

**Fluxes at the Sea Surface. IR Radiometers. Langmuir Circulation and Instability. Surface, Gravity and Capillary Waves. Wave Generation by Wind. Whitecaps and Foam.**

## Further Reading

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# BUBBLES

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## Introduction

Air–sea interaction does not solely occur directly across the sea surface, but also occurs across the surface of bubbles suspended in the upper ocean, and across the surface of droplets in the lower atmosphere. This article describes the role of bubbles in air–sea interaction.

There are three quite different types of bubbles in the oceans that can be distinguished by their sources (atmospheric, benthic, and cavitation). Benthic sources of bubbles include vents and seeps and consist of gases escaping from the seafloor. Common gases from benthic sources include methane and carbon dioxide. Cavitation is largely an unintentional by-product of man's activities; typically occurring in the wake of ship propellers. It consists of the rapid growth and then collapse of small bubbles composed almost entirely of water vapor. Cavitation may be thought of as localized boiling, where the pressure of the water falls briefly below the local vapor pressure. Cavitation is important in ocean engineering due to the damage inflicted on man-made structures by collapsing bubbles. Both cavitation bubbles and bubbles rising from the seafloor

are encountered in the upper ocean, but are peripheral to air–sea interaction. Atmospheric sources of bubbles are a product of air–sea interaction and, once generated, the bubbles are themselves a peculiar feature of air–sea interaction. The major sources of bubbles in the upper ocean are the entrapment of air within the flow associated with breaking waves and with rain impacting on the sea surface.

Once air is entrapped at the sea surface, there is a rapid development stage resulting in a cloud of bubbles. Some bubbles will be several millimeters in diameter, but the majority will be < 0.1 mm in size. Each bubble is buoyant and will tend to rise towards the sea surface, but the upper ocean is highly turbulent and bubbles may be dispersed to depths of several meters. Small particles and dissolved organic compounds very often collect on the surface of a bubble while it is submerged. Gas will also be slowly exchanged across the surface of bubbles, resulting in a continual evolution of the size and composition of each bubble. The additional pressure at depth in the ocean will compress bubbles and will tend to force the enclosed gases into solution. Some bubbles will be forced entirely into solution, but generally the majority of the bubbles will eventually surface carrying their coating and altered contents. At the surface, a bubble will burst, generating droplets that form most of the sea salt aerosol suspended in the lower marine atmosphere.

The measurement of bubbles in the upper ocean depends largely on their acoustical and optical

properties. At the same time, the effect of bubbles on ocean acoustics has long been a major motivation for bubble studies. The generation of noise at bubble inception may be exploited. For example, acoustic measurements of rainfall depend on bubble phenomena. Fully formed bubble clouds attenuate and scatter both sound and light in the upper ocean.

Climatologies of the distribution of bubbles in the upper ocean are based on both acoustical and optical measurements of bubbles. The global distribution of bubbles reflects the dominance of wave breaking as a source of bubbles, and the high sensitivity of wave breaking to wind speed. Bubbles are an important component of global geochemical cycling through their transport of material in the upper ocean and surface microlayer (*see Surface Films*), and especially their role in the air–sea exchange of gases and particles.

## Sources of Bubbles

As described already, bubbles may originate in a variety of ways, but this section will concentrate on the major natural processes of air bubble formation. The atmosphere is clearly a potential source of air bubbles, and generation involves the ‘pinching off’ of part of the atmosphere, or the ‘condensation’ of gases dissolved from the atmosphere within a body of water.

Generation of bubbles within the body of water, when the surface water is sufficiently supersaturated with air, is similar to ‘vapor’ cavitation, but involves the major constituents of the atmosphere (nitrogen, oxygen, etc.) rather than water vapor alone. In the absence of hydrodynamic pressure effects associated with flow, the radial pressure into a cavity,  $P_b$ , is the sum of the atmospheric pressure,  $P_a$ , the hydrostatic pressure at a depth,  $z$ , and a component associated with the surface tension,  $\gamma$ , and the curvature of the cavity (or radius ‘ $r$ ’):

$$P_b = P_a + \rho g z + 2\gamma/r$$

For a bubble to grow, the pressure within a bubble (equal to the sum of partial pressures of the gases diffusing into the bubble), must exceed atmospheric pressure by a margin that increases both with water depth and the curvature of the cavity. A sufficiently large initial cavity is necessary for inception. The explosive dynamics of ‘true’ cavitation are associated with the rapid transport of water vapor across the surface of the cavity. However, the conditions for water vapor cavitation can only be achieved at normal temperatures where pressure is

