

## Ocean Spray

Before proceeding with the details of the formation of spray at a liquid/gas interface, a few comments are in order regarding the most widely studied example, namely spray generation on the ocean surface. It is widely accepted that the mixing of the two components, namely air and water, at the ocean surface has important consequences for the global environment (see, for example, Liss and Slinn, 1983, or Kraus and Businger, 1994). The heat and mass exchange processes that occur as a result of the formation of bubbles in the ocean and of droplets in the atmosphere are critical to many important global balances, including the global balances of many gases and chemicals. For example, the bubbles formed by white caps play an important role in the oceanic absorption of carbon dioxide; on the other side of the interface the spray droplets form salt particles that can be carried high into the atmosphere. They, in turn, are an important contributor to condensation nuclei. Small wonder, then, that ocean surface mixing, the formation of bubbles and droplets, have been extensively studied (see for example Monahan and Van Patten, 1989). But the mechanics of these processes are quite complicated, involving as they do, not only the complexity of wave formation and breaking but the dynamics of turbulence in the presence of free surfaces. This, in turn, may be affected by free surface contamination or dissolved salts because these effect the surface tension and other free surface properties. Thus, for example, the bubble and droplet size distributions formed in salt water are noticeably different from those formed in fresh water (Monahan and Zietlow, 1969). Here, we shall not attempt a comprehensive review of this extensive literature but confine ourselves to some of the basic mechanical processes that are believed to influence these oceanic phenomena.

There appears to be some general concensus regarding the process of spray formation in the ocean (Blanchard, 1983, Monahan, 1989). This holds that, at relatively low wind speeds, the dominant droplet spray is generated by bubbles rising to breach the surface. The details of the droplet formation process are described in greater detail in the next section. The most prolific source of bubbles are the white caps that can cover up to 10% of the ocean surface (Blanchard, 1963). Consequently, an understanding of the droplet formation requires an understanding of bubble formation in breaking waves; this, in itself, is a complex process as illustrated by Wood (1991). What is less clear is the role played by wind shear in ocean spray formation (see section (Nod)).

Monahan (1989) provides a valuable survey and rough quantification of ocean spray formation, beginning with the white cap coverage and proceeding through the bubble size distributions to some estimate of the spray size distribution. Of course, the average droplet size decays with elevation above the surface as the larger droplets settle faster; thus, for example, de Leeuw (1987) found the average droplet diameter at a wind speed of  $5.5m/s$  dropped from  $18\mu m$  at an elevation of  $2m$  to  $15\mu m$  at  $10m$  elevation. The size also increases with increasing wind speed due to the greater turbulent velocities in the air.

It is also important to observe that there are substantial differences between spray formation in the ocean and in fresh water. The typical bubbles formed by wave breaking are much smaller in the ocean though the total bubble volume is similar (Wang and Monahan, 1995). Since the bubble size determines the droplet size created when the bubble bursts through the surface, it follows that the spray produced in the ocean has many more, smaller droplets. Moreover, the ocean droplets have a much longer lifetime. Whereas fresh water droplets evaporate completely in an atmosphere with less than 100% relative humidity, salt water droplets increase their salinity with evaporation until they reach equilibrium with their surroundings. Parenthetically, it is interesting to note that somewhat similar differences have been observed between cavitation bubbles in salt water and fresh water (Ceccio *et al.* 1997); the bubbles in salt water are smaller and more numerous.

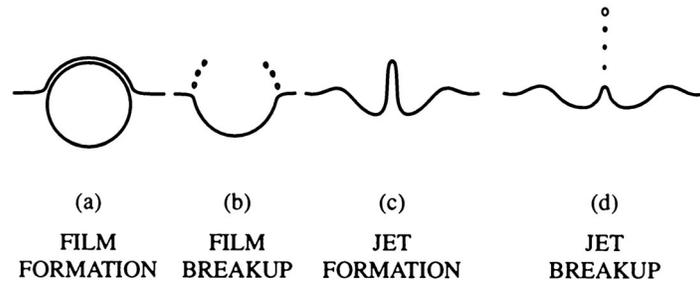


Figure 1: Stages of a bubble breaking through a free surface.

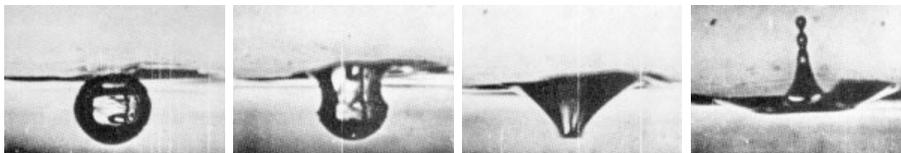


Figure 2: Photographs by Blanchard (1963) of a bubble breaking through a free surface. Reproduced with permission of the author.