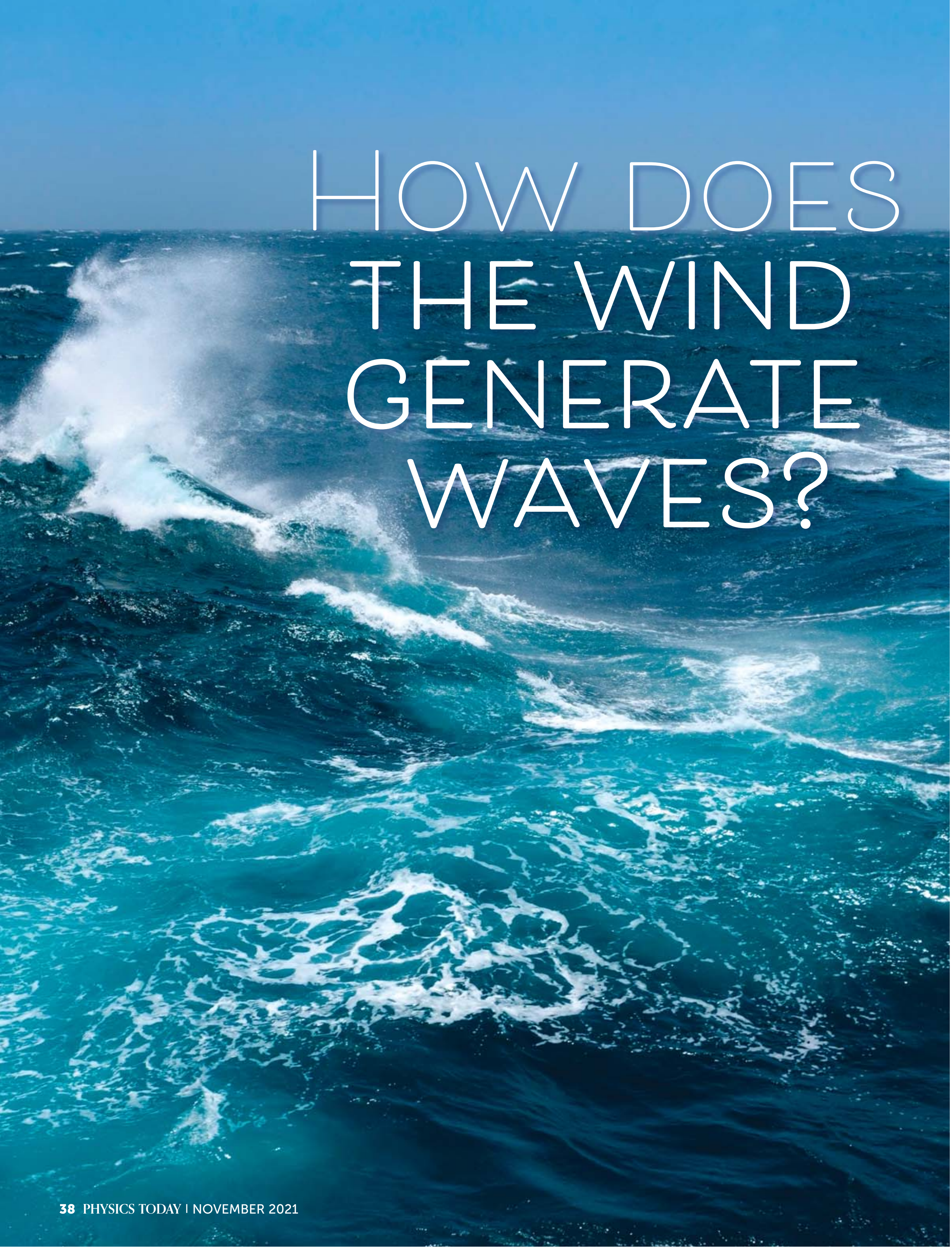
How does the wind generate waves?



