Condensation in the atmosphere

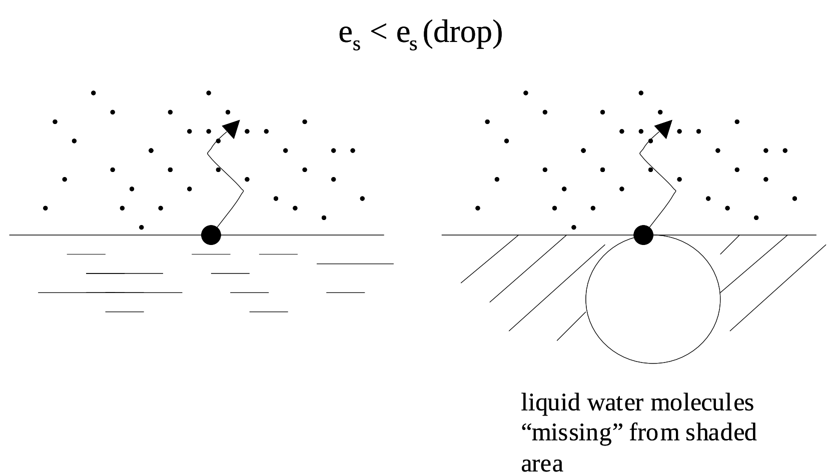
We are familiar with condensation forming when air is cooled to its dew point – condensation on a glass or can taken from a refrigerator, for example. In native, dew is formed almost every night on the grass or other vegetation, and as frost if the surface temperature is below 0 ^oC.

Our interest here is in condensation in the form of clouds or fog in the atmosphere. For the initial formation of minute droplets of water in the atmosphere, it is necessary to consider two additional factors. These are:

1) the radius or curvature effect, and
2) the solution effect

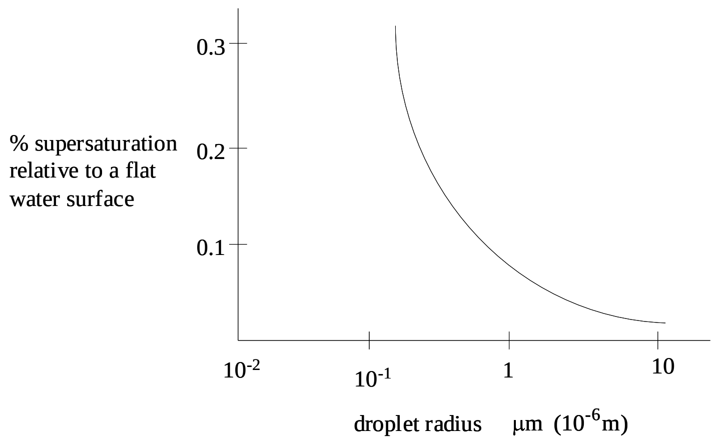
The radius or curvature effect

The equilibrium (saturation) vapor pressure e_s with respect to a small droplet of water is greater than that over plane water surface. This is because molecules at the surface of small, microscopic droplets are bound less strongly to the droplet than would be the case for a flat water surface. Since molecules can escape more easily, a high vapor pressure in the surrounding is needed to maintain equilibrium (zero net growth or evaporation).



Thus it is necessary to have certain degree of supersaturation (with respect to a flat water surface) in order to maintain a small droplet in equilibrium. The percent supersaturation needed for equilibrium is inversely proportional to the radius of the drop.

% supersaturation $\propto$ 1/deoplet radius



The question arises: “how does a droplet first form, because initially it would be a conglomeration of only a few molecules; it would be very small and would need a very large degree of supersaturation to prevent it from evaporating?”

The answer is that condensation nuclei (particles) in the atmosphere provide a surface on which microscopic droplets can form. The most common condensation nuclei in the atmosphere are particles of sea salt (NaCl). In fact, the atmosphere is loaded with condensation nuclei, roughly 10^5 per liter. Clearly, the intention of cloud seeding, which is artificially introducing particles of silver iodide or dry ice into the atmosphere, is not to enhance the condensation process. Condensation will occur in the atmosphere at the slightest degree of supersaturation and needs no help from us. As we will see later, cloud seeding is meant to enhance the freezing process in “cold” cloud.

Particles of sea salt are “hygroscopic”, wettable, and attract water even at relative humidifies below 100% (the opposite of hygroscopic is “hygrophobic” or non-wettable). This brings us to the second effect.

