

Drops and Bubbles in the Environment

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32.1	Introduction	427
32.2	Principles.....	428
	Surface Tension • Dynamics and Shapes of Drops and Bubbles • Wetting: Interaction with Solids • Marangoni Flows • Coalescence, Fracture, and Collapse • Mixing	
32.3	Applications.....	434
	Drops in the Atmosphere • Bubbles in the Lithosphere and Hydrosphere	
32.4	Challenges: Drops and Bubbles in the Biosphere	436
	Drops and the Spread of Life • Health Hazards • Biocapillarity	
	References.....	438

32.1 Introduction

Bubbles and drops are ubiquitous in nature and play critical roles in many important environmental processes. Most familiar is the life-sustaining role of rain. Less familiar are their roles in the thermal budget of the atmosphere, chemical and biological dispersion, volcanoes and exploding lakes, and disease transmission. The goal of this review is twofold. First, we review the fundamental physics of droplets and bubbles, thereby providing a framework for understanding their myriad roles in fluid transport and the sustenance of life within the aqueous and aerial environments. Second, we review the many environmental settings in which they arise, briefly reviewing well-studied problems while highlighting exciting new research directions.

Our review will highlight the processes that enable the creation of drops and bubbles. Bubbles may form in water through exsolution of dissolved gases, as may be prompted by change in chemistry or temperature, or through cavitation resulting from vigorous flow. Likewise, droplet formation in the atmosphere may arise through condensation of water vapor prompted by either cooling or dynamic low pressures. A solid phase can play a critical role in the birth of drops and bubbles: through reducing the energetic barrier to drop and bubble formation, rough solids often serve as nucleation sites. The lifetime of a water drop falling in the atmosphere is generally limited by evaporation and fracture by dynamic stresses, and may be extended through coalescence with other droplets and growth through condensation. Similarly, the lifetime of a bubble in a fluid, be it a lake, ocean, or magma chamber, will be limited by dissolution and

flow-induced fracture, and may be extended via growth through coalescence with other bubbles and exsolution of dissolved gases. The fate of drops and bubbles is thus intimately connected to the chemical, thermal, and dynamic state of the ambient. The interplay between drops and bubbles will also be made clear: droplets impacting a free surface may generate underwater bubbles, while the bursting of bubbles may be a source of microdroplets.

Our review of the basic physics of drops and bubbles will indicate that stable water drops in air or bubbles in water are generally limited in size to the capillary length, a few millimeters. While this size limitation makes them less apparent on the macroscale, it increases their range in the presence of ambient flow, making them more efficient carriers of chemical and biological material. Indeed, our review will highlight the critical role of bubbles and drops in thermal, chemical, and biological transport between atmosphere and ocean, sea, and land. Since biomaterial is often surface active, it tends to adhere to interfaces; hence, bio-dispersion is greatly enhanced by the substantial range of drops and bubbles. Such dispersion can be beneficial, as in the case of the spread of life-promoting minerals or biomaterial in the surf zone, or deleterious, as in the case of pathogen transport in closed environments such as airplanes and hospitals. Finally, our review will highlight the myriad ways in which drops and bubbles are exploited by living creatures for drinking, feeding, and breathing. Just as the subtle water-proofing strategies of plants and insects have provided important guidance in the rapid advances in the development of superhydrophobic surfaces [14], we expect that such natural strategies may inform and inspire new technologies for microfluidic transport and liquid management.

As an important caveat, we note that while this is a review article, the authors were limited to 50 references, making a complete scholarly account of this vast subject entirely impossible. Wherever possible, we have cited the most recent review on the various subjects described. It may thus appear that we are erroneously attributing the work of some researchers to writers of review articles; we thus note that most citations should be accompanied by “and references therein.” We apologize preemptively to those authors whose work is not duly cited. Finally, while we have tried to be objective in terms of topic selection, our review is to an extent idiosyncratic, reflecting our own personal tastes as to what are interesting and important drop- and bubble-related problems. For example, we do not consider non-Newtonian effects as may influence bubbles and drops in complex fluids [9], but instead focus on air–water systems. Moreover, we chose not to consider the use of bubbles and drops in man-made devices with important biomedical and environmental applications, including drug transport, environmental sensing, and surgical ablation via acoustic cavitation.

In Section 32.2, we review the fundamental physics of bubbles and droplets, drawing largely upon the literature in surface physics and chemical engineering. The birth, life, and death of drops and bubbles will be discussed through elucidating the processes influencing their formation, growth, dynamics, and break-up. In Section 32.3, we highlight the roles played by drops and bubbles in the transport of heat, chemicals, and biomaterial in the aqueous and aerial environments, giving particular focus to drops in the atmosphere and bubbles in the hydrosphere. In Section 32.4, we examine some relatively novel problems involving drops and bubbles in the biosphere, including their roles in biodispersion, transmission of respiratory disease, and their myriad uses in the animal kingdom.

32.2 Principles

We begin by reviewing the fundamental physics of bubbles and droplets. The physical origins of surface tension and its theoretical characterization are reviewed in Section 32.2.1. In Section 32.2.2, we briefly review the influence of scale on both the dynamics and the shapes of drops and bubbles. The interactions of drops and bubbles with solids are reviewed in Section 32.2.3, while the role of surface tension gradients in their dynamics is considered in Section 32.2.4. The dynamics of bubble and droplet impact and coalescence on both fluid and solid interfaces are reviewed in Section 32.2.5. Bubble- and drop-induced mixing are discussed in Section 32.2.6.

32.2.1 Surface Tension

Drops and bubbles are, respectively, fluid or gaseous volumes bound by immiscible interfaces characterized by an interfacial tension. A fundamental treatment of drops and bubbles must begin with a discussion of the molecular origins of surface or interfacial tension [17].

Molecules in a fluid feel a mutual attraction. When this attractive force is overcome by thermal agitation, the molecules pass into a gaseous phase. Let us first consider the free surface

between air and water. A water molecule in the fluid bulk is surrounded by attractive neighbors, while a molecule at the surface is attracted by a reduced number of neighbors and so in an energetically unfavorable state. The creation of new surface is thus energetically costly, and a fluid system will act to minimize surface areas. It is thus that small fluid bodies tend to evolve into spheres; for example, a thin fluid jet emerging from your kitchen sink will generally pinch off into spherical drops via the Rayleigh-Plateau instability. If U is the total cohesive energy per molecule, then a molecule at a flat surface will lose $U/2$. Surface tension is a direct measure of this energy loss per unit surface area. If the characteristic molecular dimension is R and its area thus $\sim R^2$, then the surface tension is $\sigma \sim U/(2R^2)$. Note that surface tension increases as the intermolecular attraction increases and the molecular size decreases. For most oils, $\sigma \sim 20$ dynes/cm, while for water, $\sigma \sim 70$ dynes/cm. The highest surface tensions are for liquid metals; for example, liquid mercury has $\sigma \sim 500$ dynes/cm.

The origins of interfacial tension are analogous. Interfacial tension is a material property of a fluid–fluid interface whose origins lie in the different attractive intermolecular forces that act in the two neighboring fluid phases. The result is an interfacial energy per area that acts to resist the creation of new interface. Fluids between which no interfacial tension arises are said to be miscible. For example, salt molecules will diffuse freely across a boundary between fresh and salt water; consequently, these fluids are miscible, and there is no interfacial tension between them. Our discussion of drops and bubbles will be confined to immiscible fluid–fluid interfaces (or fluid surfaces), at which an effective interfacial (or surface) tension acts.