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Although the question is a classical problem, the details of how wind transfers energy to waves at the ocean surface remain elusive.

To the modern Earth scientist, ocean waves are important because they influence the physics of the air–sea interface (see the article by David Richter and Fabrice Veron, PHYSICS TODAY, November 2016, page 34). The waves transport mass, and that wave-induced drift alters the dynamics of the upper ocean: It mixes the surface layers of water and modulates their temperatures, a crucial boundary condition between the air and sea in coupled models of Earth's weather and climate. More practically, statistical wave models describe how waves evolve and propagate across the ocean surface in various environmental conditions—such as low and high winds—and quantify how they influence the ocean's circulation and the transport of jetsam, flotsam, and pollution on its surface.

That wind produces waves in water is obvious to even the most casual observers. It has received attention for centuries from mathematicians and physicists. Even so, a complete description of the phenomenon eludes modern researchers. The difficulty comes from the fact that wave generation occurs at the interface of two fluids (here, air and water), with the flow in both generally turbulent. The waves vary sufficiently in space and time to be considered random, and the fluids interact over a broad range of scales—from millimeters to kilometers in space, and from seconds to hours in time. That range makes analytical and numerical progress extremely difficult.

The challenge in laboratory studies is to resolve the turbulent flow of air and water simultaneously over that large range on a curved and quickly changing surface. Field studies suffer from the difficulties of making measurements at sea, particularly when wind measurements are disturbed by the distortion produced by the presence of a research vessel. Despite those obstacles, much progress has been made experimentally—figure 1 shows a research platform at sea that avoids a research vessel's usual flow distortion—and theoretically to understand the phenomenon. In this article, we outline the problem, review historical approaches to solve it, and discuss some of the open questions.

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Outline of the problem

Consider a horizontal wind blowing over a quiescent ocean. Under what conditions do surface waves form? The restoring forces for ocean waves are gravity and surface tension. The dynamics of the interface between the air and sea are governed by the requirements that stress is continuous and momentum is conserved in both fluids. That system is described by the Navier–Stokes equations. For small waves, and a fluid that contains no vorticity, it's linear and behaves like a simple harmonic oscillator, with evanescent waves propagating in the horizontal direction according to a dispersion relation.

But the system becomes deceptively complicated when waves are no longer linear, or when the flow in the air or water contains vorticity. Even worse, the boundary conditions must be evaluated at the rapidly varying wave interface, which itself is a dependent variable of the system. That adds significant complexity to the problem. Solving it requires using the nonlinear

Navier–Stokes equations at all points in the air–sea boundary and over the broad range of scales.

A statistical approach

Statistical wave models are one of the biggest drivers of research in the field, and they are of tremendous practical value to mariners, national security operations, and surfers alike. The models are based on the statistics of wave heights. The quantity known as wave action, which takes into account the effects of current on the waves, is the fundamental conserved quantity.[1] A pendulum with a varying string length is a direct analogue of waves in a current. When the length of the pendulum changes, so does the energy of the system. Similarly, water waves exchange energy with the currents, but the wave action remains conserved, which makes it the central feature in statistical wave models.

Modern statistical models are based on the evolution of the wave action spectrum and take the form

$$\frac{\partial N}{\partial t} + (\mathbf{c}_g + \mathbf{U}) \cdot \nabla N = S,$$

where N refers to the wave-action density—the wavenumber energy spectrum divided by the wave's intrinsic frequency $\omega = \sqrt{(g|k|)}$. The group velocity $\mathbf{c}_g$ equals $\partial\sqrt{(g|k|)}/\partial k$, in which g is the acceleration of gravity, k is the wavenumber, and $\mathbf{U}$ is the ocean current at the surface. Note that deep water waves are dispersive, so longer waves are faster than shorter waves.

