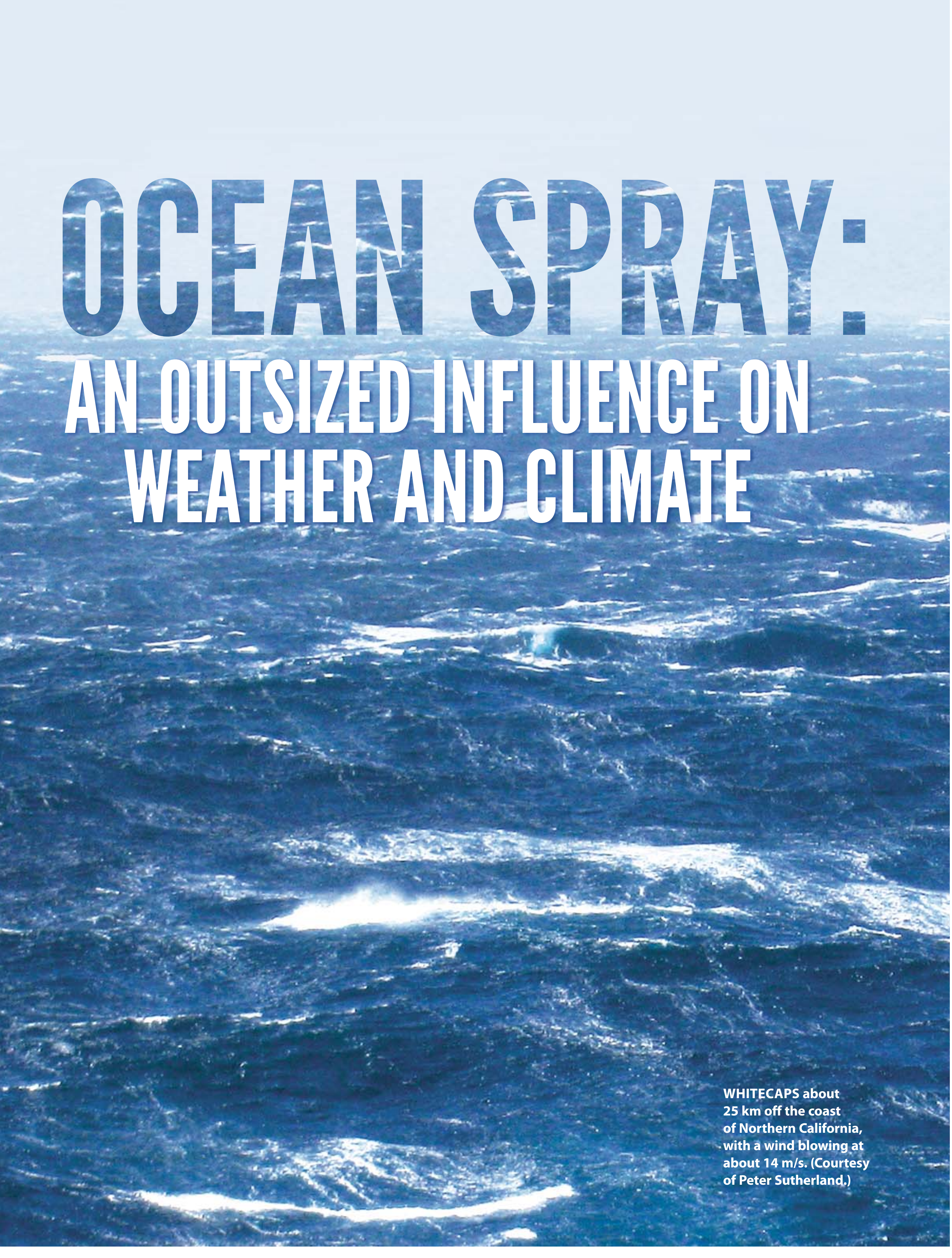
OCEAN SPRAY:

AN OUTSIZED INFLUENCE ON WEATHER AND CLIMATE



WHITECAPS about 25 km off the coast of Northern California, with a wind blowing at about 14 m/s. (Courtesy of Peter Sutherland.)