very low. A sufficient pressure anomaly may occur in an intense acoustic pulse, or in the wake of a fast moving solid object, but is not a common natural phenomenon. The conditions for growth of a bubble by diffusion of atmospheric gases are possible within the normal range of natural variability. For gases other than water vapor, molecular transport of the dissolved gases near the surface of the bubble is sufficiently slow that a virtual equilibrium between the internal and external pressures on the bubble must exist. We might observe bubble generation at home within a bucket of water, or in a soda bottle, where warming induces supersaturation (the solubility of most gases decreases with increasing temperature) and defects in the container walls provide the initial cavity. Warming, mixing, or bubble injection may occasionally force supersaturations of several percent at sea, in which case growth of bubbles on natural particles and microbubbles may release the excess pressure.

Entrapment of air at the sea surface is more common than inception within the body of the water. Most of us are familiar with plumes of bubbles generated by paddling and by boats, but the entrapment of air in the absence of a solid boundary is less intuitive. In general, air is rarely entrapped by enclosure of a large air volume, but is usually drawn into the interior (‘entrained’) where there is intense and convergent flow of water at the sea surface. Sufficiently energetic convergence occurs where precipitation impacts on the sea surface, and where waves break.

Bubble formation is associated with all common forms of precipitation (rain, hail, and snow), but the details of bubble formation are highly specific to the details of the precipitation. In particular, bubble formation by rain is known to be sensitive to the size, impact velocity, and incidence angle of the rain drops. Large drops, exceeding 2.2 mm in diameter, entrain most air. In heavy tropical downfalls, the volume of air entrained can be fairly significant ( $\sim 10^{-6} \text{ m}^3 \text{ m}^{-2} \text{ s}^{-1}$ ), although much lower than rates associated with wave breaking in high winds. Bubbles up to 1.8 mm in radius are entrained by large rain drops, but smaller drops (0.8–1.1 mm in diameter) generate bubbles of only 0.2 mm in radius.

When waves break at the seashore, the large ‘dominant’ waves dissipate their energy partly in entraining and submerging quite large volumes of air. On the open ocean, some of the largest and longest waves break, but wave breaking also occurs at much smaller scales. Some very small breaking events may be too weak to entrain air; however, small but numerous breaking events entraining

small volumes of air occur on steep waves as short as 0.3 m in wavelength. The energy dissipated in wave breaking is derived from wind forcing of surface waves, and the amount of wave breaking and air entrainment is very sensitive to wind speed. The stage of development of the wave field also has some influence on air entrainment – the size of the largest breaking event is limited to the largest wave that has developed.

An important feature of bubble generation at the sea surface is that a myriad of very small ( $< 0.1$  mm radius) bubbles is produced. Very large cavities several millimeters in diameter are likely to be torn apart by large shear forces at the sea surface, but it is difficult to explain how bubbles of  $< 1$  mm might be fragmented. Also, the same processes in fresh water (e.g. a lake or a waterfall) do not produce many small bubbles. The explanation can be found in the influence of dissolved salts on surface forces. In sea water, a surface deformation will tend to grow more and more contorted, so that when a large bubble is fragmented it will often shatter into numerous much smaller bubbles. The same factors will usually prevent the coalescence of bubbles in sea water.

## Dispersion and Development

Bubbles entrained by a breaking wave may be carried rapidly to a depth of the order of the height of the breaking wave by its energetic turbulent plume. For some wave breaking and other forms of bubble production the initial injection will be much shallower ( $\sim 1$ – $100$  mm). Most of the bubbles are very small, but the majority of the volume of air is comprised of fairly large ( $\sim 1$  mm) bubbles entrained by breaking waves. Most of these larger bubbles will soon rise to the surface (typically in  $\sim 1$  s) in a highly dynamic plume close behind the breaking wave. The less buoyant, smaller bubbles are generally carried to a greater depth and are easily dispersed by mixing processes in the upper ocean.

