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11.

11. ***Hills and Sky* by John Ruskin, undated**

Hill and sky mutually reciprocate each other in this Ruskin classic, depicting conditions close to sunrise or sunset. A bank of low, almost wavy *Stratus* or *Stratocumulus* impinges upon the hill summit (right), perhaps created by the hill itself (species *lenticularis*), due to the air being forced to lift over the hill. Patches of *Stratus fractus* lie on the left. At higher elevation, through the gaps in the lower cloud, we can see a broken deck of (probably) *Altocumulus stratiformis*, with the skylight openings revealing a pale blue half-light beyond.

6
5
4
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1

“It may perhaps be allowable
to introduce a Methodical
nomenclature, applicable to the
various forms of suspended
water, or, in other words, to
the Modifications of Cloud.”

Luke Howard, *On the Modifications of Clouds*, 1803

THE
SCIENCE
OF
CLOUDS

STABILITY AND INSTABILITY

The principle of atmospheric stability is key to the understanding of the formation of clouds, as is its direct counterpart, instability. A stable atmosphere is one in which the normal rate of drop in air temperature with height is reduced, or even inverted, creating a stable layer or an inversion that arrests the vertical development of clouds. In contrast, an unstable atmosphere is one in which the air temperature decreases rapidly with height—if this rate of temperature drop exceeds 5.4°F per 1,000 feet (0.98°C per 100 m) of height, a rate known as the "dry adiabatic lapse rate," dry air will rise of its own volition. We often see this happening on a hot summer's afternoon when warm air currents rise rapidly above a hot area of ground.

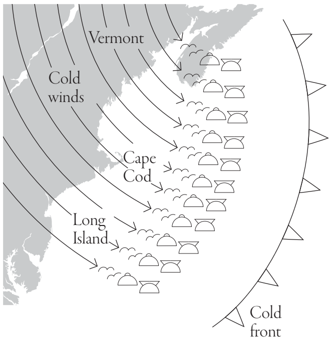
The vertical profile of atmospheric stability and instability therefore not only controls whether air starts to rise, but also whether it continues to rise after the formation of a cloud. For example, if air rising in an unstable environment encounters a layer of stable air during ascent, its upward trajectory may be checked, which can cause the rising air to either spread sideways or to sink back down toward Earth and evaporate again.

The principle of stability

In essence, the principle of stability, or rather its direct opposite, instability, is the same as that of buoyancy—warm air will rise of its own volition until it finds itself at the same density as the surrounding air, in the same way that an inflated ball placed underwater finds itself less dense than the water, forcing it to rise to the surface (see diagram, left). Stable air does not rise freely, as it is not buoyant enough. If it is forced upward, for example, by the wind flowing over a mountain, it will tend to sink quickly back downward on the other side, oscillating a little bit in the process.

STABILITY

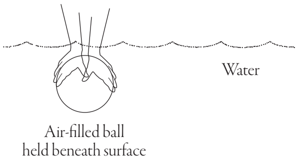
When cold Arctic air moves over warmer ocean waters, moist thermals soon rise, exporting heat and moisture upward to form cloud streets (parallel lines, variety *radiatus*), which gradually grow larger downstream.

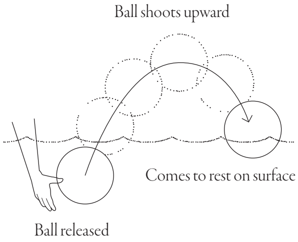


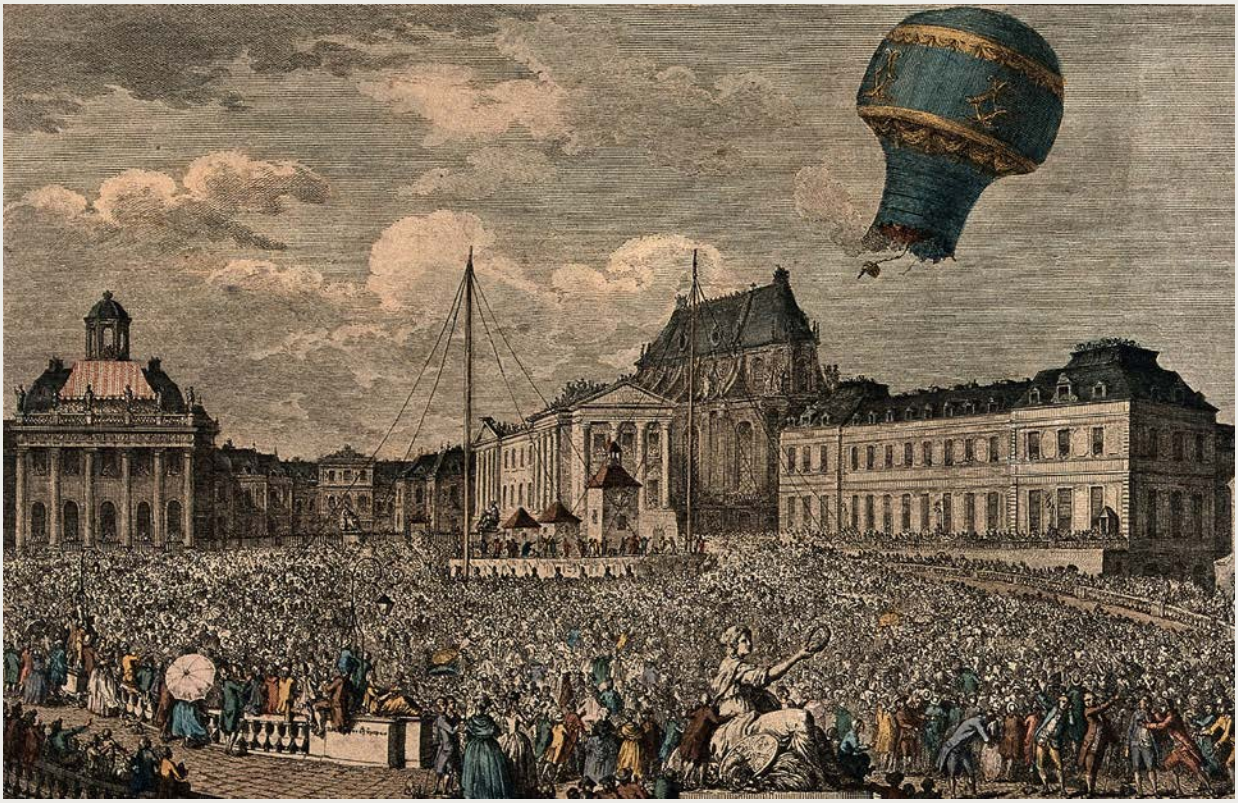
After about 30–50 miles (50–80 km), clouds develop

BUOYANCY

An air-filled ball under water, less dense than water, is forced to the surface.







