential to influence the albedo of the ocean–atmosphere system, and therefore the absorption in the ocean and its radiation balance (Gordon and Jacobs 1977). For total reflecting whitecaps, a wind speed increase from 6 to 14 m $s^{-1}$ was demonstrated to double the planetary albedo. Global average solar heating of the ocean is 168 W $m^{-2}$. The direct, globally averaged radiative forcing due to whitecaps is estimated to lie in the range of 0–0.14 W $m^{-2}$, with a most likely value of 0.03 W $m^{-2}$ (Frouin et al. 2001). While small, this value is not negligible when compared with the direct forcing estimates for some greenhouse gases and anthropogenic aerosols (0.03 W $m^{-2}$ is approximately 20% of the annual mean radiative forcing of nitrous oxide; 30%–50% of the values for hydrocarbons; and 8%, 15%, and 30% of the values for sulfate, biomass burning, and soot aerosols, respectively; see Frouin et al. 2001). It is also approximately 3 times the radiative forcing of contrail and cirrus effects caused by global subsonic aircraft operations (Forster et al. 2007). Frouin et al. (2001) used these arguments to suggest that whitecap effects should be taken into account explicitly in global climate models because of the potential feedbacks in the coupled climate system.

However, albedo is not only a function of sea surface color but also of radiation incidence angle. Janssen et al. (1996) consider how the geometry of the sea surface, in particular when rough on both large (waves) and small (ripples) scales, affects the sea surface albedo. They suggest that a rough sea tends to decrease the albedo, with only partial compensation by whitecapping. The overall effect seems to vary from area to area by wave conditions and solar azimuth. The most sensitive area is the most northern part of the Northern Hemisphere, where a rough surface and breaking waves are often present. On average differences up to 10–15 W $m^{-2}$ were found, which Janssen et al. (1996) point out as corresponding to about 50% of the local total net heat flux. An update of these results with modern wave and meteorological models and resolutions is highly recommended. Indeed, they are expected to become part of the present ECMWF operational model soon, but a direct quantification of their role would possibly convey some useful information for climate models, especially those without explicit wave model components.

*Sea ice.*

Basic ideas:

- Waves affect the ice cover extent by fracturing its borders and opening leads in the ice extent.
- This increases the heat exchange, further warming the polar air.

Sea ice, although constrained to the polar regions, is an important component of the climate system. Sea ice has a high albedo and acts as an insulator between the atmosphere and ocean. Both effects tend to cool polar temperatures, and since ice forms in cool temperatures these effects constitute important positive feedbacks on the climate. The marginal ice zone (MIZ) is the boundary between the open ocean and ice-covered seas, where sea ice is significantly influenced by wave activity. Waves are responsible for breaking up ice floes (Dumont et al. 2011; Squire 2007), and for determining the spatial extent of the MIZ and floe size distribution. When the ice is highly fragmented, openings in the sea ice, or leads, form within the MIZ. Leads reduce albedo and increase incoming solar radiation. They increase air–sea heat exchange and therefore further warm the polar air. Finally, if convective-, wind-, and wave-driven mixing in the leads is strong, then the oceanic boundary layer is deepened into the halocline, further increasing the melting of ice, warming of air, and the heat capacity of the boundary layer. All of these effects can accelerate summertime sea ice melting. However, ice formation during winter may also be enhanced by leads, creating interstices where ocean heat is lost and new ice can form. Overall, wave impacts on sea ice and polar climate are expected to be thermodynamically significant and may also affect the oceanic meridional overturning circulation. Common windrow-like features in MIZ shuga ice may indicate a role for Langmuir cells as well. Note that the action of waves on ice implies their progressive attenuation while they propagate into the ice-covered sea areas. Waves' effect on ice is felt until inner distances of the order of $10^2$ km.