The source term S in the equation refers to the sum $S_{in} + S_{diss} + S_{nl}$, in which S_{in} is the wind's input to the waves, S_{diss} is the dissipation of action primarily due to wave breaking, and S_{nl} is the nonlinear transfer of action through wave–wave interactions. The dot product term on the left-hand side of the equation represents the transport of wave action along the ocean's surface.

The nonlinear interactions S_{nl} were explained in the 1960s by Klaus Hasselmann and Vladimir Zakharov.[2,3] For surface gravity waves, they arise when four waves resonantly interact. That discovery, together with its implications for the existence of direct and inverse cascades in the water-wave system, earned Zakharov the Dirac Medal in 2003. (Hasselmann, incidentally, received the 2021 Nobel Prize in Physics for work he did on climate modeling.) A towering figure in the development of water-wave theory, Zakharov shared the medal with Robert Kraichnan, one of Albert Einstein's last postdocs, who elucidated analogous properties of two-dimensional turbulence. The behavior of the dissipation term S_{diss} is primarily controlled by wave breaking and remains an active area of research. In this article, we focus on the physics that leads to a better understanding of the wind's contribution to the waves' energy, S_{in}.

Wind-generation mechanisms in history

Many cultures have an intuitive understanding of the relationship between wind and waves. Micronesians and Polynesians, for instance, are famous for using swell to aid in their navigation.[4] The modern treatment of the relationship began with two pivotal figures of 19th-century physics, Hermann von Helmholtz and William Thomson (later Lord Kelvin), who argued that wind generates waves through a shear-flow instability. The two scientists would often discuss the issue on trips out on Kelvin's boat.[5]