1.

THE DISCOVERY OF ATMOSPHERIC STABILITY AND CLOUDS

By the 1750s, the scientists and natural philosophers of the Enlightenment had discovered the laws of motion (Isaac Newton, 1687), the latent heat of water (Joseph Black, 1750), and that lightning is electrical (Benjamin Franklin, 1751), but they had yet to grasp the full potential of the principle of atmospheric stability. This would take until 1783, when the Montgolfier brothers used a hot-air balloon to exploit the fundamental physics of the atmosphere and demonstrate the world's first aeronautical flight at the Palace of Versailles, in front of Louis XVI and more than 100,000 spectators. A complete lineage of clouds, based on form, shape, height, and texture, would not become established until the next century, after Luke Howard's *Modifications of Clouds* in 1803.

1. **Montgolfier balloon**
Color etching of a balloon ascent by the Montgolfier brothers at Versailles, France, in 1783.

CASPAR DAVID FRIEDRICH
(1774–1840)

Along with J.M.W. Turner, Friedrich represents the essence of Romanticism—a movement that rejected the tyranny of reason in favor of the greater wisdom of emotion, of the natural over the artificial. Friedrich deliberately diminished the human presence in his landscapes and insisted on an emotional response to the beauty of the natural world, shorn of the appurtenances of industrial civilization. His most famous painting, *Wanderer Above the Sea of Fog*, presents a merged landscape of sky, clouds, fog, and mountains, all contemplated by an awed yet anonymous human observer.

WHAT IS A CLOUD?

Have you ever reached out on a mountain top to try to touch a cloud and been disappointed? Or done the same on a foggy day, but feel like you are reaching into nothing? What, then, is a cloud? How can these "airy nothings" appear to form, grow, dissipate, and redevelop right before our eyes? Can they even be defined accurately within a single moment in time? Or, like most things in the natural world, do they represent instead the evolution of a continual process, one which is constantly growing, changing, and then dying, only to be reborn again shortly afterward?

The reality of the matter is that, although we all know what a cloud is, there is no precise scientific definition of a cloud. This is because it is impossible to say—with the exact deterministic precision required of science—when a cluster of cloud droplets or ice crystals has become dense enough to constitute the rather nebulous term "cloud." Were that even achievable, we would still be faced with many other questions, such as how big should that cluster be? How long should it last? Should it be a visible object, or one that is merely perceived? Should it be detectable at other non-visible wavelengths, such as in infrared light? At what intensities and at what limits of these wavelengths? This lack of precision might be viewed as a bit of an embarrassment for science, but perhaps equally as a win for the arts and humanities.

It seems the best definition that can be offered—at least from the scientific perspective—is one that describes clouds as a myriad tiny water droplets or ice crystals, collectively known as "hydrometeors," suspended in the atmosphere and continually in evolution, either visible or perceived, and which act to influence the everyday weather, as we experience it.

2. ***Wanderer Above the Sea of Fog* by Caspar Friedrich, 1818**
This masterpiece from the Romantic movement is largely artistic rather than meteorological, interpreted as a reflection along life's path. Fog "seas," or *nebelmeer* (as they are known in Switzerland and Germany), are commonly found in winter, when the Alps rise majestically above often persistent and stagnant low-level layers of *Stratus*.

2.

WHAT GOES UP...

Allegedly coined in reference to Isaac Newton's law of universal gravitation, we are accustomed to hearing the adage "What goes up must come down," but we do not often think of it in relation to clouds. And yet, how can those immense towering cathedrals of the sky, drifting by silently above our heads, be apparently unaffected by the same laws of gravity that keep both apples and humans tied to Earth's surface?

The scientific reality of the matter may be somewhat surprising—in truth, clouds are always falling down. In fact, they fall down as frequently as they rise up. The trick that nature plays on us, apart from when it rains, is that we do not usually see them "falling down"—usually we see only the opposite, when they rise. This is because clouds become visible when air rises; they are effective tracers of air that either is rising or has risen recently.

Clouds are the manifestation of both the upward movement of air and the coincidental cooling of air. Rising air expands as it encounters lower air pressure on the way up. This expansion causes cooling—something you may notice when you press the valve on a compressed tire— and is called "adiabatic" cooling. The initial warmer air was invisible before it began to rise and cool. However, cool air is unable to hold on to as much moisture as warm air, and the result is that the excess moisture condenses out of the air into tiny droplets or ice crystals, which on a large enough scale are… a cloud.

These nascent cloud droplets are usually very small in size, with typical diameters of only 2–5 microns, or thousandths of a millimeter, which is similar to the sizes of the pollen grains of most common tree species. Like all objects with mass, they experience the pull of gravity. However, given their tiny size, they fall toward Earth at greatly reduced terminal velocities; the largest cloud droplets fall at only a few millimeters per second, a speed that can easily be overcome by the rising air currents inside a developing cloud.

3.

3. ***Cloud Study (Early Evening)* by Simon Denis, ca. 1786–1806**
Cumulus congestus clouds building in an unstable atmospheric environment. The deep blue sky is suggestive of a polar-air outbreak in fall or winter near the ocean. Denis here employed a minimal strip of ground to emphasize the awesome height and scope of a cloud formation. While higher and more distant portions of these clouds are depicted in full sunlight, breaks within them are edged in the pink of early evening. To record these fleeting effects, Denis painted quickly and without making a preliminary drawing. The study was painted in or near Rome.

4.

5.

… MUST COME DOWN

So, clouds are "falling down" all the time, but to us this is mostly invisible. If we do see it happen, it is only when there is a heavy squall or downpour that approaches us rather ominously as a darkened curtain of precipitation, or *virga*. In this situation, the cloud is indeed falling down as rain, hail, or snow, but it is likely building itself up again on the leading edge of the storm not too far away, and may continue to do so repeatedly.

More commonly, clouds simply evaporate, the sinking motion warming the air as they descend due to the greater air pressure encountered, which causes adiabatic warming by compression. In this way, the cloud simply disappears, often doing so quite rapidly. That does not mean the air stops descending at the point where the cloud is no longer visible—we just cannot see its movement anymore.

The descent of air can be initiated by the simple overturning of rising vortices of air thermals, for example in *Cumulus* clouds, which drag down and entrain drier air from above as they rise, allowing evaporation and subsequent cooling, and therefore encouraging a sinking motion. This process leads to the distinctive cauliflower appearance of a well-developed *Cumulus congestus*. Sometimes, the overturning in a cloud can be caused purely by radiational effects—this refers to the process whereby the top of a cloud, usually a layered one such as *Stratus* or *Stratocumulus*, cools directly to space, in the same way as the surface of Earth cools under a clear sky at night. This causes negative buoyancy: the cooled air sinks, bringing drier air downward into the cloud, evaporating it a little.