David Richter is an assistant professor of civil and environmental engineering and Earth sciences at the University of Notre Dame in Notre Dame, Indiana, and **Fabrice Veron** is a professor and associate director of the School of Marine Science and Policy at the University of Delaware in Newark.

David H. Richter
and Fabrice Veron

Because the production, behavior, and life span of seawater droplets are complex, measuring and modeling them require a wide range of interdisciplinary techniques.

The oceans cover about two-thirds of Earth's surface. The exchange of heat, moisture, and energy between the air and sea across so large an area exerts a profound influence on the dynamic and thermodynamic state of the atmosphere, including its seasonal fluctuations and longer-term climatic trends. As little as 1–3% of that area is covered at any one time by foamy whitecaps that are created as waves break along the shore or out at sea. Perhaps surprisingly, those small-scale events, accompanied by bubbles, sea spray, and turbulence on both sides of the interface, are essential in driving the air–sea fluxes (see the Quick Study by Grant Deane, Dale Stokes, and Adrian Callaghan in PHYSICS TODAY, October 2016, page 86). Because the production of droplets from breaking waves is inaccessible to even the highest-resolution climate and weather models, however, researchers must use large-scale features, such as water and air temperatures and wind patterns, to quantitatively account for the droplets' effects. Fortunately, the past few decades have seen substantial progress in our understanding of how ocean waves couple the ocean to the atmosphere.[1]

Sea spray, which consists of liquid drops that are ejected from the ocean surface, takes part in a rich variety of physical and chemical processes. Small droplets are often lifted high into the atmosphere and can remain there for several days; their actual time aloft depends on such atmospheric conditions as wind speed, air turbulence, and precipitation. And once airborne, the drops can evaporate entirely to leave behind sea-salt aerosols that may then act as cloud condensation nuclei, scatter or absorb solar radiation, or influence atmospheric chemistry. Current estimates of the global release of salt from the ocean via sea-spray production