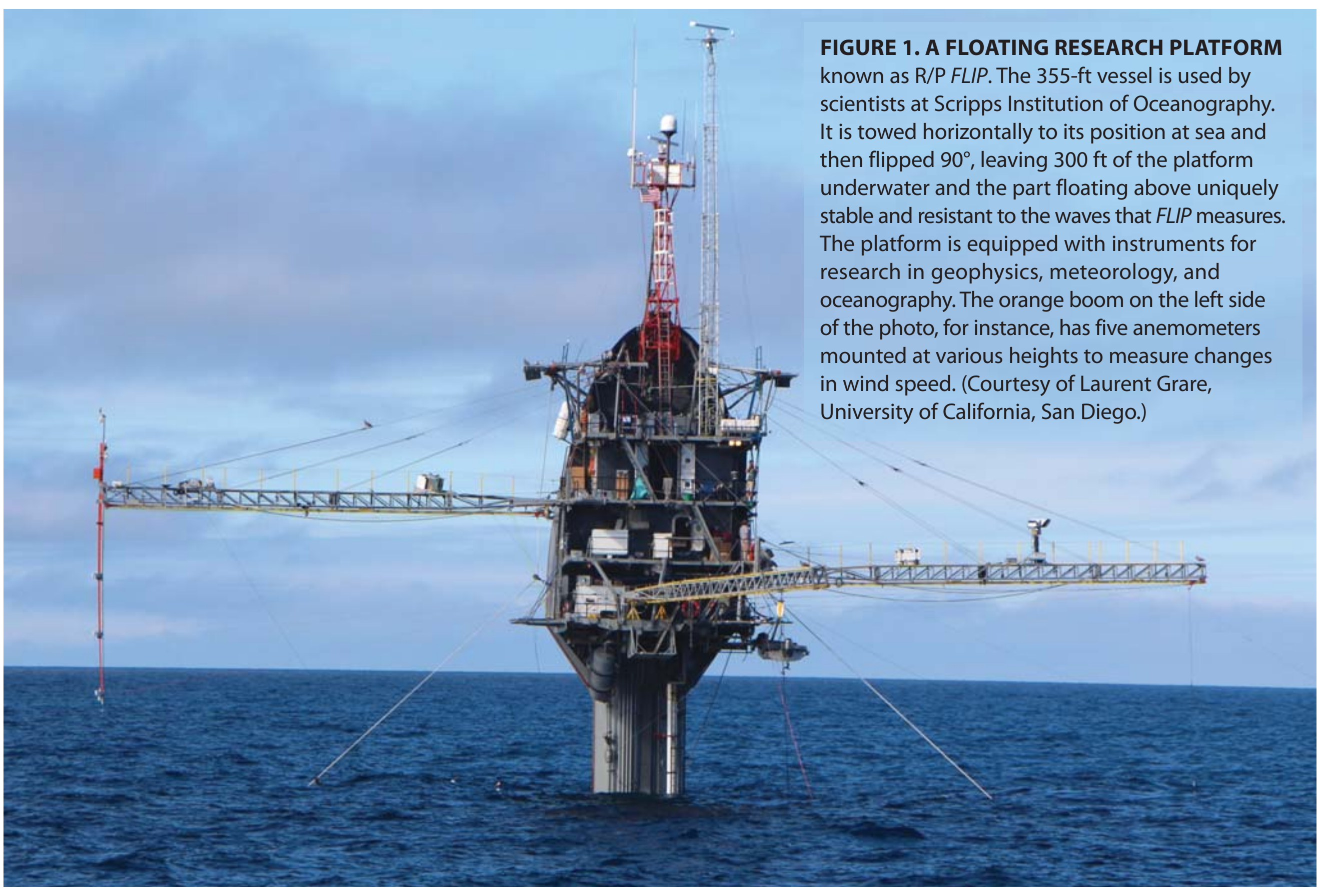

FIGURE 1. A FLOATING RESEARCH PLATFORM known as R/P *FLIP*. The 355-ft vessel is used by scientists at Scripps Institution of Oceanography. It is towed horizontally to its position at sea and then flipped 90°, leaving 300 ft of the platform underwater and the part floating above uniquely stable and resistant to the waves that *FLIP* measures. The platform is equipped with instruments for research in geophysics, meteorology, and oceanography. The orange boom on the left side of the photo, for instance, has five anemometers mounted at various heights to measure changes in wind speed. (Courtesy of Laurent Grare, University of California, San Diego.)

The process, known as the Kelvin–Helmholtz instability, occurs whenever a fluid changes speed across a region of changing density. The pair calculated that for the mechanism to operate in realistic conditions, wind speeds of 6.5 m/s were needed to generate waves. But several laboratory experiments have since recorded wave generation at much lower wind speeds. Apparently, there is more to the story than what Kelvin and Helmholtz had proposed.

In 1925 Sir Harold Jeffreys argued that air flowing over water waves is, like air flowing past a sphere, deflected by surface geometry.[6] The analogy led to an understanding of what's now known as airflow separation—a reversal in the direction of airflow over the leeward side of a wave crest (see figure 2). The geometric phenomenon, which Jeffreys called sheltering, arises from a pressure difference between the windward and leeward sides of the wave. The wind pressure and slope of the water wave are both oscillatory, and when the two are phase-shifted with respect to each other, work is done on the wave, which causes it to grow. The theory has an unconstrained scaling parameter, known as the sheltering coefficient, that estimates the work done on the waves by the wind. Preliminary laboratory experiments of wind over solid objects showed that the sheltering coefficient depends crucially on the specific geometry of the object, which the Jeffreys theory does not account for.