On a local or more regional scale, air also sinks after crossing a mountain range, which again causes the adiabatic warming of air, and the evaporation of clouds. Windward-facing hills and mountains in the midlatitudes are often much cloudier and wetter than the surrounding lowlands, being very efficient extractors of moisture from the air. The consequence of this, however, is that leeward (downwind) areas are usually much drier and often less cloudy, due to the local descent of air.

LARGE AREAS OF SINKING AIR

Large anticyclones, or areas of high pressure, cover very wide areas—sometimes continental in scale—and are composed of sinking air. In these huge sinking "blocks" of air, the downward velocity of air is very gentle, typically only a few millimeters to a few centimeters per second, but it is usually enough to evaporate most high-level and mid-level clouds, with any low-level clouds kept close to the surface.

The same mechanism operates in the quasi-permanent hemispheric features of the subtropics known as the Hadley Cells, in which upper air that has originated in convective *Cumulonimbus* cells in the tropics moves toward one of the poles and begins to sink at latitudes of around 25–30°N/S.

4. ***At Hailsham, Sussex: A Storm Approaching* by Samuel Palmer, 1821**
Large turrets of *Cumulus congestus* (right) have already built into a heavy shower (center and left), with a pronounced and dark curtain of heavy precipitation (*virga*) advancing from left to right (as indicated by the tilt of the *virga*)—this cloud is certainly falling down dramatically!

5. ***High Clouds Across the Hudson* by Frederic Edwin Church, 1870**
Two *Cumulonimbus calvus* cells tower above the landscape and reflect the evening light. They must be some distance away from the artist as their bases are obscured, although surface visibility is also restricted by a brown haze on the far side of the lake. A few wisps of *Cirrus* or *Cirrostratus* are evident (top right) against the pale blue, humid atmosphere of the evening.

HYDROSTATIC BALANCE

When the atmosphere is in a steady state of balance between the two principal forces acting upon it, namely the vertical pressure gradient force (pushing it upward from high pressure at the surface toward low pressure at altitude) and gravity (pulling it downward, acting toward the center of Earth), we say it is in a state of "hydrostatic balance," meaning it is in vertical equilibrium or "at ease."

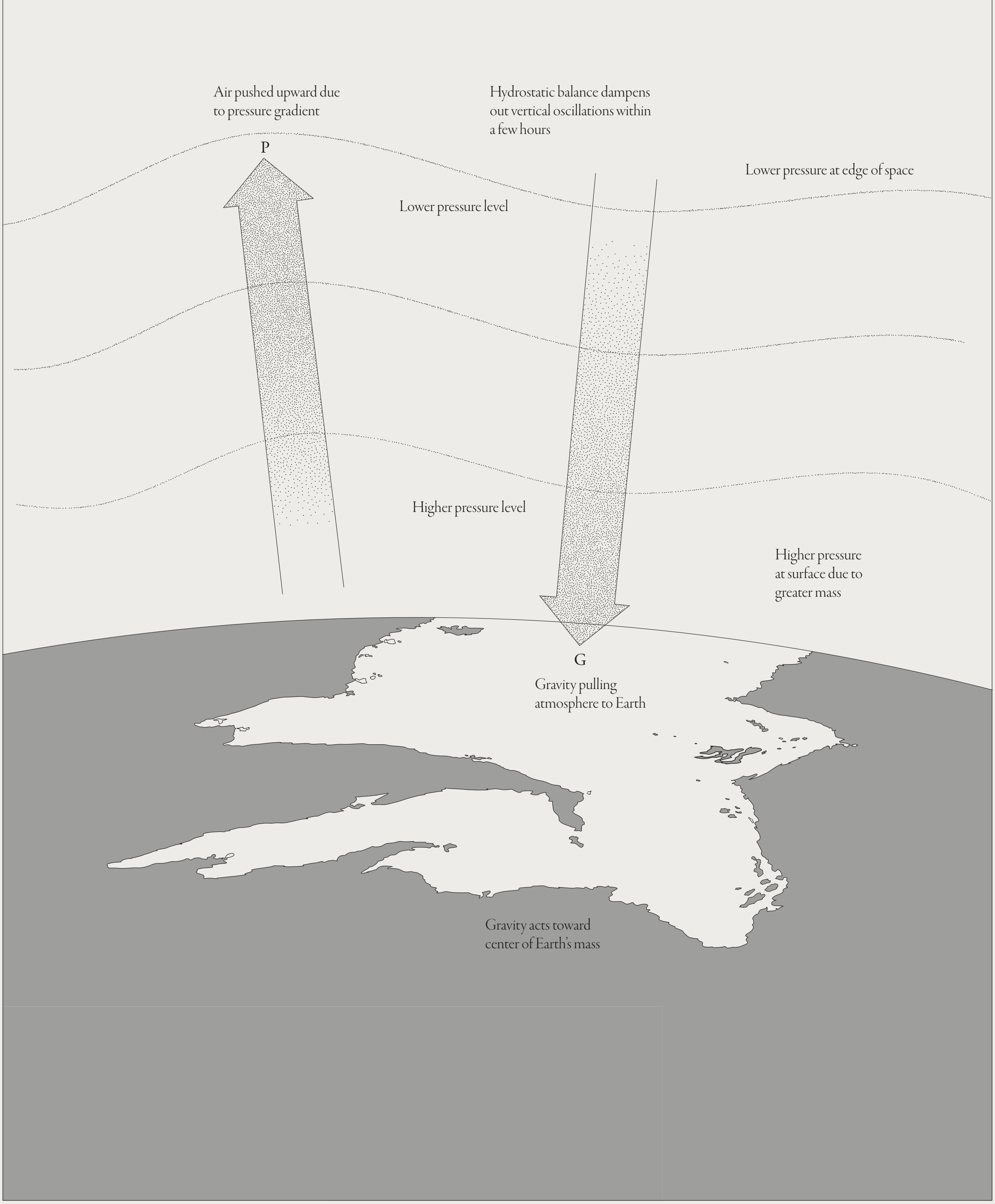
Hydrostatic balance is the normal state of affairs in the atmosphere, and it is the reason why horizontal wind velocities on Earth are much greater than vertical wind speeds: usually by two orders of magnitude or more. This situation occurs almost universally everywhere on Earth, the only exception being inside powerful but highly localized thunderstorm updrafts, when vertical wind speeds approach those of storm-force surface wind speeds—but these are rare and brief departures from the norm.

Here is a classic example. When dry, stable air is forced to blow over a range of hills by a steady, moderate, horizontal wind, after ascending to the summit ridge the air will usually descend back to its initial position on the leeward side in a fairly smooth and wave-like fashion. Indeed, the wave motions usually continue downstream in an oscillatory manner for many tens, or even hundreds, of miles, forming "mountain wave" *lenticularis* clouds (page 156) if the tropospheric profile is suitable, before gradually dissipating.