Surface tension σ has the units of force per unit length or equivalently energy per unit area, and so may be thought of as a negative surface pressure. Pressure is an isotropic force per area that acts throughout the bulk of a fluid. Pressure gradients correspond to body forces within a fluid, and so appear explicitly in the Navier–Stokes equations. Conversely, the action of surface tension is confined to the free surface. Consequently, it does not appear in the Navier–Stokes equations, but rather enters through the boundary conditions. Its effects are twofold. First, there is a jump in normal stress at the interface equal to the curvature pressure $\sigma \nabla \cdot \mathbf{n}$, where \mathbf{n} is the unit normal to the interface, and $\nabla \cdot \mathbf{n}$ the interfacial curvature. Second, the jump in tangential stress across an interface is balanced by the local surface tension gradient $\nabla \sigma$ as may arise due to gradients in temperature or chemistry along the interface.

In static fluid configurations, the normal stress balance takes the form $\Delta P = \sigma \nabla \cdot \mathbf{n}$: the pressure jump across the interface is balanced by the curvature pressure at the interface. We consider a spherical bubble of radius a submerged in a static fluid. Its curvature is simply $2/a$, so there is a pressure jump $2\sigma/a$ across the bubble surface. The pressure within the bubble is higher than that outside by an amount proportional to the surface tension, and inversely proportional to the bubble size. It is thus that small bubbles are louder than large ones when they burst at a free surface: champagne is louder than beer. We note that soap bubbles in air have two surfaces that define the inner and outer surfaces of the soap film; consequently, the pressure differential is twice that across a single interface.

Since the boundaries of drops and bubbles typically correspond to jumps in density, there is generally a net gravitational force acting on them: bubbles rise in water, while raindrops fall in air. In such dynamic situations, the jump in normal stress across the interface has a dynamic component and depends on position; consequently, moving drops and bubbles are not generally spherical. The hydrodynamic force resisting motion will in general have viscous, hydrostatic and dynamic pressure components. The relative magnitudes of these various stress components will determine both the shape and the speed of rising drops and bubbles.

32.2.2 Dynamics and Shapes of Drops and Bubbles

Bubbles may be formed in several ways. First, they may be generated by vigorous interfacial flow that mixes a gaseous phase into a liquid phase; for example, the breaking of a wave (Figure 32.1a). Second, they may arise from the exsolution of dissolved gases in a fluid, as arises when one opens a bottle of soda. Third, they may result from vigorous fluid motions that reduce the fluid pressure beneath the cavitation pressure: such cavitation bubbles arise, for example, in the wake of boat propellers. Similarly, fluid droplets may form in a gas phase by one of three principal routes. First, in response to vigorous flow, fluid volumes may fragment to sheets to filaments to drops [49] (Figure 32.1b). Second, drops may condense from moist air, as may arise due to the temperature drop accompanying an atmospheric updraft. Third, vigorous motions within the gaseous phase and associated Bernoulli low pressures can substantially reduce the pressure, thereby facilitating condensation. The generation of drops and bubbles via condensation and exsolution, respectively, is often facilitated by a solid phase providing nucleation sites. We thus present the theory of wetting in Section 32.2.3.

Consider a drop of density $\hat{\rho}$, viscosity $\hat{\mu} = \hat{\rho}\hat{\nu}$, undeformed radius a and surface tension σ falling at a characteristic speed U under the influence of gravity $\mathbf{g} = -g\hat{\mathbf{z}}$ through a fluid of density

ρ and viscosity $\mu = \rho\nu$. The eight physical variables ($\rho, \hat{\rho}, \nu, \hat{\mu}, \sigma, a, U, g$) may be expressed in terms of three fundamental units (mass, length, and time), so Buckingham's Theorem indicates that the system may be uniquely prescribed in terms of five dimensionless groups. We choose $\rho/\hat{\rho}$, $\nu/\hat{\nu}$, the Reynolds number $R_e = Ua/\nu$, the Capillary number $C_a = \rho\nu U/\sigma$, the Weber number $W_e = \rho U^2 a/\sigma$, and the Bond number $B_o = \rho g a^2/\sigma$. The Reynolds number prescribes the relative magnitudes of inertial and viscous forces in the system, the Capillary number those of viscous and curvature forces, and the Weber number those of inertial and curvature forces. We note that we might also have chosen the Ohnesorge number, $O_h = (C_a/R_e)^{1/2} = \mu/(\rho a \sigma)^{1/2}$, which prescribes the relative importance of viscous stresses and curvature pressures. The Bond number indicates the relative importance of forces induced by gravity and surface tension. These forces are comparable when $B_o = 1$, that is, on a length scale corresponding to the capillary length: $\ell_c = (\sigma/(\rho g))^{1/2}$. For a water drop in air, for example, $\sigma \approx 70$ dynes/cm, $\rho = 1$ g/cc, and $g = 980$ cm/s², so that $\ell_c \approx 2$ mm. Water drops are dominated by the influence of surface tension provided they are smaller than the capillary length: when placed on a surface, their tendency to flatten in response to gravity is then overcome by their tendency to remain spherical under the influence of surface tension. As a fluid system becomes progressively smaller, the relative importance of surface tension and gravity increases; it is thus that microfluidic systems are dominated by the influence of surface tension.

A great deal of work has been devoted to measuring and rationalizing the shape and speeds of drops falling and bubbles rising under the influence of gravity. The dependence of drop shape on B_o and R_e is detailed in Ref. [11]. The shape of small bubbles ($B_o \ll 1$) is typically dominated by the influence of surface tension, so they assume a spherical form. At low R_e , the Stokes drag on a bubble of radius a is given by $D = 4\pi\mu Ua$. Balancing this drag with the buoyancy force yields the Stokes rise speed: $U = 1/3a^2g'/\nu$, where $g' = g\Delta\rho/\rho$ is the reduced gravity, and $\Delta\rho$ the density difference between bubble and ambient. As the R_e increases, both the shape

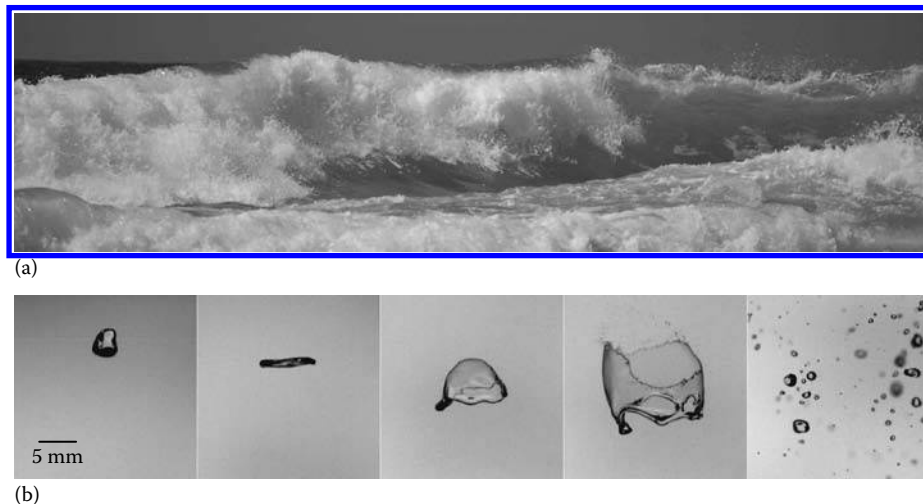


FIGURE 32.1 (a) The surf zone is an important site of drop- and bubble-induced thermal, chemical, and biological exchange between atmosphere and ocean, land and sea. (b) A water drop falls under the influence of gravity. (From Villermaux, E., *Annu. Rev. Fluid Mech.*, 39, 419, 2007. With permission.) The stagnation pressure at its nose causes it to expand into a parachute and then ultimately fracture into microdroplets.

of the bubble and the form of the flow change. The first effect of dynamic pressures on the shape of the bubble is to distort it into an oblate ellipsoid, an effect that can be understood in terms of the stagnation pressures at the nose and tail of the bubble. As R_e increases further, a stable wake adjoins the rising bubble, and the associated pressure difference breaks the bubble's fore-aft symmetry. As R_e is increased progressively, the wake becomes unstable, leading to vortex shedding and an associated path deviation: zig-zag and helical paths have been reported and rationalized [28]. At high R_e , the characteristic drag is associated with the difference in dynamic pressures up- and downstream of the bubble and so takes the form $D \sim 1/2\rho U^2 a^2$. Balancing this with the buoyancy force on the drop yields a steady ascent speed $U_s \sim ((\Delta\rho/\rho)ga)^{1/2}$. Eventually, rise speeds will increase to the point that the associated dynamic pressures ρU^2 cause bubble cleavage. However, there is also a large bubble limit in which bubbles assume a spherical cap form, surface tension is entirely negligible, and there exists a balance between hydrostatic and dynamic pressures along the streamline corresponding to the bubble surface [11].