**CONCLUSIONS AND RECOMMENDATIONS.** The Earth climate system contains a vast range of processes and feedbacks, so it is natural to focus first on the dominant ones, for example, those dominating planetary heat and carbon budgets. However, these basic processes have been modeled with increasing accuracy since the days of Arrhenius (1896a,b). Nowadays, we seek to improve representation and quantify the uncertainty of many more processes. Quite often dominant processes modulate the subdominant, and vice versa, with a whole cascade of reciprocal actions and feedbacks. This last point, feedback, is where difficulties arise, particularly if it occurs within interactions spanning multiple scales. Then practical difficulties of measuring the relevant interactions or the excessive computer power required for simulation limit our development of theoretical and quantitative assessment of how important these feedbacks may be. In this situation, we take a shortcut and use a parameterization that summarizes one, or several, processes into a simplified algorithm. Progress, bias analysis, and experience tell us how much further we need to go to have more accurate and reliable results.

Today it is obvious that the atmosphere and ocean are heavily interacting—enormous quantities of heat, energy, water vapor, and carbon dioxide are exchanged each instant through their boundary layers. After the overall radiation balance, these exchange processes are the next priority in providing predictions of the climate system from seasons to centuries. The role of these exchanges is clear, in that the heat capacity of only a few meters of the ocean equals that of the whole atmosphere, and the carbon reservoir of the ocean dwarfs all but the lithosphere. However, having in mind the scale of the planet, it is natural to look at the problem on a large scale. Waves are small in comparison, a tiny distributed detail. However, it is a beautiful example of the little process modulating the overall large-scale behavior.

Granted that some of the small-scale processes do affect the large-scale ones, the question is how much they affect the climate. One point of view is that the climate is established by the overall budget of incoming and outgoing radiation. Even if this is the case, two aspects need to be pointed out. First, the distribution of temperature and other parameters will vary based on small-scale processes rather than overall balances, and such distributions and their variations are relevant to humans even if they only slightly affect the global energy balance. Second, as climate is progressively changing through natural and anthropogenic changes, we live in a permanent transient situation. Only application of our best physical principles, rather than empirical parameterizations, can be robust in the face of a changing climate.

Science has been slow to appreciate the extent of the interaction between ocean and the atmosphere. It took even longer to understand how these exchanges are modulated by the characteristics of the surface that separates the two phases. Here, we have tried to emphasize how sea state, particularly during wave-breaking conditions and when waves are not equilibrated with the wind, strongly modulates many of the processes that have a direct influence on climate. We still do not grasp the whole physics nor an accurate measure of the degree to which the mean state and climate feedbacks are affected by these modulations, but having an idea of where we want to go is certainly a good start. Many groups worldwide are attempting to quantify these effects of waves on climate in observations, models, and theory, and we celebrate their accomplishments and look forward to their discoveries. We need to carry on, understanding more and more the physics of the thin layer of fluid that, in the immensity of space, surrounds the planet that is our home.

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## REFERENCES

Anguelova, M. D., and F. Webster, 2006: Whitecap coverage from satellite measurements: A first step toward modeling the variability of oceanic whitecaps. *J. Geophys. Res.,* **111,** C03017, doi:10.1029/2005JC003158.

Arrhenius, S., 1896a: On the influence of carbonic acid in the air upon the temperature of the ground. *London Edinburgh Dublin Philos. Mag. J. Sci.,* **41,** 237–275.

——, 1896b: Ueber den Einfluss des Atmosphärischen Kohlensäurengehalts auf die Temperatur der Erdoberfläche. *Proceedings of the Royal Swedish Academy of Science,* Vol. 22, I N. 1, 1–101.

Babanin, A. V., 2006: On a wave-induced turbulence and a wave-mixed upper ocean layer. *Geophys. Res. Lett.,* **33,** L20605, doi:10.1029/2006GL027308.

——, A. Ganopolski, and W. R. C. Phillips, 2009: Wave-induced upper-ocean mixing in a climate model of intermediate complexity. *Ocean Modell.,* **29,** 189–197.

Belcher, S. E., A. A. L. M. Grant, K. E. Hanley, B. Fox-Kemper, L. Van Roekel, P. P. Sullivan, W. G. Large, A. Brown, A. Hines, D. Calvert, A. Rutgersson, H. Petterson, J. Bidlot, P. A. E. M. Janssen, and J. A.

Polton, 2012: A global perspective on Langmuir turbulence in the ocean surface boundary layer. *Geophys. Res. Lett.,* in press.