These wave clouds perfectly demonstrate how the atmosphere always tries to return to its normal state of hydrostatic balance, even though it may not happen immediately—just as when a pebble is thrown into a still pond of water, it takes a little time for the oscillation to dampen down before hydrostatic balance is restored.

Schematic showing hydrostatic balance
Air does not "float," and nor is it "as light as a feather." Like all matter, it has a mass, with a density about 1/1000th that of fresh water at sea level. And similar to all objects with mass, the atmosphere is attracted by gravity toward Earth, keeping it close to the surface. At the same time, as air is compressible, atmospheric pressure is greatest at the surface and decreases rapidly with altitude. This vertical pressure gradient tries to push the atmosphere upward, in direct opposition to gravity. The net effect is a quasi-steady state whereby both forces cancel each other out in hydrostatic balance. Small local deviations do occur now and then near strong weather systems and when air crosses hills and mountains, but these are usually dampened out after a few hours—depicted as minor oscillations in the schematic opposite.

HYDROSTATIC BALANCE DAMPENS OUT VERTICAL OSCILLATIONS



CLOUD CONDENSATION NUCLEI

EVAPORATION OF WATER MOLECULES

Fig. A

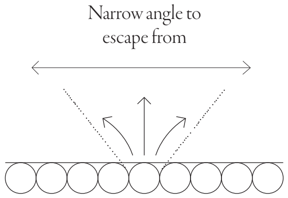
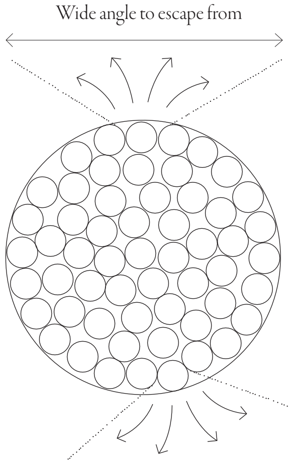


Fig. B



Evaporation
Schematic depiction of water molecules of (Fig. A) water molecules on a planar surface, and (Fig. B) on a curved surface. The molecules in (A) are more tightly bound, whereas in (B) evaporation (escape) is easier. This is why a higher saturation percentage is required to keep droplets from evaporating.

Strange things happen at small scales. This is true even without downsizing to the quantum dimensions of quarks or the Higg's boson, which has a radius of approximately 10^{-18} m and a mass of about 10^{-27} kg. In cloud formation, it is the size of the smallest constituents involved that is important. These minuscule particles are known as cloud condensation nuclei (CCN).

In their original form, CCN can be solid or liquid, and usually consist of sub-microscopic particles of aerosol such as sea salt, dust, or volatile compounds arising from combustion. Although we cannot see them directly, they are all around us, having an average concentration of around 1 million per gallon (3.8 liters) of air. Without them we would have no clouds nor any rain.

Invisible

CCN originate largely from Earth's surface. They can remain suspended in the atmosphere for many days before falling out or being washed out, and are continuously replenished by land and sea. In terms of mass, most of them are extraordinarily small, weighing around 10^{-16} grams (one-tenth of a quadrillionth of a gram) to 10^{-13} grams (one-tenth of a trillionth of a gram). Size-wise, this means that they are usually shorter than the wavelength of visible light, which is 380–700 nm, or 0.38–0.70 microns. They are therefore invisible to the naked eye and impossible to see using an optical microscope, becoming discernible only under a scanning electron microscope.

What have these tiny particles got to do with cloud formation? Well, it happens that water vapor, as a gas, finds it difficult to condense of its own volition in the free atmosphere, even when the air is heavily supersaturated (having a relative humidity above 100 percent). Indeed, spontaneous condensation of cloud water droplets does not occur until very high—and highly unnatural—supersaturations of several hundred percent are reached.

6.

Escaping from the neighbors

Furthermore, the partial pressure of water vapor, which dictates exactly when condensation or evaporation occurs, is lower over the spherical surface of a curved water droplet than over a flat-water surface (because there are fewer molecular neighbors "holding onto" a molecule on a curved surface than a planar one, and increasingly so for the tiniest droplets—see diagram). This means that any spontaneous condensation of liquid water is more than likely to evaporate again immediately. Water vapor as a gas, therefore, needs a strong helping hand in order to condense into tiny droplets, and for them to persist in the air, so that a nascent cloud may form. These helping hands are CCNs, which act as catalysts in the attraction of water vapor.

6. ***Cloud Study*** **by Frederic Edwin Church, 1860–70**
A late-evening scene, with a low setting Sun casting its final rays from the right onto the part of a *Cumulus congestus radiatus* cloud street. *Cumulus* are rich in water droplets, absorbing much light—hence the characteristic level bases (page 98) of the cloud appear dark and threatening. The airmass is clean and unpolluted, evidenced by the polar blue sky background.

THE EQUILIBRIUM RADIUS

CCN are crucial in the creation of embryonic cloud droplets. Acting similarly to chemical catalysts, CCN greatly speed up the process of condensation from gas to liquid by being "hygroscopic" (having the ability to absorb water vapor from the air). Water vapor is therefore attracted to the aerosol, even at relative humidities well below 100 percent saturation.

For example, in coastal areas where the humidity is often high, and where this is a steady supply of oceanic aerosols, such as sea salt, water vapor will condense on such CCN at relative humidities of approximately 78 percent and above, initially forming a haze or mist, which restricts visibility. Over land and continental areas, the same process will also occur on tiny dust or clay particles. This permits the aerosols to grow significantly in size as they scavenge water vapor from the air.