The progression with increasing size of the shape and dynamics of droplets falling through air is similar. The smallest drops ($B_o \ll 1$, $R_e \ll 1$) remain spherical and settle at their Stokes settling speed. As they get larger, they become distorted by aerodynamic forces, and, eventually, wake instability leads to their being deflected off a straight path, though these deflections are small relative to those of rising bubbles owing to the large mass of the drop relative to that of the shed vortices. At sufficient speed, aerodynamic stresses are sufficient to cleave a falling droplet. Given the critical life-sustaining role of rain drops, it is illustrative to review the considerations that determine their size. Raindrops have a diameter range of roughly

100 μm to 5 mm, and fall at high R_e , so the characteristic drag $D \sim 1/2\rho U^2 a^2$. Balancing this with the weight of the drop yields a steady descent speed $U_s \sim ((\Delta\rho/\rho)ga)^{1/2}$. The aerodynamic stresses experienced by the drop will cleave the drop unless they are balanced by curvature pressures. Specifically, the stagnation pressure on the nose of the drop will cause the drop to balloon out into a parachute before fracturing (Figure 32.1b). Drop integrity requires that $\rho U_s^2 a^2 < \sigma/a$. Substituting for U_s reveals that raindrops will be fractured by aerodynamic stresses unless they are smaller than the capillary length $\ell_c = (\sigma/(\rho g))^{1/2} \sim 2 \text{ mm}$. This simple scaling relation has vast consequences for life: if surface tension was drastically higher, rainstorms would be perilous to humans and fatal for some of Earth's smaller denizens. As we shall see in what follows, however, the nucleation of raindrops would also be more energetically costly, so rain itself more of a rarity.

32.2.3 Wetting: Interaction with Solids

The interaction between fluid drops or bubbles with solids arises in a wide range of problems of environmental significance, including the nucleation of raindrops and the impact of rain on plants and soil. Wetting arises when a liquid-gas interface comes into contact with a solid [17]. The degree of wetting is in general determined by both the material properties of the solid and fluid phases and the topography of the solid surface. Just as a fluid-fluid interface has an associated energy per unit area, so do solid-fluid interfaces. For the case of a liquid-gas interface with interfacial tension σ in contact with a solid, the relevant surface energies are those of the wet and dry surfaces, respectively, γ_{SL} and γ_{SG} (Figure 32.2). The tendency of the liquid to wet the solid

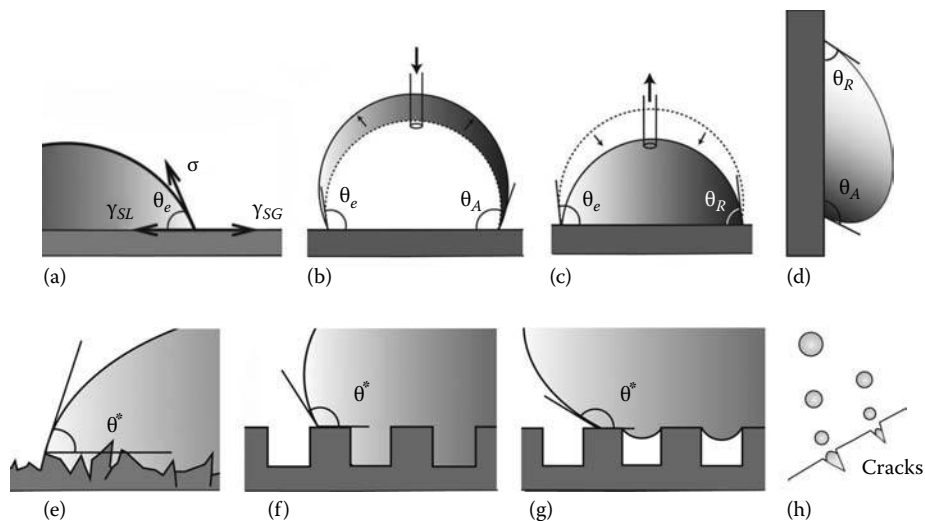


FIGURE 32.2 Wetting. (a) A droplet on a solid substrate makes contact over a region bounded by its contact line. The equilibrium contact angle θ_e is prescribed by the relative magnitudes of the surface energies of the three interfaces: σ , γ_{SL} , and γ_{SG} . (b–c) Static contact angles have a finite range, $\theta_A < \theta < \theta_R$; this so-called contact angle hysteresis results in drops sticking to rigid surfaces, for example, raindrops to window panes (d). (e) Through increasing the energetic cost of wetting, surface roughening generally acts to increase the apparent contact angle θ^* . (f) If the fluid impregnates the roughness elements, a Wenzel state is achieved, and contact angle hysteresis enhanced. (g) If air is trapped within the roughness elements, a Cassie state obtains, the contact angle hysteresis is minimized, and water-repellency achieved. (h) Rough solids may reduce the energetic cost of forming bubbles and drops, and so serve as nucleation sites.

depends on the relative magnitudes of the surface energies σ , γ_{SL} , and γ_{SG} through the spreading parameter $S = \gamma_{SG} - (\gamma_{SL} + \sigma)$. If $S > 0$, the surface energy of the solid is lower wet than dry, so the liquid spreads completely into a thin film. Such is the case for oils spreading on most solids, including glass. Conversely, when $S < 0$, it is energetically favorable for the solid to stay dry, so the fluid remains in the form of a droplet with a finite equilibrium contact angle θ_e (Figure 32.2a). Given σ , γ_{SL} , and γ_{SG} , one can calculate the contact angle θ_e by considering the horizontal force balance at the contact line, $\sigma \cos \theta_e = \gamma_{SG} - \gamma_{SL}$, known as Young's relation. For an air–water interface in contact with a solid, complete wetting arises only if $\theta_e = 0$; otherwise, the normal situation of partial wetting is obtained. The solid is said to be hydrophilic if $\theta_e \leq 90^\circ$, hydrophobic if $\theta_e \geq 90^\circ$, and superhydrophobic if $\theta_e \geq 150^\circ$. Water is totally wetting on perfectly clean glass, but partially wetting on most solids. Given the contact angle and drop volume, the static drop shape is uniquely prescribed by the normal stress boundary condition that applies at its surface: $p_0 + \rho g z = \sigma \nabla \cdot \mathbf{n}$.

While the definition of an equilibrium contact angle is useful conceptually, for a given solid–fluid combination, a range of static contact angles may be observed [17,37]. Consider a drop of fluid emplaced on a solid (Figure 32.2). If the drop is filled, it will grow, and its contact angle increase progressively until reaching a critical value, θ_A , at which the contact line begins to advance (Figure 32.2b). If conversely, fluid is withdrawn from the drop, its contact angle will decrease progressively until reaching a critical value, θ_R , at which the contact line begins to recede (Figure 32.2c). Observed static contact angles θ may thus lie anywhere within the range $\theta_A > \theta > \theta_R$, bounded above and below by the advancing and receding contact angles. This finite range of static values for a given three-phase system results from microscopic surface irregularities, and is referred to as contact angle hysteresis: $\Delta\theta = \theta_A - \theta_R$. An important consequence of this hysteresis is that there is a concomitant force of retention that causes droplets to adhere to surfaces: differences in the contact angle around the perimeter of a drop may result in a net contact force that resists its motion. For example, rain drops may stick to window panes because of the difference in the contact angles on their upper and lower edges (Figure 32.2d), provided the resulting retention force exceeds the drop's weight: $Mg \lesssim \pi R \sigma (\cos \theta_R - \cos \theta_A)$ where R is the drop's contact radius [17].