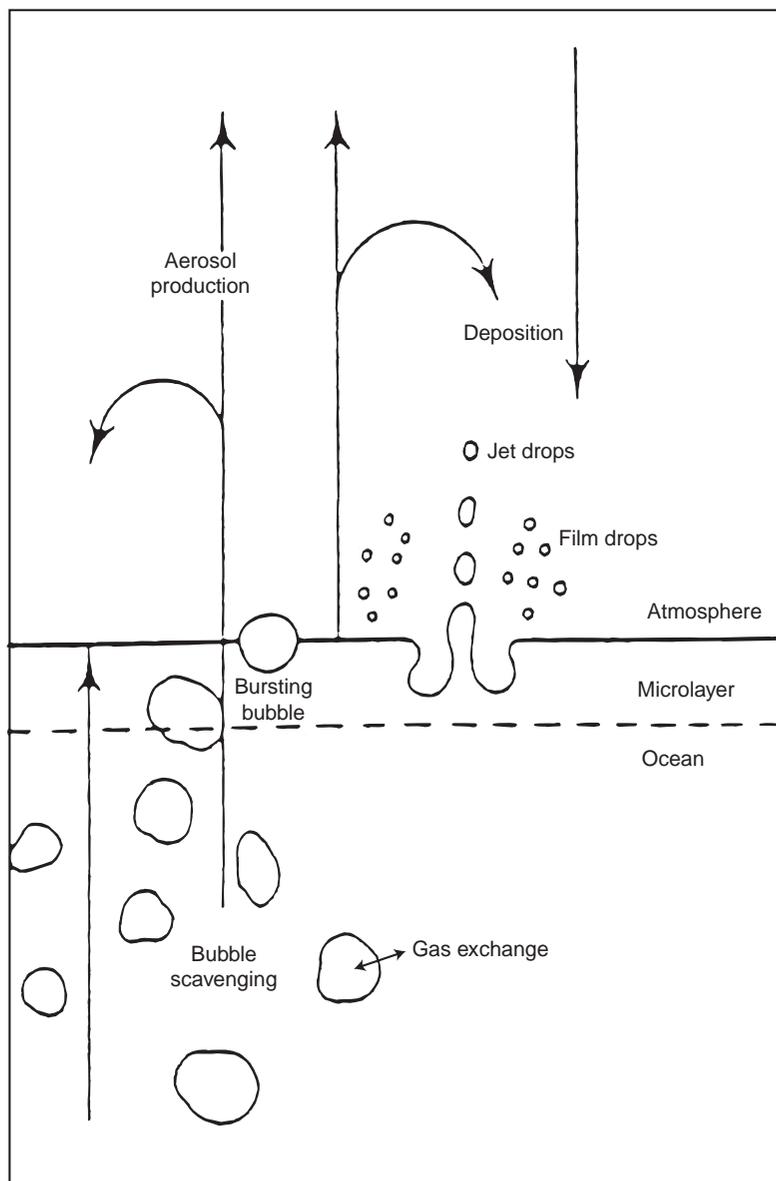
Bubbles are mixed into the ocean by small-scale turbulence associated with the ‘wind-driven upper ocean boundary layer’, but also by relatively large and coherent turbulent structures, especially Langmuir circulation (*see Langmuir Circulation and Instability*). Langmuir circulation comprises sets of paired vortices (cells) aligned to the wind. Bubbles will be drawn to the downwelling portions of the Langmuir cells, producing lines of enhanced bubble concentration, parallel to the wind. Langmuir cells can be up to tens of meters deep and wide, and downwelling speeds may exceed  $0.1 \text{ m s}^{-1}$ . In prin-

ciple, even quite large bubbles may be forced downwards, but generally bubbles of only  $\sim 20 \mu\text{m}$  radius are most common at depths of  $\geq 1$  m. Concentrations fall off rapidly with increasing radius, at radii exceeding the modal radius.

The development of a bubble cloud does not solely concern the movement of bubbles, but also concerns the development of each and every bubble. Material will be transferred between the bubble and the surrounding water as a result of the flow of water around the bubble (largely induced by the buoyant rise of bubbles relative to their surroundings) and molecular diffusion close to the surface of the bubble. This transport plays a large part in the role of bubbles in geochemical cycling, which is illustrated schematically in **Figure 1**. The transport of both volatile (i.e. gases) and nonvolatile substances is of interest.

Nonvolatile substances will not penetrate the bubble itself, but may be transported between the surface of the bubble and the surrounding water. Many substances are ‘surface-active’, that is, they tend to stick to the surface and alter the dynamic properties of the surface. Some substances will already be adsorbed on the surface at the point of formation at the sea surface. During the lifetime of a bubble, further material (both dissolved and small particles) will accumulate on the surface of a bubble. One consequence of the ‘bubble scavenging’ process is the cycling of surface-active substances. Also, the surface-active material will alter the dynamic properties of the bubble, critically affecting the rise velocity of the bubble and transport across the surface of the bubble. A pure water surface is ‘mobile’, but it may be immobilized by surface-active material. The flow near a mobile (or free) surface and a rigid surface is quite different. Generally, a ‘dirty’ bubble with a contaminated, rigid surface will rise more slowly and will exchange gas at a much slower rate compared with a ‘clean’ bubble of the same size. The surface of small bubbles is immobilized by only a small amount of contamination, and bubbles  $< 100$  mm radius are likely to behave as dirty bubbles for most or all of their life. Larger bubbles will also be contaminated, but their dynamic behavior may remain close to that of a ‘clean’ bubble for several seconds (depending on bubble radius and the contamination level of the water).