Tipping point

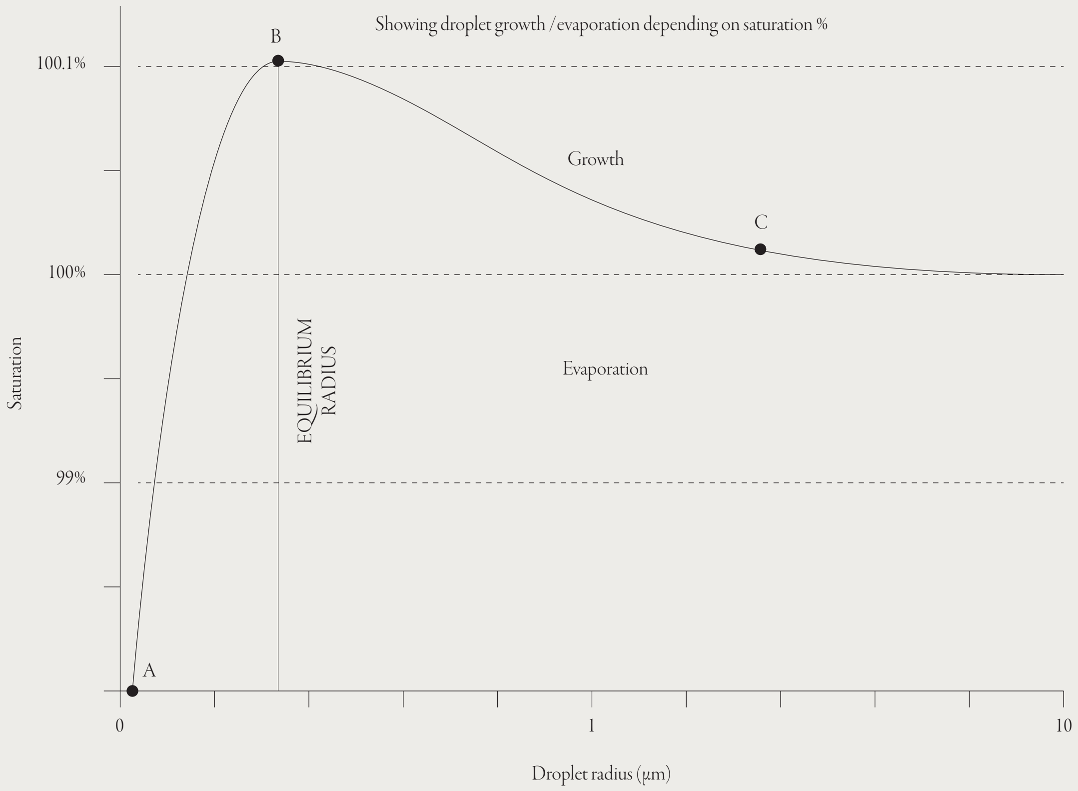
If the relative humidity continues to increase to saturation, or even a slight supersaturation—a little over 100 percent—the CCN will continue to grow until an "equilibrium radius" is reached (see illustration). Such CCN are now said to be "activated" and a stable cloud droplet is born. In equilibrium, typical radii range from a few tenths of microns to a few microns, depending on the type and mass of the original aerosol—they can be as large as 20–30 microns for "giant" aerosols.

When this tipping point is reached, the level of supersaturation required to keep the droplet growing actually decreases as the droplet gets bigger (see illustration, where curve starts to decrease to right). This means that droplet growth is now unimpeded, and it can keep on growing as long as adequate moisture is available. In practice, though, this is not always the case, as other droplets nearby will be competing for the same moisture—as such, if a cloud is to be sustained and generate rainfall, a supply of water vapor needs to be maintained.

Droplets with ambition

So if our growing droplet is to have any ambition of becoming part of a rain cloud, a tentative balance needs to be struck between the rate of production of available water vapor—maintained by the lifting and adiabatic cooling of the cloud itself—and the removal of water vapor through condensation, as well any mixing caused by entrainment of dry air from outside the cloud. If these processes are sustained, it will take at least 20 minutes or so for the cloud droplets to grow by diffusion to a size of 10 microns in radius, even in the most rapidly developing convective clouds (*Cumulus* or *Cumulonimbus*; pages 90–101 and 126–135, respectively).

DROPLET GROWTH/EVAPORATION CURVE



Humidity
As the relative humidity increases from below 99% (point A) to a slight supersaturation of 100.1% (point B), the cloud droplet will grow in size. If, however, the air humidity falls before the droplet reaches point B in size (its "equilibrium radius"), the droplet will start to evaporate. Once the droplet surpasses its equilibrium radius (point B), it can continue to grow, even at lower humidities than at B, for example as indicated by point C on the growth curve. If the humidity drops to values below the curve, however, the droplet will start to evaporate again.

DROPLET GROWTH BY DIFFUSION

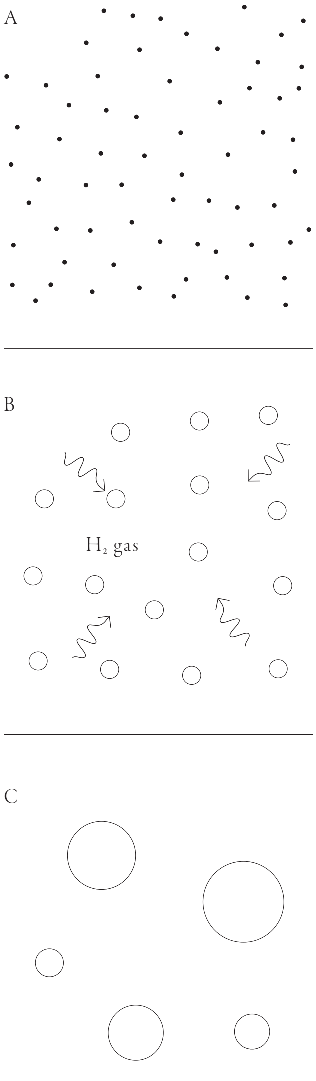
The process that controls how nascent cloud droplets start to grow on CCN is the diffusion of water vapor. Whether we know it or not, we are all familiar with the principle of diffusion: for example, when we enter the door of a café, bakery, or pizzeria, we are usually greeted by a pleasant warm aroma, which is caused by the diffusion (and also convection) of fragrant gases emanating from a kitchen oven or coffee machine, moving toward our noses. In this case, diffusion can be explained as the random movement of gas molecules, which naturally mix and spread out from regions of high concentration to low concentration over time.

In the same way, where there is a high concentration of water vapor—high relative humidity—in the air, gas molecules diffuse from it onto tiny CCN, the process being initiated first by the water-attracting hygroscopic aerosols. The aerosols then grow rapidly in size (within microseconds), as long as water vapor is available. However, as other aerosols nearby will be competing for the available water vapor, such growth is not assured.

Although extremely fast to begin with, the rate of diffusion of water vapor onto a cloud droplet starts to decrease rapidly as the droplet radius increases beyond 2–3 microns—it slows down considerably and takes many minutes more to grow larger than 5 microns, and many hours to grow beyond 20 microns. This is because diffusion becomes increasingly inefficient as the droplet's surface area increases (the surface area of a sphere [$4\pi r^2$] increases in proportion to the square of its radius [r]). The direct consequence of this slowdown in the growth rate of cloud droplets is that most clouds never rain.

Clearly, other processes acting much faster than a few hours are required if a droplet is to continue toward its ultimate destiny of becoming a raindrop. But only a few cloud droplets will ever achieve this, and they are associated with a few specific, special cloud types, usually *Nimbostratus* (page 122), deep *Cumulus* (pages 90–101), or *Cumulonimbus* (pages 126–135). In most non-precipitating clouds, the cloud droplet radius tends to remain in the 5–10 micron range, with a global average of around 6 microns. Such clouds simply do not have sufficient numbers of large droplets to create precipitation—or even if they do briefly, the clouds are too thin and too tenuous for them to endure, or their cloud lifetimes are too short, and any aspiring, suitably sized droplets evaporate soon after leaving the cloud.