If a solid surface is not smooth, the microscopic contact angle θ_e will generally differ from that observed on a macroscopic scale, the apparent contact angle θ^* (Figure 32.2e). Moreover, the energetic cost of wetting will depend not only on the surface chemistry (which prescribes γ_{SG} and γ_{SL}) but also on the surface roughness. Consider the case of a water drop on a roughened surface. If the roughness is relatively mild, the water impregnates the roughness elements, and the drop will be in a so-called Wenzel state (Figure 32.2f). If the surface is sufficiently rough, air pockets are trapped beneath the drop, and a Cassie state is attained (Figure 32.2g). In both Wenzel and Cassie states, the apparent contact angle $\theta^* > \theta_e$; however, the contact angle hysteresis is, respectively, increased and decreased in the two states.

The maintenance of a Cassie state is thus critical to reducing the force of adhesion of water droplets on rough solids, and so is considered the primary criterion for water-repellency [37]. It is noteworthy that roughness serves to amplify the intrinsic wettability of a solid: roughening a hydrophobic surface will tend to render it superhydrophobic, while doing likewise on a hydrophilic surface will make it more wettable. Water-repellency is generated in the same way in both plant and animal kingdoms (on plant leaves, animal fur, and bird feathers): roughness increases the energetic cost of wetting a hydrophobic (typically, waxy or oily) surface and so ensures the maintenance of a Cassie state [8].

The presence of rough solids may also facilitate the nucleation of gas bubbles from a saturated fluid (Figure 32.2h), or the condensation of water drops from moist air. It is readily observed that champagne bubbles tend to nucleate at specific points on the walls of a glass. It is less apparent that these points correspond to surface irregularities where either the glass has been scratched or a small piece of cloth has adhered. Such surface irregularities facilitate the degassing of champagne by reducing the surface energy of the incipient bubbles and so reducing the energetic barrier to bubble production. Likewise, adding a teaspoon of salt to a bottle of carbonated soda greatly facilitates exsolution, and can have explosive consequences. In an analogous fashion, particulate matter such as dust encourages the condensation of rain drops in clouds, a matter to be considered further in Sections 32.3 and 32.4.

32.2.4 Marangoni Flows

Marangoni flows are those driven by surface tension gradients. In general, surface tension σ depends on both temperature and chemical composition; consequently, Marangoni flows may be generated by gradients in either temperature or chemical concentration at an interface. Surfactants (or surface-active reagents) are molecules that have an affinity for interfaces; common examples include soap and oil. Owing to their molecular structure (often a hydrophilic head and hydrophobic tail), they find it energetically favorable to reside at the free surface. Their presence reduces the surface tension; consequently, gradients in surfactant concentration result in surface tension gradients and a special class of Marangoni flows. There are many different types of surfactants, some of which are insoluble (and so remain on the surface), others of which are soluble in the suspending fluid and so may diffuse into the bulk. For a wide range of common surfactants, surface tension is a monotonically decreasing function of surfactant concentration until a critical concentration is achieved, beyond which it remains constant. Most organic materials are surface active; therefore, surfactants are ubiquitous in the natural aqueous environment, and their transport via drops and bubbles plays an important role in the biosphere.

The presence of surfactants will generally serve not only to reduce σ but also to generate Marangoni stresses, that is, surface tension gradients. The principal dynamical influence of surfactants is thus to impart an effective elasticity to the interface through suppressing any fluid motions characterized

by non-zero surface divergence. Consider a fluid motion characterized by a radially divergent surface motion. The presence of surfactants results in the redistribution of surfactants: surfactant concentration is reduced near the point of divergence. The resulting Marangoni stresses act to suppress the surface motion, resisting it through an effective surface elasticity. Similarly, if the flow is characterized by a radial convergence, the resulting accumulation of surfactant in the region of convergence will result in Marangoni stresses that serve to resist it. It is this effective elasticity that gives soap bubbles their longevity: the divergent motions that would cause a pure liquid bubble to rupture are suppressed by the surfactant layer on the soap film surface.

Theoretical predictions for the rise speed of very small drops or bubbles do not adequately describe observations. For example, in all but the most carefully cleaned fluids, air bubbles rise at low Re at rates appropriate for rigid spheres with equivalent buoyancy. This discrepancy may be rationalized through consideration of the influence of surfactants on the surface dynamics. The flow generated by a clean spherical bubble of radius a rising at low Re is a familiar one. The interior flow is toroidal, while the surface motion is characterized by divergence and convergence at, respectively, the leading and trailing surfaces. The presence of surface contamination changes the flow qualitatively. The effective surface elasticity imparted by the surfactants acts to suppress the surface motion. Surfactant is generally swept to the trailing edge of the bubble, where it accumulates, giving rise to a local decrease in surface tension. The resulting tail-to-nose surface tension gradient results in a Marangoni stress that resists surface motion, and so rigidifies the bubble surface. The air bubble thus moves as if its surface was stagnant, and it is thus that its rise speed is commensurate with that predicted for a rigid sphere: the no-slip boundary condition is more appropriate than the free-slip for small bubbles in contaminated fluids.

The ability of surfactant to suppress flows with non-zero surface divergence is evident throughout the natural world. It was remarked upon by Pliny the Elder, who noted the absence of capillary waves in the wake of ships. The ability of surfactants to suppress capillary waves was also widely known to spearfishermen, who poured oil on the water to increase their ability to see their prey, and by sailors, who would do similarly in an attempt to calm troubled seas [27]. The influence of natural surfactants is often evident as wind blows over puddles. While capillary waves are evident in the lee of the puddle, they are suppressed in the aft side by the surfactants swept downwind. The suppression of capillary waves by surfactant is also partially responsible for the “footprints of whales.” In the wake of whales, even in turbulent roiling seas, one sees patches on the sea surface (of characteristic width 5–10 m) that are remarkably flat. These are generally thought to result in part from the whales sweeping biomaterial to the surface with their tails; this biomaterial serves as a surfactant that suppresses capillary waves. Finally, surfactants may have a dramatic effect on the wettability of rough solids such as the integument of plants,

insects, and birds: by decreasing the equilibrium contact angle below 90° , they may in fact render an initially superhydrophobic surface superhydrophilic. It is thus that chemical contamination can be fatal to plants or sea-going creatures that rely on their water-repellency for survival.

32.2.5 Coalescence, Fracture, and Collapse

Droplets often arise in the form of suspensions, as they do in clouds and hurricanes. Likewise, bubbles often arise in swarms, as they do in magma chambers and volcanic vents. Given the dependence of the speed and transport properties of drops and bubbles on their size, the possibility of coalescence is an important one that has received considerable attention. The most striking coalescence event arises every time a raindrop hits a puddle. When a water droplet is placed on a quiescent water bath, it ultimately collapses into the bath due to gravity; however, this merger is generally delayed because the air layer between the droplet and the bath must first drain to a thickness at which Van der Waals forces between droplet and bath become important, approximately 100 nm. The resulting coalescence may take a number of distinct forms. Complete coalescence arises when the entirety of the drop merges with the underlying reservoir (Figure 32.3b). Partial coalescence arises when only some fraction of the drop coalesces, leaving behind a smaller daughter droplet that is ejected from the bath and bounces several times before itself undergoing a partial coalescence. This coalescence cascade continues until the daughter droplet becomes sufficiently small that viscosity comes into play, and complete coalescence occurs [5]. Droplet–droplet collision and coalescence have also received considerable attention owing to their importance in raindrop accretion in clouds [50]. While the geometry is slightly different, the physical picture is the same: drop merger is anticipated, provided the impact time is greater than the drainage time of the intervening air layer. The coalescence may be partial or complete. We note that when a drop or bubble coalesces at an interface, the impulsive release of curvature pressure generally produces a vigorous vortex ring (Figure 32.3b) that can transport their payload a considerable distance, and so enhance local mixing.