The transfer of gases across the surface of bubbles is important to the evolution of each bubble, and to the atmosphere–ocean transport of gases. Gases will diffuse across the surface of a bubble. The net transport of each gas across the surface of a single bubble depends on its concentration in the two media and



**Figure 1** A schematic illustration of the role of bubbles in geochemical cycling.

the mechanics of transport:

$$\text{bubble-water flux} = -j4\pi r^2[C_w - Sp_b]$$

As explained in the previous section, the gases within a bubble are compressed so that the pressure of gases in the bubble generally exceeds those in the atmosphere. This excess leads to a tendency for bubbles to force supersaturation of gases in the upper ocean. Many bubbles may be forced entirely into solution (possibly leaving a fragment enclosed in a shell of organics and small particles – a microbubble). The total (integral) effect of bubble clouds on air-sea gas exchange can be described by the

following formula (*see Air-Sea Gas Exchange*):

$$\text{air-sea flux} = -K_T[C_w - Sp_a(1 + \Delta)]$$

(per unit area of sea surface)

$$= K_b[(1 + \delta)C_a/H - C_w] + K_o[C_a/H - C_w]$$

The effect of bubbles on air-sea exchange is described by two coefficients: the contribution to the transfer coefficient,  $K_b$ , and a ‘saturation anomaly’,  $\Delta$ . Both of these coefficients depend greatly on the solubility of the gas and the bubble statistics. For relatively soluble gases, such as carbon dioxide, the

saturation anomaly due to bubble injection is generally negligible, but for less soluble gases, including oxygen the anomaly is usually significant, particularly at high wind speeds. The contribution to the transfer coefficient is again greater for less soluble gases, but is likely to be significant for most gases, at least for high wind speeds.

We have focused on unstable bubbles that will either surface or dissolve within a few minutes of their creation. When a bubble totally dissolves it may leave a conglomeration of the particles and the organic material it accumulated. Some of the bubbles may not entirely dissolve, but may be stabilized at a radius of a few micrometers by their collapsed coating. (The mechanism of stabilization is rather mysterious, external pressures will be high and the coating can not entirely prevent the diffusion of gas, therefore total collapse must be resisted by the structural integrity of the coating – perhaps like a traditional stone wall.) Stable microbubbles might also be generated by a biological mechanism. Microbubble populations are denser in coastal waters where biological productivity and organic loading are generally higher. Microbubbles influence the acoustic properties of natural waters and are a common nucleus for cavitation.

### Surfacing and Bursting

Many small bubbles dissolve in the upper ocean, but generally the majority of the bubbles (and almost all the large bubbles) eventually surface. Phenomena that occur when a bubble surfaces are again significant to geochemical cycling (Figure 1). The release of gas from a bubble to the atmosphere completes the process of air–sea gas exchange mediated by the bubble. The approach of a bubble, or more especially a plume of bubbles, can disrupt the surface microlayer, enhancing turbulent transport directly across the sea surface. The bubble carries material to the sea surface accumulated by scavenging within the upper ocean. Most important are the energetic processes that occur when a bubble bursts on the sea surface. Bubble bursting is responsible for ejecting droplets into the atmosphere, creating the sea salt aerosol. Droplets can also be torn directly from wave crests, but bubbles generate almost all of the very small droplets that are easily suspended in the lower atmosphere and that will be dispersed over large distances. When a bubble surfaces its upper surface will project beyond the sea surface. This ‘film cap’ will drain and shatter. The shattering of the film cap produces ‘film drops’. In some cases, the film cap can shatter into many remarkably small ( $< 1 \mu\text{m}$ ) droplets, while in other cases a few large

$\sim 10 \mu\text{m}$  radius droplets will be produced. The open cavity left after the film cap shatters will collapse inwards, leading to the upward ejection of a ‘Worthington jet’. This jet will pinch off into a few ‘jet drops’. The drop radii will typically be one-tenth of the radius of the parent bubble, producing drops from  $\sim 2 \mu\text{m}$  to tenths of a millimeter in radius from a typical bubble population. The droplets generated by bursting bubbles will be enriched by material brought to the sea surface by the bubble and drawn from the sea surface. The sea salt aerosol will include organic material, metals, viruses, and bacteria.