Craik, A. D. D., and S. Leibovich, 1976: A rational model for Langmuir circulation. *J. Fluid Mech.,* **73,** 401–426.

D'Asaro, E., 2001: Turbulent vertical kinetic energy in the ocean mixed layer. *J. Phys. Oceanogr.,* **31,** 3530–3537.

de Leeuw, G., E. L Andreas, M. D. Anguelova, C. W. Fairall, E. R. Lewis, C. O'Dowd, M. Schulz, and S. S. Schwartz, 2011: Production flux of sea spray aerosol. *Rev. Geophys.,* **49,** RG2001, doi:10.1029/2010RG000349.

Dumont, D., A. Kohout, and L. Bertino, 2011: A wave-based model for the marginal ice zone including a floe breaking parameterization. *J. Geophys. Res.,* **116,** C04001, doi:10.1029/2010JC006682.

Fairall, C. W., and Coauthors, 2011: Implementation of the coupled ocean-atmosphere response experiment flux algorithm with $CO_2$, dimethyl sulfide, and $O_3$. *J. Geophys. Res.,* **116**, C00F09, doi:10.1029/2010JC006884.

Fangohr, S., and D. K. Woolf, 2007: Application of new parameterizations of gas transfer velocity and their impact on regional and global marine $CO_2$ budgets. *J. Mar. Syst.,* **66,** 195–203.

Forster, P. M., and Coauthors, 2007: Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007: The Physical Science Basis,* S. Solomon et al., Eds., Cambridge University Press, 129–234.

Frouin, R., S. F. Iacobellis, and P.-Y. Deschamps, 2001: Influence of oceanic whitecaps on the global radiation budget. *Geophys. Res. Lett.,* **28,** 1523–1526.

Garfinkel, C. I., A. M. Molod, L. D. Oman, and I.-S. Song, 2011: Improvement of the GEOS-5 AGCM upon updating the air-sea roughness parameterization. *Geophys. Res. Lett.,* **38,** L18702, doi:10.1029/2011GL048802.

Gong, S. L., L. A. Barrie, and M. Lazare, 2002: Canadian aerosol module (CAM): A size-segregated simulation of atmospheric aerosol processes for climate and air quality models 2. Global sea-salt aerosol and its budgets. *J. Geophys. Res.,* **107,** 4779, doi:10.1029/2001JD002004.

Gordon, H. R., and M. M. Jacobs, 1977: Albedo of the ocean-atmosphere system: Influence of sea foam. *Appl. Opt.,* **16,** 2257–2260.

Hanley, K. E., S. E. Belcher, and P. P. Sullivan, 2010: A global climatology of wind-wave interaction. *J. Phys. Oceanogr.,* **40,** 1263–1282.

Harcourt, R. R., and E. A. D'Asaro, 2008: Large-eddy simulation of Langmuir turbulence in pure wind seas. *J. Phys. Oceanogr.,* **38,** 1542–1562.

Holthuijsen, L.H., M.D.Powell, and J.D.Pietrzak, 2012: Wind and waves in extreme hurricanes. *J. Geophys. Res.,* in press, doi:10.1029/2012JC007983.

Jähne, B., and H. Hauβecker, 1998: Air-water gas exchange. *Annu. Rev. Fluid Mech.,* **30,** 443–468.

Janssen, P. A. E. M., 1989: Wave-induced stress and the drag of air flow over sea waves. *J. Phys. Oceanogr.,* **19,** 745–754.

——, 1991: Quasi-linear theory of wind-wave generation applied to wave forecasting. *J. Phys. Oceanogr.,* **21,** 1631–1642.

——, 2004: *The Interaction of Ocean Waves and Wind.* Cambridge University Press, 300 pp.

——, B. Becker, and J.-J, Morcrette, 1996: Note on the sea-state dependence of the ocean surface albedo. ECMWF Tech. Memo. 228, 22 pp.

Lamarre, E., and W. K. Melville, 1991: Air entrainment and dissipation in breaking waves. *Nature,* **351,** 469–472.

Langmuir, I., 1938: Surface motion of water induced by wind. *Science,* **38,** 119–123.