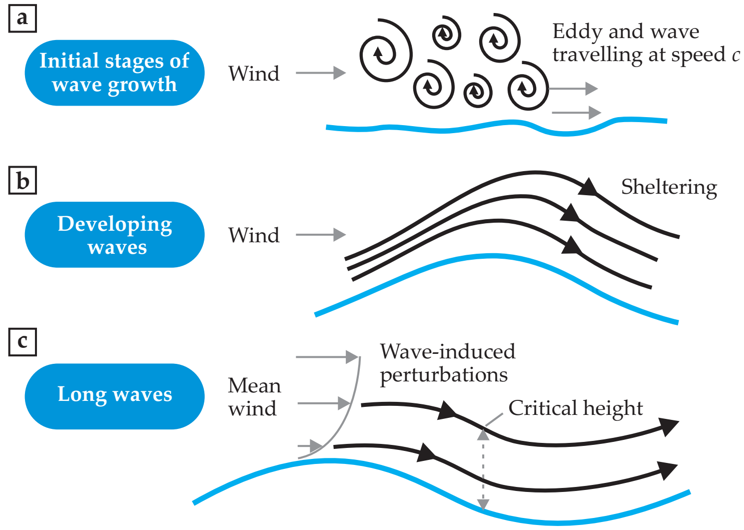

FIGURE 2. WAVE-GENERATION mechanisms. **(a)** Turbulent eddies in the air disturb an initially calm ocean and create ripples with wavelengths on the scale of centimeters. **(b)** Those ripples grow to meter-scale wavelengths, and the wind becomes "sheltered" on the downstream (leeward) side of the wave crest. The pressure difference between the windward (left) and leeward (right) sides of the crest transfers energy from the wind to the wave, causing it to grow. **(c)** The wind's speed is highest well above the water and decreases until it reaches zero at the ocean surface. At a critical height where the wind's speed equals the phase speed of the wave, the wind's shear resonates with the wave and transfers further energy to it. (Image by Donna Padian.)

The problem then lay dormant for 15 years. It was not until World War II that it was taken up again, when accurate meteorological predictions of waves and surf became crucial for the transport and amphibious landings of supplies and soldiers. Researchers working in the US—mainly Harald Sverdrup and Walter Munk at the Scripps Institution of Oceanography in California—needed predictions of the heights of locally generated waves in "fetch"-limited seas, the type of storm waves that crashed onto beaches near Normandy, France, during D-Day. They used simple scaling arguments to estimate those wave heights from the intensity and duration over which the wind was blowing. The relation between those variables forms the foundation of an empirical model for how winds locally generate waves, and these relationships are still used nowadays.

In the UK, meanwhile, Group W—whose initial stood for "waves"—primarily focused on swells that affected the South Pacific during wartime. The group became interested in how those long-wavelength waves traveled great distances. They turned to 19th-century mathematicians Augustin Louis Cauchy and Siméon Poisson, whose work had predicted swell behavior. They answered the question of how waves emanate from a rock dropped into a pond. Researchers used that theory—modeling distant storms as "the rock dropped into the pond"—to predict arrival times of those swells.

Around the time Group W was working on swell predictions, physics Nobel laureate Peter Kapitza re-examined Jeffreys's sheltering mechanism.[7] But instead of focusing on airflow separation in the thin layer of air close to the water's surface, he considered airflow separation events on the scale of a wavelength. And although that work received little attention, his intuition regarding large airflow-separation events near wave crests was well founded.

Munk supplemented those theoretical works with some much-needed observations. But he did not restrict his attention to fetch relationships. Working with Charles Cox on a seminal study of photographs taken from a B-17 bomber,[8] he investigated the connection between wind speed and the slope of the sea surface. Their observations led to the realization that the two variables are strongly correlated. Building on that work, Munk further suggested that short-wavelength waves are the ones most actively coupled to the wind and that the intensity of that coupling, or growth, depends on their slope.[9] Even so, the mechanism behind that fundamental process, which Munk called "an inconvenient sea truth," is still not understood.

Miles and Phillips

In his 1956 review of the subject, Group W member Fritz Ursell wrote that oceanographers' understanding of wave generation by wind was "unsatisfactory."[10] Two young scientists answered his call to action: the University of California's John Miles and Cambridge University's Owen Phillips.