### Acoustical and Optical Properties

Our knowledge of bubble distributions in the upper ocean is based on acoustical and optical measurements. Bubbles also have a significant impact on the acoustical and optical properties of the upper ocean. The acoustic properties of bubbles have attracted a great deal of attention. The generation of bubbles, both by breaking waves and rain, is an important source of noise in the upper ocean. Bubbles also absorb and scatter sound. The scattering of sound by an individual bubble is frequency-dependent with three primary regimes: close to, above, and below the ‘breathing frequency’ of the bubble. The breathing frequency of a bubble is the natural frequency at which a bubble will oscillate radially (‘breathe’) and is determined by its radius, surface tension, and the external pressure. The breathing frequency is inversely related to bubble radius, and in the upper ocean, bubbles of different radii will respond in resonance to acoustic frequencies from 10 kHz to a few hundred kHz. Scattering cross-sections close to resonance are very high. When the acoustic frequency is much higher than the breathing frequency of the bubble, the scattering by the bubble is related simply to its physical size (‘geometric scattering’). At low acoustic frequencies the acoustic cross-section of an individual bubble is much lower than its geometric cross-section (Rayleigh scattering). The scattering by a bubble is equal in every direction (isotropic) at most practical frequencies, but becomes more anisotropic at very low frequencies. At low acoustic frequencies ( $< 10 \text{ kHz}$ ), scattering is largely a communal response of clouds rather than of individual bubbles.

Many measurements of bubbles have taken advantage of the resonant response of bubbles to sound. In particular, measurements at a number of acoustic frequencies can be inverted to calculate the size distribution of bubbles. A pair of transmitting and receiving ‘transducers’ can measure backscatter

remotely along a profile. This technique has been used to infer the concentration and size of bubbles as a function of depth. The very high scattering by the concentrated plumes near breaking waves defy remote measurement. Instead bubbles near the surface may be studied by measuring absorption or scattering along a short path length. Other techniques include applying the influence of air void on the conductivity of the water, and optical measurements.

Casual observation of the milky water marking a developing bubble cloud is enough to understand that bubbles in the upper ocean can alter the optical properties (e.g. color and brightness) of the sea, but among the numerous and complicated influences on ocean optics, bubbles have received relatively little attention. Bubble populations have been measured photographically, but for the sparse populations a meter or so beneath the sea surface this method is tedious if ultimately effective. Video footage of wave breaking and the early development of bubble plumes can be used to understand the many processes involved.

### Summary of Bubble Distribution

Measurements of bubbles in the ocean are still fairly sparse, and the relationship of wave breaking and bubble injection to environmental conditions is only partly understood, but we can at least summarize the general relationship of unstable bubble populations to wind forcing. Away from the immediate plume of a breaking wave, the mean concentration of bubbles of radius,  $r$ , at a depth  $z$ , typically follows a distribution of the form,

$$N \propto r^{-4} \exp(-z/L)$$

for radii as small as  $30 \mu\text{m}$ , but there is a maximum in  $N$  typically at  $25 \mu\text{m}$  radius. A typical attenuation depth,  $L$ , is 1 m. Some studies have suggested only a weak, approximately linear relationship between the attenuation depth and wind speed, but recent extensive studies imply attenuation depths proportional to the square of wind speed. There are fewer measurements of bubbles in the upper ocean within

half a meter of the sea surface, but it is clear that concentrations are much higher near a breaking wave, and larger bubbles are far more common. The injection rate of bubbles is expected to increase with the third or fourth power of the wind speed. As vertical dispersion of the bubbles (and the attenuation depth) also increase with wind speed, the concentration of bubbles below the sea surface is extremely sensitive to wind speed. Air-sea gas exchange, scavenging, and other geochemical transport processes associated with bubbles will share this sensitivity to wind speed, suggesting that a large fraction of activity may occur in fairly rare storm conditions.

### See also

**Acoustic Noise. Air-Sea Gas Exchange. Air-Sea Transfer: Dimethyl Sulphide, COS, CS<sub>2</sub>, NH<sub>4</sub>, Non-methane Hydrocarbons, Organo-halogens; N<sub>2</sub>O, NO, CH<sub>4</sub>, CO. Breaking Waves and Near-surface Turbulence. Carbon Dioxide (CO<sub>2</sub>) Cycle. Evaporation and Humidity. Heat and Momentum Fluxes at the Sea Surface. Langmuir Circulation and Instability. Photochemical Processes. Sonar Systems. Surface Films. Upper Ocean Mixing Processes. Wave Generation by Wind. Whitecaps and Foam. Three-dimensional (3D) Turbulence.**

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