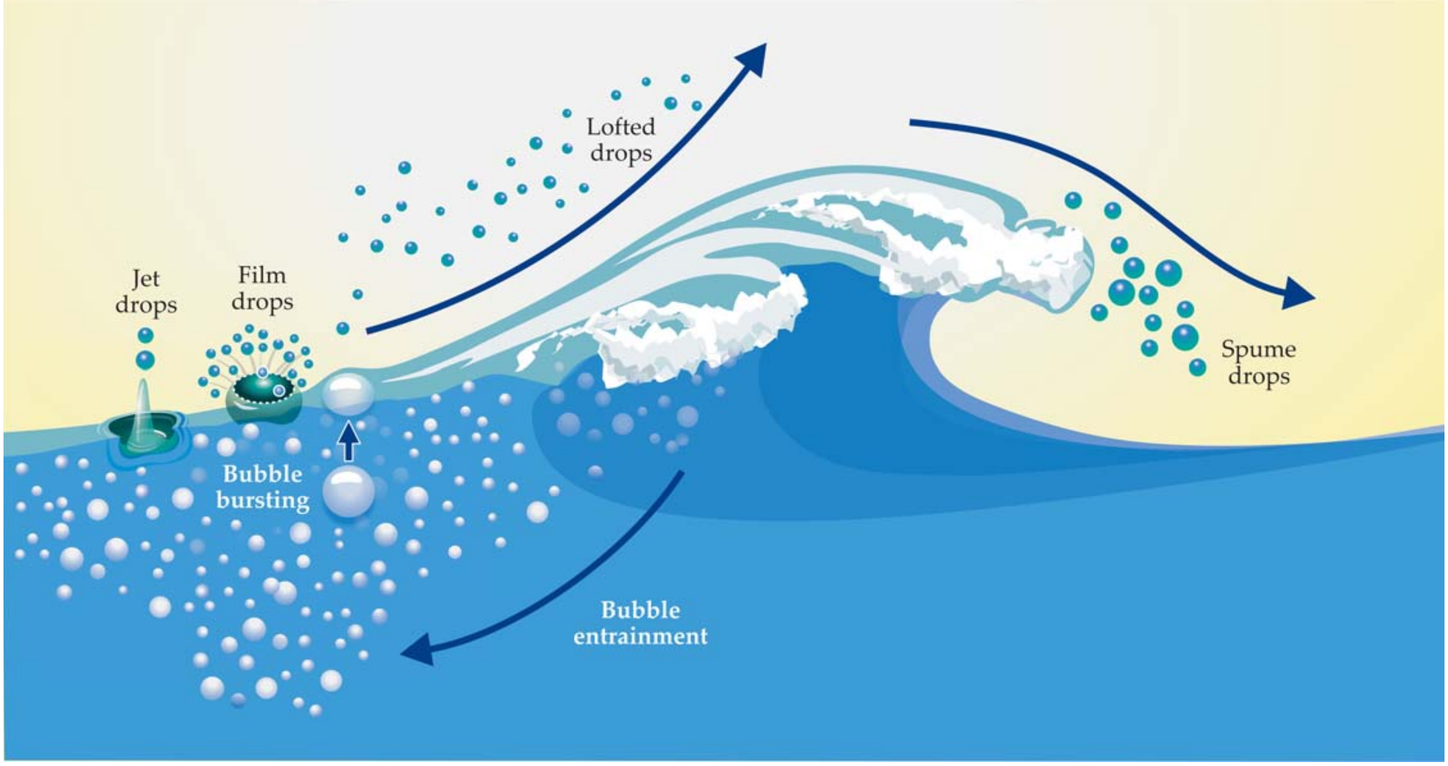


FIGURE 1. THE FORMATION OF WATER DROPS. Spume drops, between roughly 20 micrometers and several millimeters in radius, are torn by the wind from the crest of a breaking wave. Film and jet droplets are smaller, generated when air bubbles entrained by breaking waves rise to the surface and burst. The film droplets, typically 0.01–2 μm in size, are sprayed outward. Immediately afterward, surrounding water surges in to fill the cavity left behind and creates a rising jet whose tip pinches off the jet droplets, with sizes between 2 μm and 100 μm. Both classes of smaller droplets can become lofted upward with the wind. (Illustration courtesy of Tamara Beeson, University of Delaware.)

range between 2 billion and 20 billion metric tons per year.[2] That's enough to cover the city of Houston, Texas, with up to 6 m of salt every year.

The larger droplets that most of us are familiar with by getting wet near the beach on a windy day generally remain in the atmosphere for a far shorter time—from a fraction of a second to perhaps minutes or hours—and do not loft high into the atmosphere. They remain local and usually return to the ocean after having directly exchanged momentum, heat, and moisture with lower atmospheric layers. That means those large drops have the greatest potential to influence local weather by affecting winds, humidity, and air temperature. In fact, in certain circumstances, such as in a hurricane or typhoon, high concentrations of large spray droplets are thought to have a significant influence on the thermodynamic conditions near the air–sea interface.

In this article we focus our discussion on how ocean spray influences the dynamic and thermodynamic interactions between air and sea. The magnitude of the interactions is, at least in principle, easy to estimate. It simply depends on three factors: the rate at which the drops exchange heat, moisture, and momentum with the ambient air; how long they remain in the air; and how many of them are generated at the air–sea interface. Let us start with the last factor.