Lewis, E. R., and S. E. Schwartz, 2004: *Sea Salt Aerosol Production: Mechanisms, Methods, Measurements and Models—A Critical Review. Geophys. Monogr.,* Vol. 152, Amer. Geophys. Union, 413 pp.

Li, M., and C. Garrett, 1997: Mixed layer deepening due to Langmuir circulation. *J. Phys. Oceanogr.,* **27,** 121–132.

McWilliams, J. C., and J. M. Restrepo, 1999: The wave-driven ocean circulation. *J. Phys. Oceanogr.,* **29,** 2523–2540.

——, and P. P. Sullivan, 2000: Vertical mixing by Langmuir circulations. *Spill Sci. Technol. Bull.,* **6,** 225–237.

——, ——, and C.-H. Moeng, 1997: Langmuir turbulence in the ocean. *J. Fluid Mech.,* **334,** 1–30.

Monahan, E. C., 1995: Coastal Aerosol Workshop Proceedings. Naval Research Laboratory Rep. NRL/MR/7542-95-7219, 138 pp.

Ocampo-Torres, F. J., and M. A. Donelan, 1995: On the influence of fetch and the wave field on the $CO_2$ transfer process: Laboratory measurements. *Air-Water Gas Transfer,* B. Jähne and E. Monahan, Eds., AEON Verlag, 543–552.

——, ——, N. Merzi, and F. Jia, 1994: Laboratory measurements of mass transfer of carbon dioxide and water vapour for smooth and rough flow conditions. *Tellus,* **46B,** 16–32.

Shu, Q., F. Qiao, Z. Song, C. Xia, and Y. Yang, 2011: Improvement of MOM4 by including surface wave-induced vertical mixing. *Ocean Modell.,* **40,** 42–51.

Song, Z., F. Qiao, and Y. Song, 2012: Response of the equatorial basin-wide SST to non-breaking surface wave-induced mixing in a climate model: An amendment to tropical bias. *J. Geophys. Res.,* **117,** C00J26, doi:10.1029/2012JC007931.

Squire, V. A., 2007: Of ocean waves and sea ice revisited. *Cold Reg. Sci. Technol.,* **49,** 110–133.

Sullivan, P. P., and J. C. McWilliams, 2002: Turbulent flow over water waves in the presence of stratification. *Phys. Fluids,* **14,** 1182–1195.

——, and ——, 2010: Dynamics of winds and currents coupled to surface waves. *Annu. Rev. Fluid Mech.,* **42,** 19–42.

——, ——, and W. K. Melville, 2004: The oceanic boundary layer driven by wave breaking with stochastic variability. Part 1. Direct numerical simulations. *J. Fluid Mech.,* **507,** 143–174.

Tkalich, P., and E. S. Chan, 2002: Breaking wind waves as a source of ambient noise. *J. Acoust. Soc. Amer.,* **112,** 456–463.

Van Roekel, L. P., B. Fox-Kemper, P. P. Sullivan, P. E. Hamlington, and S. R. Haney, 2011: The form and orientation of Langmuir cells for misaligned winds and waves. *J. Geophys. Res.,* **117,** C05001, doi:10.1029/2011JC007516.

Veron, F., W. K. Melville, and L. Lenain, 2008: Wave-coherent air–sea heat flux. *J. Phys. Oceanogr.,* **38,** 788–802.

——, ——, and ——, 2011: The effects of small-scale turbulence on air–sea heat flux. *J. Phys. Oceanogr.,* **41,** 205–220.

Webb, A., and B. Fox-Kemper, 2011: Wave spectral moments and Stokes drift estimation. *Ocean Modell.,* **40,** 273–288.

——, ——, W. G. Large, and S. Peacock, 2010: Demonstrated sensitivity to Langmuir mixing in a global climate model (CCSM). *Eos, Trans. Amer. Geophys. Union,* **91** (Ocean Sci. Meeting Suppl.), Abstract PO31B-04.

Woolf, D. K., 2005: Parameterization of gas transfer velocities and sea state dependent wave breaking. *Tellus,* **57B,** 87–94.