The so-called Miles mechanism[11] is a shear-flow instability in the spirit of the original theory of Kelvin and Helmholtz. Miles, however, had the crucial insight to account for a mean wind profile, based on flow properties close to a boundary. He produced a semilaminar inviscid model, in which the shear-flow instability occurs at a critical height—specifically, where the wind speed matches the phase speed of the growing wave (see figure 2). The instability couples the surface wave to its induced perturbation at that height, and the coupling, in turn, removes energy and momentum from the wind and produces waves with it. The growth rate of those waves depends not on the wind speed or its gradient, but on the curvature of the wind profile at the critical height.

Just as Miles was publishing his paper, Phillips proposed a mechanism that relies on a resonance between surface waves and pressure fluctuations in the wind.[12] That is, wind has a turbulent component—composed of an ensemble of eddies—as it blows over water. The pressure disturbances associated with those eddies do work on the water surface, generating wavelets. If those wavelets, and hence the pressure perturbations, travel at the speed of a free-surface gravity wave, a resonance occurs, and the wavelet can grow into a wave. (See the article by Callum Shakespeare, PHYSICS TODAY, June 2019, page 34, and the article by Erdal Yiğit and Alexander S. Medvedev, page 40.)

The validity of Phillips's theory has only recently been explored through detailed laboratory experiments and numerical simulations of turbulent flow. The results suggest that the theory is accurate at early stages in the wave-generation process and provides a mechanism by which the ocean surface goes from being perfectly smooth to rippled (see figure 2). Once those ripples attain an amplitude of a few millimeters, other growth mechanisms occur and the nonlinear transfer of energy between waves becomes dominant.

Despite their appeal, both mechanisms have limitations. On the one hand, the Phillips theory predicts that wave amplitudes grow linearly in time but weakly. And as mentioned above, that seems to apply only during the early stages of growth. Once waves become larger and longer, the Miles mechanism becomes dominant: Waves grow exponentially in time and with a much larger growth rate than happens in the Phillips mechanism.

Miles's mechanism, however, ignores turbulence and its effects on wave-induced perturbations of atmospheric flow. For short waves, the critical height lies close to the surface—a region where turbulent eddies are advected slowly compared with their lifetime. It is then reasonable to think that those eddies can interact with the waves and that alternative, possibly turbulent, processes can hence become dominant in that short-wavelength regime. Other limitations of the Miles mechanism include that it does not treat nonlinear effects in the flow,[13] the effects of viscosity, and interactions between short- and long-wavelength waves.

Difficulties of corroborating theories

The Phillips and Miles theories assume that ocean waves are not steep, treat waves as (nearly) monochromatic, and do not account for the multiscale nature of turbulent flow. In an attempt to overcome those shortcomings, Stephen Belcher and Julian Hunt proposed, in 1993, an extension of Jeffreys's sheltering mechanism to turbulent flow.[14] They used tools from turbulence theory to quantify how the pressure difference caused by sheltering is affected in the presence of turbulent eddies. The resulting mechanism is based solely on the deformation of airflow on the leeward face of the wave. And it produces realistic estimates of wave growth for short waves.

In realistic field conditions, the sea surface can be described by a broadband wave spectrum that interacts with turbulent air. Hence theoretical growth rates should be tested against observations in the laboratory and in the field. A full validation, however, would require knowledge of the airflow structure. Moreover, the Miles critical height is proportional to the length of the waves. Hence, for short waves, which are expected to be strongly coupled to the wind, that height is just tenths of a centimeter from a quickly changing surface. That makes atmospheric properties just above the wave extremely difficult to measure.

To experimentally confirm the theories of wave growth, researchers must verify the consequences of Miles's theory. Those consequences include the form of the streamlines predicted by the theory and the scaling of the wave growth rate with wind speed. Furthermore, because of the scarcity of accurate measurements near the ocean surface, one must generally approximate the expression for the wind profile from boundary-layer theory. Several important scaling parameters arise from that theory—the roughness length scale is one example—and they have proven hard to constrain because they are strongly modulated by the wave field. Despite the difficulties, the predictions and observations of wave growth largely agree for long waves.[13]