DIFFUSION OF WATER VAPOR



Cloud condensation
Schematic depiction of: (A) Cloud condensation nuclei (CCN); (B) Water vapor being attracted to the hygroscopic CCN by diffusion and condensing on their surfaces; (C) Activated large cloud droplets after growth by diffusion and collision and coalescence.

A GROWING DROPLET

There is yet more to come in the existential voyage of a nascent cloud droplet as it attempts to attain its ultimate destiny—one necessary for human life on Earth—that of a raindrop falling to Earth. First, the droplet must grow to a radius of approximately 10–20 microns if there is to be any hope of rain developing, and it needs to do so by diffusion alone. If we pick one droplet at random, such growth is unlikely to occur by diffusion alone, as it would take several hours to achieve a radius of this size. However, if we take a statistical approach and consider the cloud as a whole, which is composed of quadrillions to quintillions of cloud droplets, the chances are much greater that at least one droplet out of all of these will have achieved the necessary size, due to random collisions between the cloud droplets. Some droplets simply get lucky.

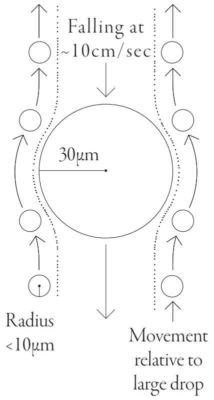
Pinball and dodgems

It is also at this crucial stage of cloud and droplet growth, that other important effects begin to take over and make their influence felt. The principal one is a force that we are all familiar with: gravity. Gravity starts to become significant now because as a cloud droplet's radius surpasses 10 microns, the effects of air resistance start to diminish appreciably, with the cloud droplet's fall velocity increasing to more than 1 cm (0.4 in) per second. This means that it now has the potential to fall through the cloud. And in an ascending updraft of air, it will ascend at a slower rate than its smaller neighbors, increasing the chance of collision. Once a certain proportion of drops reach beyond this critical radius, a game of celestial pinball begins, with the largest cloud drops falling faster (or ascending more slowly) than the smaller ones, causing them to bump into one another like dodgem cars, colliding and coalescing, or breaking up (unlike dodgem cars, thankfully), in a sort of unmitigated chain reaction. As the large cloud drops collect the smaller droplets, they continue to become larger still, and fall even faster, thus increasing the chance of ever more collisions.

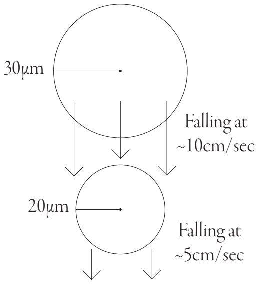
It turns out that cloud droplets in oceanic clouds, which contain "giant" sea-salt CCN, are more likely to reach a critical radius of 10–20 microns within a time frame that is considerably shorter than the lifetime of the cloud itself. This has important consequences for the development of rainfall and explains why *Cumulus mediocris* (page 94) and some *Stratocumulus* (page 112) clouds are more likely to produce precipitation over oceanic and coastal environments than over continental areas. Precipitation can also develop quickly within towering *Cumulus congestus* clouds after approximately 20 minutes, as soon as suitably sized droplets are produced by the diffusion process. Then, the "collision and coalescence" mechanism quickly takes over.

7. ***Clouds* by Thomas Cole, ca. 1838**
A powerful *Cumulus congestus*, likely soon to grow into a *Cumulonimbus calvus* (a non-glaciated *Cumulonimbus*). The characteristic bright white and fractal cauliflower appearance of the rising cloud surface is caused by the cloud's high water content, together with the entrainment of drier air from above as the cloud tower rises. On close examination, there appear to be two or three rings of cloud encircling the cloud summits—these are the variety *velum*, found only with rapidly ascending *Cumulus* or *Cumulonimbus*.

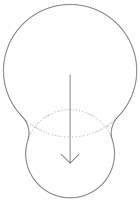
COLLISION EFFICIENCY



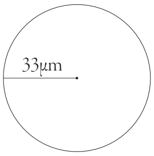
Large cloud droplets fall much faster relative to very small ones, sweeping them aside as they fall.



Similarly sized large droplets are more likely to coalesce together. Here, the faster-falling larger droplet collects up and joins together with the slightly smaller droplet.



The two droplets combine to form a single larger droplet. If conditions remain suitable in the cloud and there are many more collisions, eventually this droplet will fall from the cloud as a raindrop.



BIG DROPS FALL FASTER

It transpires that the collision efficiency of cloud droplets—that is, whether they join together after colliding with one another—depends strongly on their absolute size. The largest drops have the highest collection efficiencies, meaning that they are more likely to coalesce with each other. This is because air has a certain degree of "viscosity," or cohesiveness, which allows small droplets to be swept aside by the air currents surrounding them, but this process becomes less effective for larger droplets. In fact, cloud droplets with radii below 10 microns rarely coalesce. Not all large droplets coalesce, however: they may also split each other apart when they collide.

In the consequent melee of a rapidly developing cloud in which droplet collision and coalescence has begun, we now need to start considering the different fall velocities of the various drops and droplets, both relative to one another and also relative to ascending and descending air currents within the cloud. These are summarized in the table opposite: as one might expect, the larger the droplet, the faster it falls.

When cloud droplets grow beyond a radius of approximately 30 microns (0.03 mm), they are referred to as "drizzle drops." This size coincides with fall speeds of greater than about 4 inches (10 cm) per second: greater than the speed of ascending air currents in most layer clouds, such as *Stratus*. This partly explains why we often experience drizzle from low-level clouds on a damp, humid day, but not from higher-level layer clouds. For example, a drizzle drop of 100 microns (0.1 mm) radius that exits a cloud base at an altitude of 650 feet (200 m) and falls at a rate of 1.8 miles per hour (2.9 km/h) will reach the ground within 4 minutes (see table). However, any drizzle from mid-level cloud is much more likely to evaporate during the longer descent time.

At the other extreme, the largest raindrops fall at speeds of up to 25 miles per hour (40 km/h). At these velocities, they are no longer spherical because they are deformed by the air as they fall, becoming oblate in shape. Raindrops with a radius larger than 3–4 mm are unstable and tend to break apart as they fall.

8. ***Dark Cloud Study* by John Constable, 1821**
This cloud may be dark as seen from below, but only because it is rich in water droplets. Its upper surface is likely to be very bright, reflecting and scattering most of the Sun's rays. The cloud is convective—the texture suggests building heaps of *Cumulus congestus*.

8.