Classes of drops

Sea spray is mainly generated three ways, all associated with breaking waves.[3] When the wind is strong enough, it literally tears water drops from the ocean surface; in the open ocean, the threshold wind speed is about 7 m/s. The ejection of those spume drops—the largest class of sea-spray drops—is thought to happen at the front of a wave as it starts to break, as shown in figure 1. Moments later, the crashing wave forces air bubbles below the ocean surface. Bubbles entrained in the water rise to the surface, where they are usually visible as whitecaps. When they burst, the bubbles splatter so-called film drops into the air. The cavity left behind then collapses, which produces a liquid jet that shoots upward and pinches off several so-called jet drops.

Together, the three classes make up the whole population of spray drops injected into the atmospheric airflow. Their concentration can be expressed by a size-distribution function, which yields the number of droplets per volume of air at a particular height and within a given size range. But a more convenient quantity, called the sea-spray generation function (SSGF), is the number flux of droplets generated at the surface—that is, the rate at which droplets of a given size range are produced per unit area. Because that flux is generally difficult to measure directly, it is often empirically derived from more readily available data, such as wind speed or whitecap statistics.

For jet and film droplets, one can construct an SSGF based on the physical principles behind their formation because the physics of bubble bursting is well understood. And recent advances in optical and other techniques to directly measure droplet sizes and velocities have helped confirm SSGF estimates and reduce their uncertainties.[4] Details behind the formation of spume droplets, by contrast, are less clear because they are more closely linked to the complex process of wave breaking. The complexity precludes constructing an SSGF from theoretical principles alone. Moreover, because spume droplets are larger and thus tend to stay closer to the ocean surface, measuring their concentration is harder than for the smaller droplets, which reach heights more convenient for measurement purposes.

Adapted from a recent review article,[5] figure 2 plots the production flux, as estimated by several different SSGFs, of the various sizes of spray droplets. Because the fluxes of momentum and heat driven by the spray depend on the total momentum and available energy carried by each drop, the SSGFs have been scaled by the volume of the drops. The scatter among the different estimates of spume-droplet volumes illustrates the need for better, more accurate SSGFs before scientists can effectively parameterize the effects of spume in climate and weather models. What's more, to evaluate the effects of ocean spray on the exchange of energy and moisture between sea and air, one needs to estimate not only the number flux of droplets that are made but also the rate at which they exchange energy and mass with the atmosphere.

Microphysics and transport

A droplet sent flying over the ocean surface interacts dynamically and thermodynamically with the turbulent air around it. Dynamically, it feels gravity and hydrodynamic forces, which together determine how much momentum it exchanges with surrounding air via frictional drag. If the droplet is small and light, it quickly adjusts to the local air speed because of its low inertia. Those properties are embodied in a small value of the dimensionless Stokes number St = τ_p/τ_f, where τ_p is an acceleration time scale associated with droplet inertia and τ_f is a characteristic time scale associated with the surrounding airflow. In the limit of zero Stokes number, droplets become fluid tracers that instantaneously adjust their speed to that of the local airflow.

Large droplets, on the other hand, have a Stokes number on the order of one or more; they are less likely to travel along with the local air velocity because of their higher mass. And with the greater mismatch in velocity, more momentum is exchanged between droplet and atmosphere. In the limit of a very high Stokes number, the droplets become ballistic particles with little or no influence on their trajectory from surrounding air.

In the simplest models, a droplet, large or small, is assumed to be smaller than the smallest scales of air turbulence and is thus represented as a point particle. The governing equation for the droplet velocity is then a straightforward application of Newton's second law, with the hydrodynamic force described by the product of a drag coefficient and the difference in velocities of the droplet and the surrounding air.

Just as the local velocity differences drive the exchange of momentum, local differences in temperature and humidity drive the exchange of heat and water vapor. A droplet caught up in the airflow has an initial temperature equal to that of the ocean surface and exchanges sensible heat—the heat associated with a change in temperature but not phase—with the atmosphere during its airborne lifetime. That exchange is generally dominated by convection, and models typically express the heat transfer rate as a product of a (usually empirically derived) convection coefficient and the droplet–air temperature difference.