The use of Miles's theory, and simple extensions of it, forms the basis for modern wind–wave growth parameterizations—that is, S_{in}—that are used in spectral wave models. Those models do not usually resolve short waves, so their spectral shape and response to wind forcing are parameterized using only

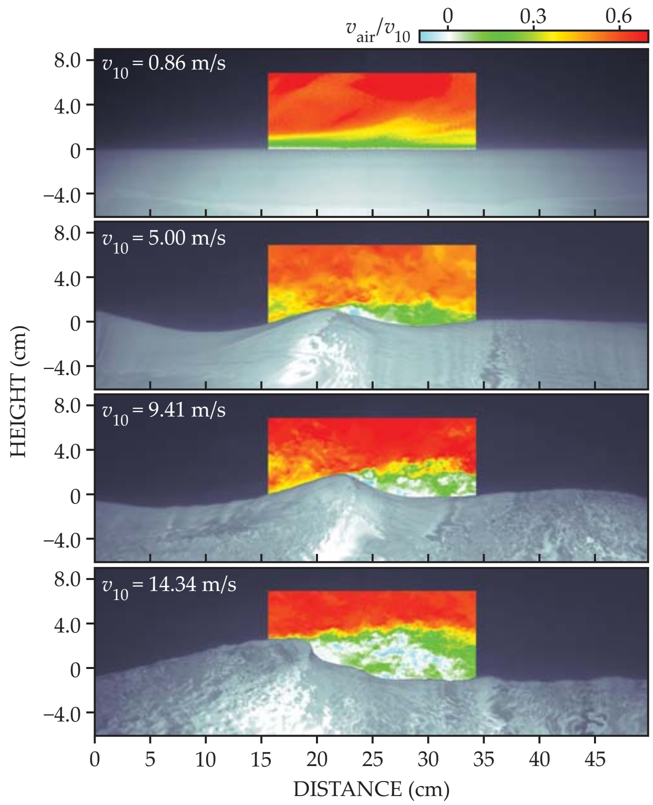

FIGURE 3. AIRFLOW SPEED, in color, as measured above water waves. In this laboratory experiment, each panel illustrates the horizontal flow of the air above the water surface as a function of different wind and wave conditions. The colors represent the airflow speed v_{air} divided by the wind speed v_{10} that would be measured at 10 m above the water's surface. The airflow goes from being approximately laminar at low wind speeds to turbulent at high speeds, with the airflow being strongly "separated" from the water surface near the crest of steep waves. (Courtesy of Marc Buckley and Fabrice Veron.)

(possibly incomplete) physical grounds as a basis.[15,16]

Current research challenges

Recent advances to understanding how wind generates waves have been driven by technological developments in computational and observational capabilities, and in improved theoretical formulations of the problem.

Measurements made in the laboratory and in the field have shown the existence of a critical height—a necessary feature of Miles's theory—and its importance in controlling the flux of momentum to long waves. Natural reference frames, which measure distances normal and tangential to the surface, not from some fixed point, have greatly clarified the observational data. The development of large-eddy simulations of the atmospheric boundary layer have also shed light on various regimes, particularly for low winds and long waves. In those regimes, significant momentum can even be transferred from the waves back to the atmosphere.

The dynamics of short waves are more complex than those of long waves because of the effects of wave breaking. The steep slopes that occur when waves break induce 3D airflow separation downwind of the wave crest (see figure 3). Wave-breaking events become even more important as the wind strength increases to hurricane levels. Experiments in laboratory facilities capable of producing such extreme conditions indicate that the reattachment of separated air streamlines occurs much less frequently at higher wind speeds than at lower ones and isolates the waves from the bulk airflow. That modification of properties in the near-surface flow has proven to be important in hurricane-strength conditions and is an active area of research.