Terminal velocities of cloud droplets, drizzle, and raindrops

RADIUS (MICRONS*)	TERMINAL VELOCITY	NAME	TIME TO FALL 1 KM (0.621 MILES)
0.1	0.001 mm/sec	Cloud condensation nuclei	----
1	0.12 mm/sec	Cloud droplet	----
5	2.9 mm/sec	Cloud droplet	----
10	1.2 cm/sec	Cloud droplet	23 hours
30	10.7 cm/sec	Drizzle	2 hours 35 minutes
100 (0.1 mm)	80 cm/sec	Drizzle	21 minutes
300 (0.3 mm)	2.4 m/sec	Raindrop	7 minutes
3000 (3 mm)	10 m/sec	Largest raindrops	90 seconds

*One micron is one-thousandth of a millimeter (0.00004 inches)

THE DROPLET FAMILY

THE CLOUD DROPLET SPECTRUM

The total number of collisions that a single drop can make during its journey toward Earth can be upward of tens of thousands. This statistic is more easily appreciated looking at the illustration (left), which shows the comparative sizes of a cloud condensation nucleus, a freshly activated cloud droplet, a drizzle drop, and a typical raindrop. Bearing in mind that the volume of a sphere increases with the cube of its radius—the volume of sphere (V) with respect to its radius (r) is given by $V=\frac{4}{3}\pi r^3$—the volume of a 1 mm radius raindrop is therefore 1 million times greater than that of an activated cloud droplet of 10 microns in radius.

Newly formed clouds tend to have a much greater concentration of cloud droplets than older clouds. This is because the droplets have not yet had sufficient time to grow into larger droplets: a process that reduces the total number of droplets but increases their average size and volume. Hence clouds such as *lenticularis* tend to have high numbers of very small droplets (page 156). On the other hand, relatively "old" clouds, such as *Stratus* or marine *Stratocumulus*, tend to have lower droplet concentrations, but with a larger average size.

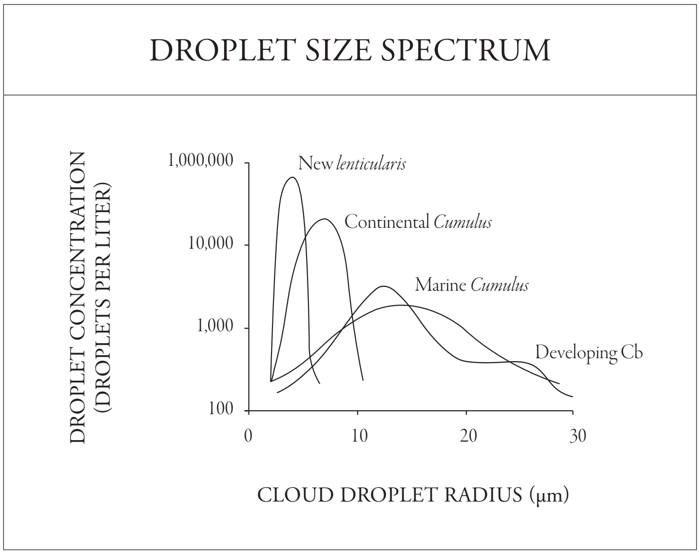
As already mentioned, due to differences between the type of CCN available in oceanic and continental regions on Earth, maritime and coastal clouds tend to have lower cloud droplet concentrations, but with a larger average droplet size than their continental equivalents. In maritime areas, this is thought to be due to the presence of giant aerosols such as sea salt, which scavenge the cloud environment of its tiniest droplets. Having larger activated cloud droplets therefore increases the chance of precipitation, as collision and coalescence can start earlier than in other clouds.

Here comes the rain

Returning to our cloud droplet: once a critical radius of about 10–20 microns is reached, the dual processes of collision and coalescence now start to take over. A rapid broadening of the droplet spectrum ensues, as the larger drops quickly sweep up the smaller ones. If the cloud is shallow in depth, such as in a relatively thick layer of *Stratus* or *Stratocumulus* close to the surface, a slight drizzle may start to fall. Alternatively, in the case of rapidly developing convective clouds such as large *Cumulus* and *Cumulonimbus*, a few fat drops of rain may start to splash down, as these are the only drops large enough to escape the rising updrafts of the ascending cloud.

Recent research increasingly points toward the entrainment of dry air from immediately outside the cloud environment, drawn into the cloud and diluting it as it ascends, as being instrumental in the development of a broad or multi-modal droplet spectra in a convective cloud—a characteristic of mature rain-bearing *Cumulonimbus*. This happens because when dry air is brought into the cloud, the smallest droplets will evaporate first, leaving behind only the larger ones; these may, after a brief period of descent, start to ascend again in a fresh updraft a few minutes later, when they will begin to grow again to an even larger size. This process may be repeated many times over in a large *Cumulus congestus* or in a *Cumulonimbus* cloud, sorting the raindrops (or hailstones) quite efficiently in a mechanism described by the English cloud physicist Sir John Mason as a giant "winnowing" machine (in reference to machines that separate the lighter chaff, or seed casings, from heavier plant or cereal grains). The net result of this is a rapid broadening of the droplet size distribution or spectrum with a long tail toward the right (see illustration below) with occasional multi-modal peaks.

However, these processes are reserved for only a few clouds, those producing precipitation—the fact of the matter is simple: most clouds never rain. Should we spare a thought for the countless quintillions of cloud droplets that "never make it"? All those tiny droplets that never get near the raindrop stage? No need! These so-called "non-achieving" droplets make up the vast majority of clouds that we see and marvel at. Together, they create nature's celestial landscape right before our eyes. Each droplet, big and small, momentary or otherwise, has its own place in the magnificent orchestral tableau of the skies that we call "clouds."



Opposite: Schematic illustration of comparative sizes (scaled relatively) of a typical cloud condensation nuclei, cloud droplet, large cloud droplet, drizzle drop, and raindrop. Also listed are their typical radius (r), concentration per liter (n) and terminal velocity/fall speed (v). Values are based on Macdonald (1958) and Mason (1975).

Left: Schematic example of the droplet size spectrum (their statistical distribution) for four different clouds: *lenticularis* (freshly formed); continental *Cumulus*; marine or oceanic *Cumulus*, and a developing *Cumulonimbus*. The plotted values are approximate: cloud droplet spectra are continuously changing within clouds; no two clouds have the same spectrum.

9. ***Staffa, Fingal's Cave***
by J.M.W. Turner, 1832
It's a common enough squally day on the west coast of Scotland. A shaft of heavy precipitation (right) falls from a passing *Cumulonimbus*, the tall cloud creating great contrasts between light and shade. Surface visibility appears restricted to only a few miles by buoyant sea spray, which lends a pale yellow hue to the watery skies. The sea is raging, but the steamer boat appears to be coping; its lofting, dispersive plume tells us both the direction of the gale and alludes to the unstable but well-mixed state of the lower atmosphere.