More energetic impacts of droplets on both fluid and solid surfaces have also been examined extensively. Indeed, progress in high-speed videography has allowed workers to go well beyond the original observations of Worthington to elucidate a host of subtle effects that continue to fuel supporting theoretical developments [47]. The normal impact of droplets generally gives rise to interfacial structure, including submerged bubbles and ejected jets, sheets and droplets, whose complexity increases with the energy of impact [36] (Figure 32.3). Jayaratne and Mason [24] considered the case of droplets striking a deep fluid layer obliquely, and experimentally deduced criteria for rebound, partial, and complete coalescence.

Richard et al. [38] have considered the impact of droplets on water-repellent surfaces, and deduced criteria for droplet rebound and fracture (Figure 32.4). In general, one expects

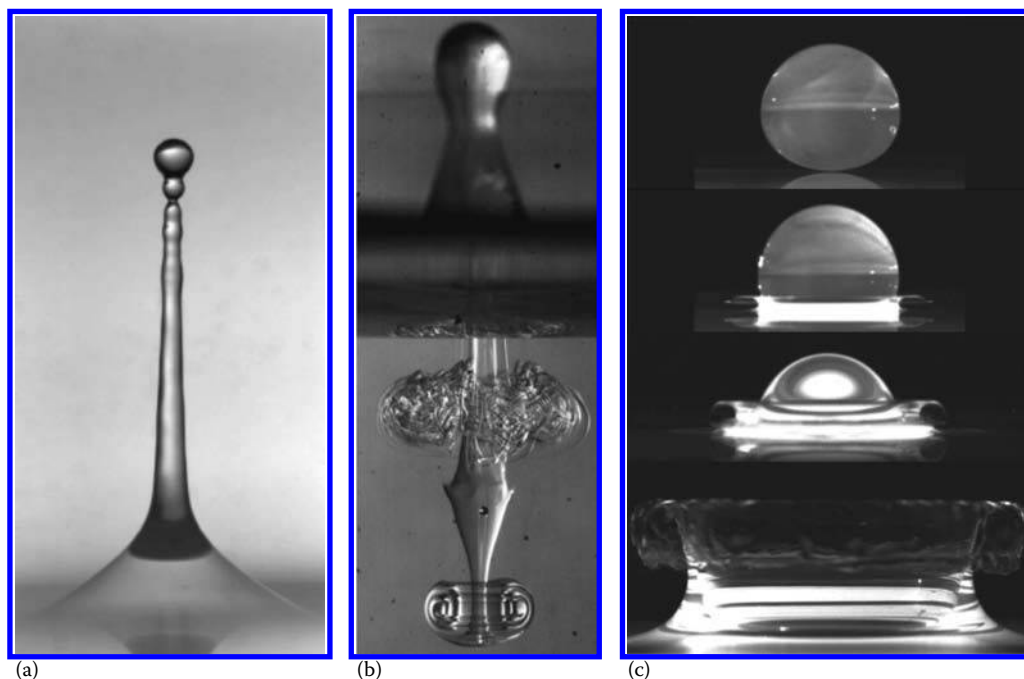


FIGURE 32.3 (a) The Worthington jet resulting from the collapse of the cavity generated by the impact of a 1 mm steel sphere on a water surface. Note the initiation of jet pinch-off via the Rayleigh-Plateau instability. (b) The coalescence of a droplet generates a subsurface vortex that transports the drop fluid downward. (c) The impact of a droplet onto a bath is accompanied by the ejection of a fluid sheet, the collapse of which may generate microbubbles and microdroplets. (a: Courtesy of J.M. Aristoff; b and c: Courtesy of S. Thoroddsen.)

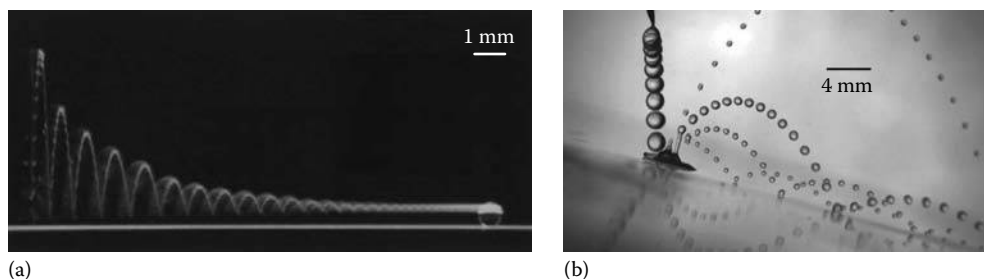


FIGURE 32.4 (a) A water droplet bouncing off a slightly inclined superhydrophobic surface. (Courtesy of D. Quéré.) (b) A silicone oil droplet impacts a thin layer of the same fluid, fracturing then rebounding in the form of four microdroplets. Similar impacts may arise as pathogen-bearing droplets are transported along the respiratory tract. (Courtesy of T. Gilet.)

droplet fracture when the incident kinetic energy exceeds the surface energy of the drop, that is, when the droplet Weber number is greater than one. Moreover, one expects pure rebound only when the substrate is sufficiently rough to resist impregnation and so maintain a Cassie state. Deducing criteria for the rebound and adhesion of impacting droplets is a problem of considerable interest in the design of water-repellent materials; likewise, in understanding the dynamics of rain-splash and its roles in disease transmission between plants and the evolution of topsoil in arid regions (Section 32.4.1).

Bubble bursting may also be accompanied by remarkably subtle structure. Puncturing a bubble composed of a film of thickness h and density ρ causes the resulting hole to expand under the influence of the tensile force per unit length 2σ . If the O_h characterizing the rim is sufficiently low, the rim will retract at

the constant Culick speed $(2\sigma/\rho h)^{1/2}$, engulfing the fluid film as it advances [42]. As the rim grows, it will eventually begin to pinch off via the Rayleigh-Plateau instability. As the resulting bulbous rim regions retract along the curved bubble surface, they may be flung outward and give rise to filaments that themselves pinch off via Rayleigh-Plateau, giving rise to a cloud of microdroplets [25]. This process is illustrated in Figure 32.5 and may play a significant role in the chemical and biological transport between atmosphere and ocean.

32.2.6 Mixing

Quite generally, drops and bubbles represent discrete density anomalies within their suspending fluid, and so are in a dynamic state, either falling or rising under the influence of gravity.

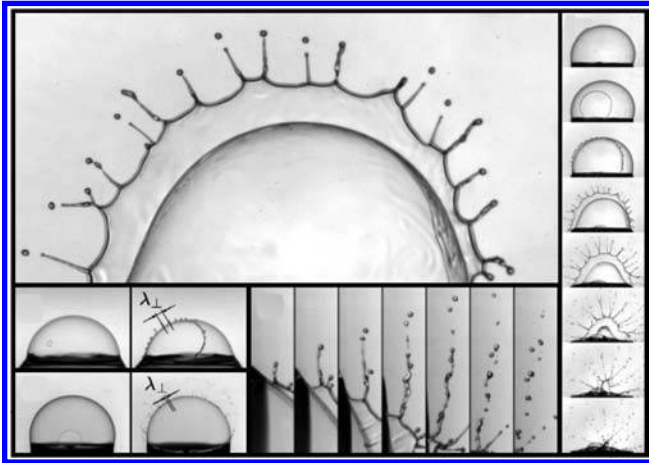


FIGURE 32.5 The fragmentation of a bursting bubble. Puncturing the bubble surface causes its rim to retract, and expel filaments that pinch off into microdroplets. Such a process accompanies bubble bursting in the surf zone, and influences the transport of chemicals and biomaterial between air, land, and sea. (From Lhuissier, H. and Villermaux, E., *Phys. Fluids*, 21, 091111, 2009. With permission.)