Likewise, evaporation and condensation of a droplet are also convective processes, in which the total mass-transfer rate of the water depends on the difference between the ambient vapor pressure and that at the droplet's surface. The latter is usually estimated from the saturation pressure at the droplet temperature, as governed by the Clausius–Clapeyron equation. But the vapor pressure at the droplet's surface can vary from that estimate, as it is heavily influenced by salinity and surface contamination, which reduce the evaporation rate as the droplet shrinks and salt or contaminant concentrations grow.

If the ambient vapor pressure is less than that at the droplet surface, the droplet evaporates. Because the droplet is the source of latent heat for the phase transformation, evaporation can lower the droplet's temperature; our skin feels cool on stepping out of a swimming pool for much the same reason. But if the

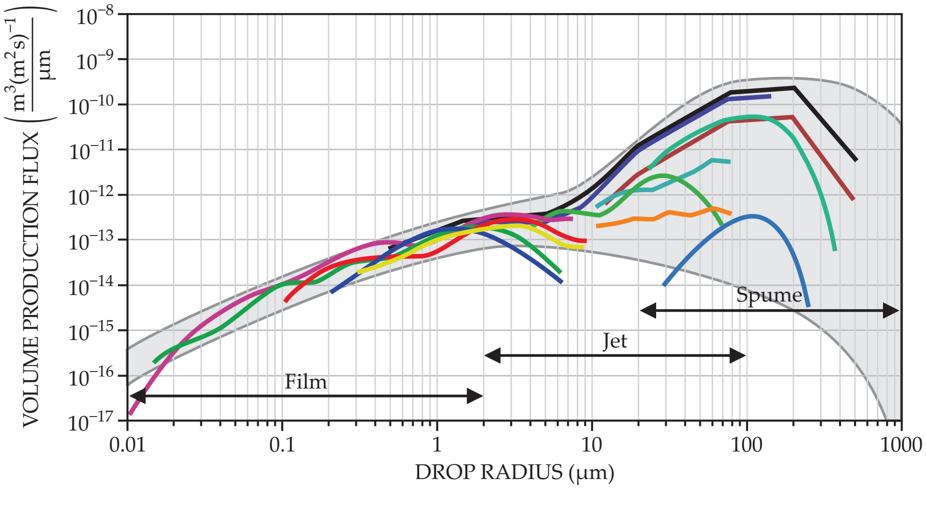


FIGURE 2. THE VOLUME PRODUCTION FLUX is the total volume of spray droplets in a given size range generated per unit area per second. Values of the flux, derived from various models and measurements (the different colored lines), are plotted as a function of the droplet radius for a wind speed of 15 m/s. The different estimates agree to within an order of magnitude for film droplets and the smallest jet droplets. For spume drops, the largest produced in sea spray, the different estimates span several orders of magnitude. (Adapted from ref. 5.)

ambient vapor pressure exceeds that of the droplet surface, the converse is true: Water vapor condenses onto the droplet, and the latent heat given to the droplet warms it. A droplet's temperature therefore depends on its rate of evaporation or condensation and on how much heat it convects. That's why it's possible for a droplet to cool below the ambient air temperature during its lifetime. For a more complete treatment of the thermodynamics, see references 4 and 6.

As we've seen, droplets smaller than 50 μm or so can remain airborne for days because of their low inertia; large ones remain aloft for mere seconds. The difference matters because the time it takes a droplet to cool is substantially shorter than the time it takes to evaporate, as shown in figure 3. The disparities in droplet lifetimes, temperature evolution, and size evolution produce a complex physical picture. For example, despite not carrying much mass, smaller droplets may possess a greater capacity to transfer latent heat to the atmosphere because of their longer time aloft. Any modeling scheme designed to predict the fate and feedback of spray droplets must therefore account not only for the detailed processes controlling the velocity, size, and temperature of each droplet but also for the meteorological conditions that control its suspension time.