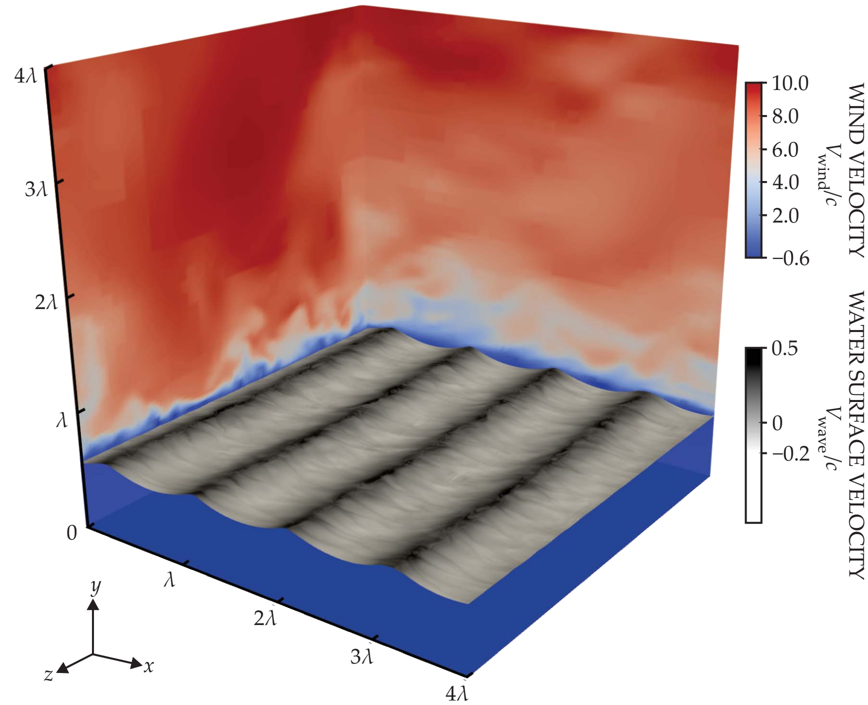

FIGURE 4. NUMERICAL SIMULATIONS of waves growing under a turbulent wind akin to the strongest wind conditions in figure 3. The waves' slope $2\pi A/\lambda = 0.2$, where A is the waves' amplitude and λ is their wavelength. Notice the three-dimensional structures in the dimensionless wind-velocity field V_{wind}/c near the surface of the water; c represents the waves' phase speed. The dimensionless wave-velocity field V_{wave}/c varies not only in the wind-forcing direction (x) but also in the transverse (z) direction along the crests. The simulation solves the 3D Navier–Stokes equations for the water flow, airflow, and interface between them. (Courtesy of Jiarong Wu, Stéphane Popinet, and Luc Deike.)

Some experiments and computations that resolve the fully coupled air–water turbulent system have already been achieved and are starting to become more routine. Experimentally, the challenge is to perform measurements of the turbulence in air and water simultaneously. Computationally, the challenge is to solve the two-phase Navier–Stokes equations over the wide range of scales that are involved.

Figure 3 shows snapshots of the airflow in recently performed laboratory experiments just above water waves of various slopes and in increasing wind intensities. Figure 4 shows an example of fully coupled simulations of waves growing under a turbulent boundary layer. Both experiments and simulations resolve the airflow close to the surface. The numerical simulations have the added benefit of capturing the full 3D velocity and pressure fields along with the water flow.

Both studies highlight the complex coupling between water waves and the turbulent wind. The numerical simulations in figure 4, produced by members in one of our groups (Deike's), set the stage for an investigation of all 3D fields, such as the pressure field at the ocean's surface. That's a notoriously difficult field to measure in the lab because waves move so rapidly. An analysis of energy and momentum transfer from the wind to the waves is another example. It could help further test the proposed theories on wave growth in various regimes.

Although many details remain elusive, a combination of theoretical, numerical, laboratory, and field advances have led researchers to a better understanding of wave generation by wind. The simple question of how it happens will, no doubt, continue to inspire research into the underlying structure of the ocean and coupled ocean–atmosphere models in a warming climate.

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