As such, they make important contributions to vertical transport and mixing within a two-phase system. Three principal modes of transport may arise. Their first contribution is the most obvious, the vertical transport of the fluid bound within their interface. Second, we have seen that surface-active materials tend to stick to the surface of drops and bubbles. Such material, which may be biological or chemical in nature, will be transported as part of their payload. As we shall see in Section 32.3, this scavenging of surface-active material by bubbles in the ocean and rain in the atmosphere plays a critical role in the biosphere.

The third mode of bubble- or drop-induced mixing results from the rearrangement of the ambient. For example, as a bubble rises at high R_e , it will typically transport ambient fluid in its wake, and also displace ambient fluid forward, the volume of which depends on the volume of the compound body that is the bubble plus wake. Potential flow theory indicates that the volume of fluid displaced vertically across an initially horizontal plane is equal to the Darwin drift volume, specifically, the added mass of the bubble plus wake [28]. This longitudinal dispersion may be accompanied by lateral dispersion in the case of vigorous shedding of vortices from the wake of the bubble. As we shall see in Section 32.3.2, bubble-induced mixing of stratified lakes has a number of important consequences.

It also bears mentioning that drops and bubbles arising in swarms will not necessarily settle or rise, respectively, at the rate expected for individuals. Consider, for example, a swarm of small bubbles that would rise at low R_e if in isolation. Gradients in bubble concentration will generally arise, prompting large-scale convective overturning. In such circumstances, bubble concentration can be considered to some extent as a passive scalar that affects the bulk fluid density as would, for example, temperature; consequently, all the rich behavior of thermal convection can be observed in two-phase fluids. More subtle, novel

features may also arise in two-phase convection as a result of the discreteness of the density anomalies, including the formation of shock-like features. A familiar example arises in a glass of Guinness: the degassing of the beer is marked by horizontal stripes corresponding to regions of high bubble concentration that ultimately go unstable, giving rise to vertical bubble plumes. Similar dynamics may arise in magma chambers (Section 32.3.2).

32.3 Applications

32.3.1 Drops in the Atmosphere

Clouds play a critical role in the Earth's climate through their influence on the water cycle and radiative budget. Clouds are air masses with sufficient moisture to support either water droplets or ice crystals. Cloud droplets (ranging in size from μm to mm) form by condensation from chilled water vapor, while ice crystals form either by the direct deposition of water vapor (reverse sublimation) or by the freezing of liquid droplets [39]. The size, phase, and composition of the droplets determine the macroscopic properties of the clouds, including their spatial extent, lifetime, and radiative properties.

Condensation of pure water vapor into droplets requires higher vapor pressures than are typically found in clouds; however, condensation nuclei are ubiquitous in the atmosphere and facilitate the initiation of the condensation process in both warm (non ice-bearing) and mixed-phase (liquid- and ice-bearing) clouds. Droplets can remain suspended in clouds provided their settling speeds are small relative to the turbulent flow or updraft speed. Within clouds, updrafts of warm air expand and cool, leading to condensation and the release of latent heat; the hot air continues to rise due to its buoyancy. This process continues until some droplets reach a critical size at which their settling speeds exceed the updraft speeds. These large, falling droplets initiate the final phase of raindrop growth, which is dominated by collision and coalescence. Turbulence plays a key role in this last phase, by enhancing the collision and clustering process [45].

Tropical cyclone formation and intensification depend critically on the transfer of heat, moisture, and momentum at the sea-air interface. Moist air and sea spray droplets are the principal source of heat for these storms: the condensation of droplets leads to the release of latent heat at the sea surface and an associated buoyant updraft of warm, moist air. As in clouds, the upwelling of supersaturated air results in its expansion and cooling, leading to further condensation of droplets and the release of latent heat. Provided the droplets so formed fall back and coalesce with the sea before significantly evaporating, there will be a net transfer of heat and buoyancy to the air [2].

Condensation nuclei can be inorganic or organic, insoluble or soluble when wetted. Large condensation nuclei lead to larger droplets that are more likely to trigger precipitation, while a larger number of condensation nuclei lead to the formation of a large number of small droplets more likely to delay precipitation and increase albedo. Hence, anthropogenic and biological particles released into the atmosphere can have a drastic effect

on the formation, evolution, and precipitation of clouds [34]. For the same ambient water content, larger concentrations of condensation nuclei typically lead to the formation of clouds with a larger number of relatively small cloud droplets. Typically, maritime cumulus clouds contain less condensation nuclei, resulting in low concentrations ($\sim 45 \text{ cm}^{-3}$) of large droplets (average diameter $30 \mu\text{m}$); for the sake of comparison, continental cumulus clouds contain a relatively high concentration ($\sim 230 \text{ cm}^{-3}$) of small droplets (average diameter $\sim 10 \mu\text{m}$) [23]. The efficiency of coalescence upon collision increases with the size ratio between the colliding drops. All other things being equal (e.g., moisture and temperature), polluted clouds are less conducive to precipitation owing to the prevalence of more condensation nuclei resulting in small drops with a limited size range [23].

The incorporation of atmospheric aerosols and pollutants into cloud droplets is an important mechanism for atmospheric cleansing and planet-wide aerosol dispersion. Pollutants or suspended components can either play the role of condensation nuclei at the core of raindrops or remain in the cloud as free suspended aerosols that may be removed by adhesion onto cloud droplets. The aerosols, either scavenged during droplet nucleation or coalescence, may then be transported to the ground by precipitation. Indeed, precipitation removes 70%–80% of the mass of aerosols in the tropopause in temperate latitudes, the larger aerosols being removed more efficiently [23]. Some condensation nuclei such as organic compounds and microorganisms are surface active and can give rise to surface films on water droplets that may influence the drop dynamics and resulting cloud properties. Such films can inhibit droplet evaporation and decrease the diffusion of water-soluble compounds into the droplets, thus reducing the efficiency of droplet nuclei scavenging and cleansing. The radiative properties of the cloud may also be altered by the reduction in the UV reaching the droplet interior [19].

Acid rain is a dramatic illustration of the interplay between aerosols and droplets. When the pollution concentration is sufficiently high, the reduction of the rain's pH leads to damage of lake and river ecosystems, forest vegetation, as well as man-made materials and infrastructure. Acid clouds are the result of the scavenging (by nucleation and precipitation) of sulfate- and nitrate-bearing aerosols, such as SO_2 and NO_2 , produced by the combustion of biomass and fossil fuels. Through a chain of chemical reactions, these compounds are converted into acidic sulfates and nitrates, which lower the pH below neutral, resulting in acid rain. Acid deposition poses a similar threat, and occurs when acidic drops come into direct contact with land; for example, when contaminated clouds collide with mountains. The damage resulting from such deposition can be relatively severe since suspended cloud droplets are generally more acidic than the acid rain droplets that strike the ground [43]. Owing to its enormous economic and ecological consequences, the factors influencing the production of acid rain and acid deposition continue to receive a great deal of attention [23,39].

Cirrus clouds cover up to 30% of the Earth's surface and have a major impact on the atmospheric radiative budget.