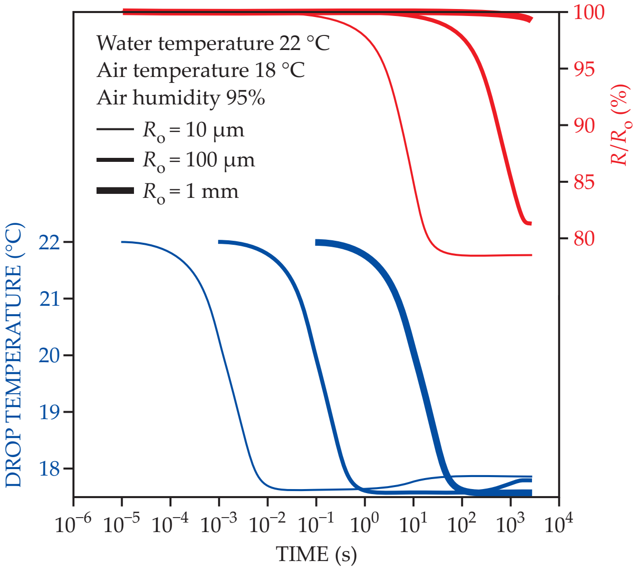


FIGURE 3. THE EVOLUTION OF A DROP'S TEMPERATURE (blue) and its radius (red) occur at time scales that differ by orders of magnitude. The initial radii (R_0) of three differently sized droplets at given ambient conditions are distinguished by the thickness of the plot lines; thicker lines represent larger drops. As a droplet evaporates, its radius R shrinks. But before it shrinks, the droplet completely cools off—regardless of initial radius—and transfers its sensible heat to air. A 10-μm-radius droplet, for example, cools to near ambient temperature in 10 ms, but it requires nearly 100 s to evaporate substantially.

Making models

At low wind speeds, when few waves break and sea spray is minimal, the fluxes of momentum and energy are largely governed by diffusive molecular-transport processes at the air–sea interface. But as the winds pick up speed, more spray is produced, which can, in turn, modify or redistribute the momentum and energy transport throughout a boundary layer filled with suspended droplets. Spray is thought to exert a particularly large effect in tropical cyclones, in which wind speeds can exceed 60 m/s near the ocean surface. Under those extreme conditions, sea spray is pervasive—the normally sharp air–sea interface is replaced by a thick, foamy mixture that gradually approaches pure air on one side and pure water on the other.

A lot of effort has gone into predicting the degree to which the spray can influence the drag felt by the winds over the ocean or enhance the flux of energy from the relatively warm sea to the air. Understanding the impact of strong winds and the resulting spray on the air–sea fluxes is particularly important because the relative balance of energy dissipation through drag (that is, the momentum flux) to energy input through sensible and latent heat heavily affects the development and intensity of large storms.[7] To appreciate how spray may affect air–sea exchange, imagine what happens locally: A droplet goes airborne, partially evaporates, and cools before falling back to the sea. The heat given to the air helps drive the storm.

Three main ingredients are required in a sea-spray model capable of predicting air–sea momentum and energy transfer. The first, outlined earlier, is an understanding of droplet microphysics and thermodynamics, which can be used to calculate the size, velocity, and temperature evolution of a suspended droplet for a given set of ambient conditions. Because those ambient conditions are not usually known, however, the second ingredient is a stochastic model that estimates them based on the suspension lifetimes of droplets of different sizes. The final ingredient is the concentration of suspended spray, given by an SSGF. Uncertainty in the production flux of droplets and their concentrations is one of the key factors that limit current models.

To compute the bulk impact of the spray, it may be tempting to simply take the energy or momentum transfer rate experienced by a single isolated droplet in the atmosphere and multiply it by the total number of suspended droplets. But spray generated at the ocean surface only to return to the ocean forms something of a closed system. For example, a droplet torn from a wave crest and accelerated horizontally extracts momentum from the air and, on impact with the ocean surface, delivers that momentum directly to the sea. From the ocean's perspective, the total drag would be unchanged; the momentum is merely split between the air and spray. Similarly, a small droplet that evaporates entirely transfers no net heat because during the process the latent heat provided by evaporation is equal to the sensible heat extracted from the air. Only those droplets that partially evaporate can have a net impact on air–sea heat flux.