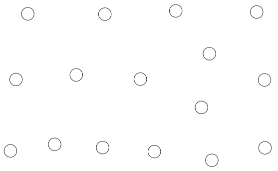
ICE CRYSTAL GROWTH

So far we have only dealt with *liquid droplets* that lead to the formation of rain within clouds in a mechanism described by atmospheric scientists as the “warm rain” process, even if the droplets involved are really quite cool or indeed cold (but not frozen). This warm rain process is common in tropical and subtropical climates, and in warm seasons elsewhere, especially at low and midlevels in the troposphere. However, away from the tropics, a far more important rain-producing mechanism is often at work, mainly at mid- and upper levels of the troposphere, and particularly during the passage of weather fronts and cyclonic weather systems whose coherent cloud structures often reach up to these levels.

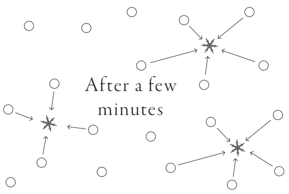
Contrary to intuition, supercooled liquid water droplets can exist quite freely in clouds right down to temperatures of -4°F (-20°C) and below, as spontaneous freezing of all liquid water droplets in a cloud does not occur until an ambient temperature of -36°F (-38°C) is reached. However, if a frozen ice crystal or a “seeding particle” is introduced into a strongly supercooled cloud, freezing will usually take place immediately, and spread throughout the cloud within a few minutes in a rapid chain-like-reaction (see *cavum*, page 199). This is because the degree of saturation required for ice crystals to form in a cloud is lower than its equivalent for liquid water droplets (see illustration, left)—at an air temperature of -22°F (-30°C), when the relative humidity with respect to ice is 100 percent (saturated), it is only 75 percent with respect to water (unsaturated), so only ice crystals can form. This important attribute arises because of the stronger intermolecular bonds in ice crystals, compared to those in liquid water droplets.

Once ice crystals start to grow in very cold clouds, they do so through the diffusion of water vapor onto their crystal surfaces *at the expense of* liquid water droplets. The ice crystals therefore grow quickly, scavenging nearby water droplets as well as additional moisture from surrounding air, because the humidity threshold required for their growth is much lower than for water droplets. Soon, these crystals will be large enough to fall to Earth, growing even bigger as they pass through other clouds on their descent (again, by scavenging their water), before finally melting into raindrops in the final few thousand feet, if the surface air temperature is a few degrees above freezing point.

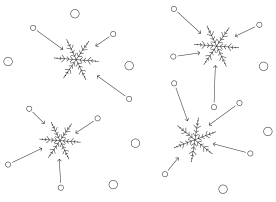
GLACIATION



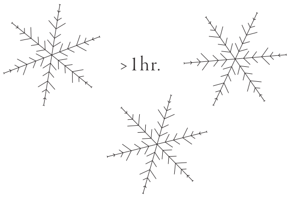
Stage 1 Water droplets only



Stage 2 Ice crystals develop



Stage 3 Ice crystals grow at expense of water droplets



Stage 4 Glaciation complete

Glaciation stages
Stage 1: Supercooled water droplets suspended in a cloud with a temperature of well below freezing and at a humidity saturated with respect to ice. Stage 2: Introduction of ice nuclei, allowing the commencement of freezing and growth of ice crystals at ice nucleation sites. Stage 3: Rapid growth of ice crystals at the expense of cloud droplets. Stage 4: Glaciation complete, the cloud now consists of ice crystals only, which, if large enough, will begin to precipitate toward Earth.

10.

A large range of ice crystal shapes, or "habits," exist, such as hexagonal plates, ice columns, needles, and small dendritic snowflakes. Large snowflakes do not aggregate together until the lowest levels of the troposphere, close to the melting point of 32°F (0°C). This is why snowflakes tend to remain small during the coldest snowstorms, but are large and feathery in heavier and wetter falls, which usually take place at an air temperature near freezing point.

The cold precipitation mechanism described here is known in meteorological circles as the Wegener–Bergeron–Findeisen process, after the three scientists who first theorized it in the early twentieth century, namely Alfred Wegener, Tor Bergeron, and Walter Findeisen. It is a critical and fundamental part of the meteorological operation of the atmosphere, without which we would, quite literally, die of thirst, because much of the precipitation falling across the middle latitudes originates in this way.

10. ***Ice Clouds over Coniston Old Man* by John Ruskin, 1880**
A gap in the cloud layers reveals high-frequency *undulatus* billows (top left), as well as dark lower-frequency *Stratocumulus lenticularis* mountain waves (lower third). These mimic the general topography but appear to obscure most of the mountain view. Some of the other waves (left of center) appear to be an expressionist depiction of local turbulence. The low-level *Stratocumulus* clouds are certainly not frozen, although the higher white clouds (upper center) may represent icy *Cirrocumulus* or *Cirrostratus*.

CLOUDS AND RADIATION

Absolute zero—zero Kelvin, or -459.67°F (-273.15°C)—is the lowest possible theoretical temperature. All objects that have a temperature above it therefore contain some energy; as a result, they will emit some form of electromagnetic radiation, such as microwaves, visible light, or X-rays. The type of radiation an object emits depends on how hot it is, according to a relationship known as the Stefan–Boltzmann law.

As the Sun's surface temperature is approximately 10,800°F (6,000°C), the Stefan–Boltzmann law states that solar radiation emitted from it peaks at visible wavelengths of about 500 nanometers (0.5 microns, near what we call the color blue) but also covers a large proportion of the ultraviolet and near infrared parts of the electromagnetic spectrum. In contrast, radiation from objects at everyday temperatures—including terrestrial radiation from Earth and its envelope of clouds, which largely lie in the range of approximately -100°F to +100°F (-73°C to +38°C)—is almost entirely infrared, peaking at about 10,000 nm (10 microns, or 0.01 mm). Because of its longer wavelength, and therefore lower frequency, infrared radiation carries less energy than solar radiation.

Clouds, like any other object, intercept, reflect, absorb, and re-emit different forms of electromagnetic radiation. This can happen in a variety of ways. Regarding solar radiation, clouds may intercept a proportion of it and absorb it, or, depending on their albedo (reflectivity), they may reflect it. (Some upper cloud surfaces are brighter than others—page 73—which also means some cloud bases are darker than others too). As all clouds have temperatures within the modest terrestrial range as stated above—they principally emit infrared radiation both to the ground and the sky above, or to other clouds nearby. These clouds will then absorb and re-emit infrared radiation themselves in the same manner.

Humans are able to perceive only a very small fraction of the electromagnetic spectrum, namely visible light (300–780 nm, or 0.3–0.78 microns), which we can see, and infrared radiation, which we feel as heat gained or heat lost. Without the necessary equipment and instrumentation, it is impossible for us to detect most other types of electromagnetic radiation, although we may experience its consequences, for example when ultraviolet radiation causes sunburn.

(continued...)

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