Condensation trails, or contrails, form behind airplanes in the upper troposphere and are suspected to trigger the formation of cirrus-like clouds. Cirrus and cirrus contrails are both composed of ice particles; however, particles in contrails are smaller and more dense than those in natural cirrus clouds [54]. The cruise altitude of international flights ranges from 8 to 13 km. Two types of contrails are generated by such upper tropospheric flights: engine exhaust and aerodynamic contrails [18]. Exhaust contrails are the result of the mixing of the emitted hot moist gas and the cold, dry ambient. In order to form, the mixture of expelled gas and ambient air in the expanding plume must reach water saturation, in which case water vapor condenses onto the solid particles emitted by the exhaust that serve as droplet nuclei; these droplets subsequently freeze. Downstream, if conditions of ice supersaturation of the ambient are reached, the exhaust particles can also serve as ice nuclei and so directly trigger the formation of cirrus clouds. Aerodynamic contrails can form at higher temperatures than those required for exhaust contrails. They are the result of water condensation and subsequent possible freezing associated with the drop of pressure and temperature resulting from the air's acceleration over the wings [18,54].

32.3.2 Bubbles in the Lithosphere and Hydrosphere

Drops and bubbles generated at the sea surface play a critical role in coastal ecology. Most of the material ejected from the water surface into the atmosphere is due to droplet generation via wave breaking (Figure 32.1a), bubble bursting (Figure 32.5), and the impact of raindrops (Figure 32.3). When bubbles that have scavenged large concentrations of surface-active material (e.g., sea-salt and microorganisms) burst, they release their harvest into the atmosphere. The scavenging process is particularly effective for surface-active microorganisms (e.g., some bacteria) and can lead to the ejection of droplets with concentrations a thousand times higher than in the bulk fluid [4]. The minerals and biomatter produced by the sea and carried inland by droplets are typically advantageous to shoreline vegetation; however, this enrichment of droplet ejecta may have deleterious effects if the water is polluted. Aerosol production and biodispersion in the surf zone remains an active area of research [31].

Volcanic eruptions are characterized by the ejection of magma, a mixture of melt and bubbles; consequently, bubbles play a critical role in their dynamics. Various styles of eruption are observed, from relatively tranquil outpourings of lava to short-lived explosive eruptions, the most violent of which can release vast quantities of particulate matter high into the atmosphere. Indeed, it has been suggested that the biblical plagues of Egypt were a consequence of the particulate matter launched skyward by the explosion of Santorini. The rise of magma from the chambers underlying volcanoes is typically accompanied by decompression and the formation of bubbles of exsolved gas. As they form and expand with increasing height, the bubbles cause the acceleration of the rising melt [20]. The explosiveness of an eruption depends on the magma composition and

viscosity, both of which are greatly affected by the mechanisms of bubble nucleation and growth.

In 1984, 37 people died from the degassing of CO_2 from Lake Monoun in Cameroon. In 1987, a similar eruption of Lake Nyos led to casualties as far as 26 km away. The increase of pressure with depth in the lakes supports the accumulation of dissolved CO_2 at depth, where it leaches in from the underlying volcanic crater. A stable stratification of the lake persists until the bottom layer becomes saturated in dissolved CO_2 , at which point exsolved CO_2 bubbles (10–100 μm) can rise to the surface in the form of turbulent bubble plumes. The trigger for such an event may be any kind of disturbance causing substantial overturn, for example, landslides or vigorous wind-driven flows. As the bubbles rise, they can either reach the surface or be reabsorbed in the upper layer of the lake, where the water remains undersaturated. If they do reach the lake surface, they release a cloud of CO_2 more dense than air that spreads down the mountain as a gravity current and so may suffocate nearby residents. This form of natural bubble-induced disaster is only present in equatorial climates where seasonal mixing of the lakes is precluded, and is now mitigated by controlled degassing of such lakes via artificial bubble plumes [52].

Large quantities of methane hydrates are naturally stored in various geological formations and at the bottom of the ocean. Their stability at depth depends on factors including temperature and pressure [22], which may change in response to sea level changes or landslides, possibly leading to the release of gaseous methane into the atmosphere via bubble plumes. Indeed, adherents to the view of the Earth as a self-regulating organism [26] note that such deposits provide a natural check on runaway global cooling: planetary cooling is necessarily accompanied by the growth of polar ice caps, a concomitant diminution in sea level, and so a release of this greenhouse gas. The analogous capture and storage of anthropogenic carbon dioxide in deep-ocean reservoirs is currently being explored as a means of mitigating global warming. The sequestration of CO_2 might be accomplished by injecting it into either geological reservoirs (e.g., saline formations or depleted oil and gas reservoirs) or into the ocean. In the first approach, the CO_2 is injected at depth in either gaseous or liquid form in order to dissolve it into the ambient fluid or trigger its reaction with local minerals to form solid compounds. In the second, ocean-sequestration approach, liquid CO_2 is injected at depths where it is heavier than sea water, and so sinks to the ocean bottom to form CO_2 lakes [21,52].

32.4 Challenges: Drops and Bubbles in the Biosphere

32.4.1 Drops and the Spread of Life

Drops also play a key role in the spread of life through remote terrestrial regions. Bacteria, pollen, fungi, and marine algae serve as condensation nuclei, thereby enhancing their range of dispersal: clouds can transport and deposit such organisms even to the

remotest areas [29,41]. Such bioaerosols serve as giant condensation nuclei and, when hydrophilic, are particularly favorable to initiating precipitation in warm clouds. A possible feedback loop between biological nucleation of droplets leading to precipitation and the natural emission of bioaerosols has recently been suggested [33].

As well as serving as droplet nuclei, some microbiological and organic material is known to multiply and grow in cloud water [1,41]. The resulting surfactant at the droplet surface can lead to major changes in the cloud microphysics. The increase of anthropogenic pollution, which is known to extend the life of clouds, could enhance this process and lead, in turn, to enhanced microbial activity within clouds [1]. Finally, the enrichment of surface-active organic compounds during the collision-coalescence phase of droplets and their ability to concentrate molecules has been suggested as a medium for key prebiotic reactions, and so may have played a role in the very conception of life [10,46].

Much of the early work on fluid–solid interactions was motivated by the desire to optimize insecticides designed to coat their insect target while leaving the plant unharmed. This task is made all the more challenging since the two coverings are often virtually identical due to their coevolution. Many plant leaves are known to be both water-repellent and self-cleaning owing to their complex surface structure. Their surface is characterized by roughness on two scales (the smallest being submicron) and a waxy coating, which together render it superhydrophobic [8]. When water drops strike a water-repellent plant, instead of sticking, they typically bounce or roll off, taking with them any residual material (e.g., dust, spores, pathogens) that might have collected on the plant. If the impact is sufficiently vigorous, it may lead to droplet fracture and the associated ejection of relatively small droplets [38]. The resulting rain-splash plays an important role in disease transfer between plants [15]. A similar process may arise when rain impacts sandy, water-repellent soils in arid regions, and the associated rain-induced stripping of top soil has been identified as an important contributor to the expansion of deserts [12].

32.4.2 Health Hazards

Bubble-bursting and atomization of jets in recreational and therapeutic aquatic facilities is known to generate pathogenic bioaerosols [4]. In therapy pools, the presence of detergents and elevated temperatures reduces surface tension and enhances aerosol release [3]. Moreover, the bacterial enrichment of the ejected droplets relative to their originating pool is thought to be facilitated by surface-active bacteria aggregating on gas bubble surfaces. Angenent et al. [3] examined the case of a particular therapeutic swimming pool and found greatly elevated levels of several pathogens such as those involved in sinusitis, ear infections, meningitis, and necrotizing fasciitis.