Moreover, any attempt to model the bulk effects of spray must consider a wide range of feedback effects. Gravity stratifies a suspension of droplets according to its density, with lighter air-spray mixtures sitting atop heavier ones, and some researchers argue that the stable configuration damps turbulence and modifies turbulent fluxes.[8] Others argue that spray could only affect turbulence through more direct interactions and that the momentum carried by the droplets themselves must be taken into account.[9] Droplet evaporation and heat transfer can likewise directly modify air–sea energy transfer, and the additional moisture and heat put into the atmosphere can change near-surface temperature and humidity profiles—and therefore buoyancy. That cascade of effects produces a nonlinear feedback that alters near-surface wind patterns and the spray they create.

Numerical and theoretical models designed to incorporate such feedback effects generally predict that modifications to the overall air–sea momentum flux from sea spray are modest whereas modifications to the overall heat flux can be substantial. In large-scale climate and weather models, those results suggest that spray effects need to be explicitly accounted for in high-wind conditions. Even in conditions where the modifications to the total air–sea momentum flux and energy flux remain small, droplets can still carry a significant fraction of each.

Laboratory and field observations, on the other hand, have yet to quantitatively or conclusively confirm the direct influence of spray predicted by many models. That's due partially to the difficulty of making measurements in strong winds and partially to the near impossibility of parsing total flux measurements into their interfacial and spray-induced components. Only indirect evidence is currently available,[10] and research is ongoing to provide better validation data for the spray-based models.

Outlook

Estimates of the production flux of droplets at the ocean surface continue to improve as a result of theoretical, laboratory, and observational investigation, and researchers are striving to reduce uncertainties in the concentrations and lifetimes of the spume drops in particular. The stakes are high: The importance of spray in the marine environment goes well beyond its physical effects on air–sea transport. As mentioned earlier, droplets that either are small at inception or become small by evaporating can be carried to altitudes throughout the entire troposphere. They absorb and scatter light, seed clouds, and influence precipitation.

Chemical and biological components of sea spray—the small amounts of oils and other organic debris that mix with water—likewise affect aerosol chemistry in important ways and influence reactions in the marine atmosphere. Ocean spray thus contributes to numerous highly complex and influential processes. It also serves as an example of how a wide range of scientific disciplines and research techniques can be applied to better understand the natural world around us.

REFERENCES

1. P. P. Sullivan, J. C. McWilliams, *Annu. Rev. Fluid Mech.* **42**, 19 (2010).
2. C. Textor et al., *Atmos. Chem. Phys.* **6**, 1777 (2006).
3. E. L. Andreas et al., *Boundary-Layer Meteorol.* **72**, 3 (1995).
4. E. R. Lewis, S. E. Schwartz, *Sea Salt Aerosol Production: Mechanisms, Methods, Measurements, and Models*, American Geophysical Union (2004).
5. F. Veron, *Annu. Rev. Fluid Mech.* **47**, 507 (2015).
6. H. R. Pruppacher, J. D. Klett, *Microphysics of Clouds and Precipitation*, 2nd ed., Kluwer (1997).
7. K. A. Emanuel, *J. Atmos. Sci.* **43**, 585 (1986).
8. G. I. Barenblatt, A. J. Chorin, V. M. Prostokishin, *Proc. Natl. Acad. Sci. USA* **102**, 11148 (2005).
9. D. H. Richter, P. P. Sullivan, *Geophys. Res. Lett.* **40**, 656 (2013).
10. D. H. Richter, D. P. Stern, *Geophys. Res. Lett.* **41**, 2997 (2014). PT