Droplets also play a critical role in the transmission of many respiratory diseases. Exhalation can transform an infectious

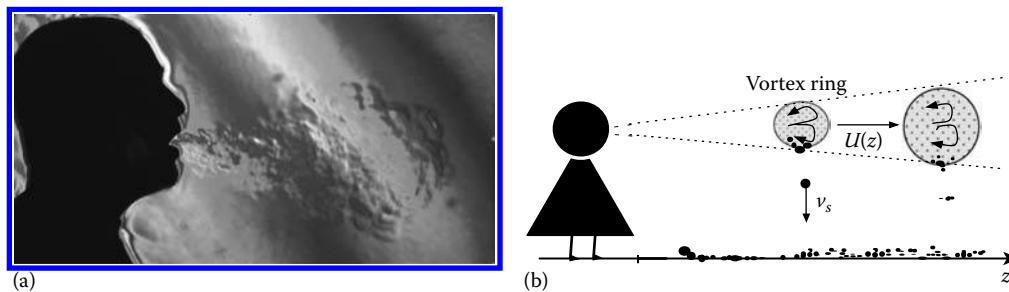


FIGURE 32.6 Coughing and sneezing may be accompanied by the ejection of pathogen-bearing droplets critical to the transmission of respiratory diseases. (a) The cough. (Courtesy of G.S. Settles.) (b) The cough releases a droplet-bearing vortex ring, the dynamics of which determine the range of the pathogens.

patient into a potent source of pathogen-bearing droplets [44] (Figure 32.6). Several routes of respiratory disease transmission have been examined [51]. Large droplet transmission may arise through the spraying of infected droplets via coughing or sneezing directly onto a susceptible host, while airborne transmission may arise through inhalation of relatively small ($<5\text{--}10\ \mu\text{m}$) infected droplets or droplet nuclei, the pathogen-bearing residual solids that survive evaporation. The size of the droplets emitted by exhalation events (e.g., coughing, sneezing, speaking, and breathing) varies from a few μm to 1 mm, but the drop size distribution remains poorly understood [13,30]. As the fate of the emitted drops and their viral or bacterial payload is strongly dependent on their initial size, understanding the formation mechanisms and subsequent dynamics of the emitted droplets will be critical to mitigating airborne disease transmission. While the formation mechanisms of droplets in the respiratory tract have received some attention [6], their subsequent dynamics, including their

impacts within the respiratory tract (Figure 32.4b) and their dispersal via vortex rings (Figure 32.6b), remain poorly understood. The role of droplets in the transmission of infectious diseases in confined environments such as hospitals and airplanes is an area of interdisciplinary research with enormous potential for human impact [13].

32.4.3 Biocapillarity

We have seen in Section 32.2.3 that surface tension dominates fluid systems on a scale small relative to the capillary length. It is thus that the lives of the world's smallest denizens are dominated by the influence of surface tension. Interfacial effects are used by the majority of water-walking creatures for propulsion [7], while bubbles and drops are used by insects and spiders in a variety of ingenious ways, for feeding, drinking, adhesion, and even respiration (Figure 32.7). A number of spiders can survive

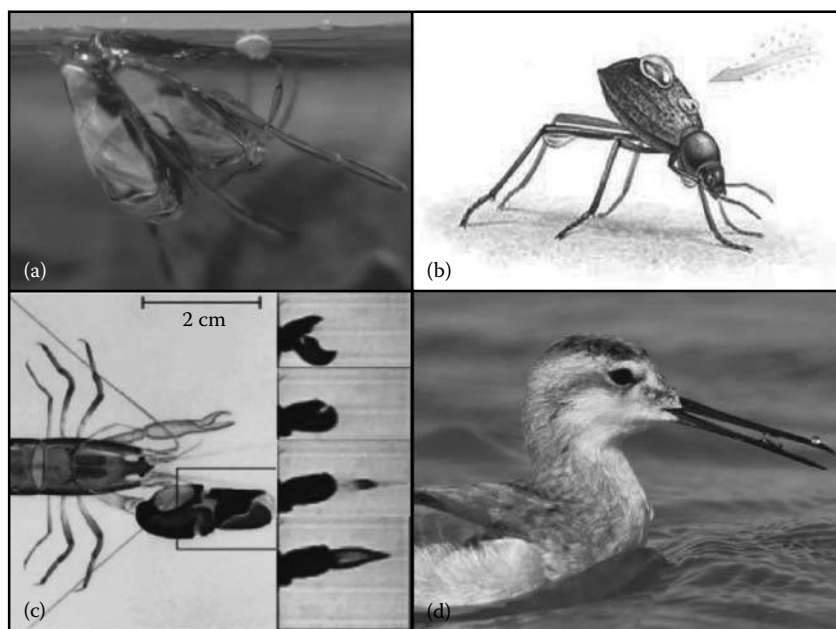


FIGURE 32.7 Bubbles and drops in the biological world. (a) The backswimmer breathes underwater by using its plastron, the thin bubble trapped on its water-repellent surface, as an external lung. (b) The Namib Desert beetle harvests drinking water by condensing fog droplets on its back. (Courtesy of Roberto Osti Illustrations.) (c) The trigger shrimp hunts by propelling a millimetric cavitation bubble toward its prey. (Courtesy of Detlef Lohse.) (d) The phalarope feeds by transporting prey-bearing droplets mouthward. (Courtesy of Robert Lewis.)

stints beneath the water surface using diving bubbles, while some insects employ a plastron bubble trapped on their water-repellent surfaces as an external lung that allows them to remain submerged indefinitely [16] (Figure 32.7a). Many insects, lizards, and birds employ curvature pressures associated with drops to drive flow, assisting them in either drinking or feeding. The interfacial mechanisms exploited by nature are as diverse as life itself. Given space limitations, we here simply highlight three of the more remarkable.

The Namib beetle resides in a desert where it rarely rains; nevertheless, it is able to condense water from micron-scale fog droplets that sweep in daily from the coast (Figure 32.7b). Their surface is composed of hydrophilic bumps on hydrophobic valleys. The fog droplets thus stick to the peaks, remaining pinned there by contact angle hysteresis, then grow through accretion until becoming large enough to be blown by the wind onto the hydrophobic valleys, across which they roll with little resistance. By guiding these droplets toward their mouths, the beetles may thus reap the rewards of the refrigeration-free condenser on their back [32]. This technique has inspired the creation of a new surface, “Super Plastic,” whose analogous ability to condense water is being applied to water harvesting in arid regions of the developing world [53].

The trigger shrimp resides on the ocean floor, and uses bubbles for both communication and hunting [48]. By rapidly closing one of its claws, it ejects a water jet toward its prey at such high speed that the fluid pressure drops below the cavitation pressure, and a millimetric bubble of water vapor forms (Figure 32.7c). When it collapses, the bubble stuns the prey, which then makes for an easy target. The bubble collapse has also been known to emit light, an effect termed “shrimpoluminescence.” This novel hunting strategy, which has been exploited by the trigger shrimp for millions of years, was thus a natural precursor to both depth charges (antisubmarine weaponry) and sonoluminescence.

Phalaropes are shorebirds that prey on small organisms such as miniature shrimp and phytoplankton. By swimming in a tight circle on the surface of shallow bodies of water, they generate a vortex that sweeps their prey upward, like tea leaves in a swirling cup [40]. By pecking the free surface, they capture a prey-bearing droplet in the tip of their beak. Then, by successively opening and closing their beaks in a tweezing motion, they draw the droplet mouthward (Figure 32.7d). This “capillary ratchet” mechanism relies critically on contact angle hysteresis, typically an impediment to drop motion [35].

This class of problems highlights the sensitivity of an enormous class of creatures to contamination at the free surface as may arise from pollution or chemical spills: the resulting alteration of their wetting properties may make it impossible for them to function. Moreover, they suggest novel mechanisms for discrete droplet transport in microfluidic systems. While microfluidics is a relatively new endeavor for mankind, it has long been explored by nature. As water management is a problem of increasing human concern, it would seem prudent to explore and familiarize ourselves with nature’s own ingenious solutions.

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