The solution effect

The presence of dissolved solute reduces the equilibrium vapor pressure below that of pure water so that condensation can occur when $e < e_s$ (defined for pure water), or at relative humidifies below 100%.

We can think of the dissolved solute as inhibiting the loss of water molecules from the surface, meaning that a smaller vapor pressure is needed to maintain equilibrium. The effect increases as the concentration of solute increases. Thus, for a fixed mass of solute (originating as a small salt particle, say) the concentration and the effect increase as the droplet becomes smaller, or vice versa.

Since concentration $\propto$ 1 /(radius)^3

While the radius or curvature effect causes the required supersaturation to be proportional to the inverse of the first power of the radius, for very small particles, the solution effect can overcome the curvature effect and small droplets can exist and growth at RH < 100%.

The attached diagram shows the net results of the two effects for four different masses of salt as the nucleus for water droplets. Increasing salt mass implies that a smaller degree of supersaturation is needed for continued droplet growth. Not only that, but because hygroscopic nuclei are “wettable”, they attract water from the atmosphere at relative humidifies even below 100%. For continued growth, however, the relative humidity must ultimately be greater than 100% but the degree of saturation needed is dependent on the mass of solute present in the droplet. For example, with a mass of salt equal to 10^{-13} g, a supersaturation of only 0.01% is needed for continued growth by condensation.

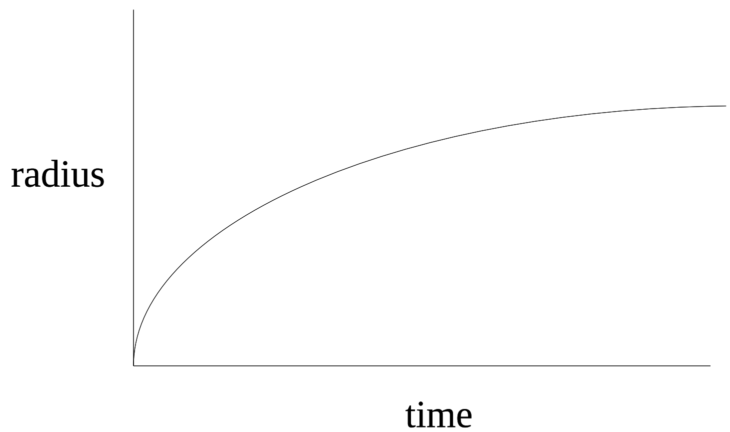
Droplet growth

There are three mechanisms by which droplets grow within a cloud. It is usually a combination of all three of them that produces drops large enough to fall as rain, except in warm climate clouds where only two are sufficient. The three mechanisms are:

1) condensation on existing droplets
2) collision between droplets and coalescence
3) the Bergeron three-phase processes

Condensation

Cloud droplets do not grow large enough by continued condensation of vapor onto liquid drops because the process would take far too long. This is because the surface area of a droplet is proportional to r^2, which the mass of the droplet $\propto r^3$. So, as the droplet grows, the surface area (upon which molecules of vapor condense) does not keep up with the increasing mass, and the rate of increase of droplet radius decreases with time. Schematically, the following diagram shows the change of growth rate with time.



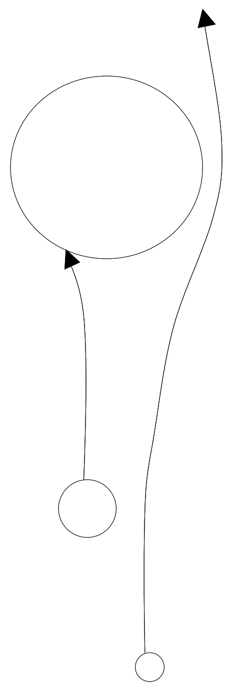
The result is that it is very difficult to create droplets larger than about 20 μm by condensation alone, except in warm, moist tropical climates.

Collision-coalescence

Droplets of different size have differet fall velocities. The smallest droplets will be moving upward with the cloud updraft, while the largest droplets will be falling against such updraft. With such differences, there is the potential for collision between droplets of different sizes and for coalescence of droplets into a single larger drop. Fall velocities (in still air) of droplets of different size are shown in the table below:

drop radius	fall velocity (m/s)
1 μm	1.2 10^{-4} (more than 2 hrs to fall 1 m)
10 μm	1.2 10^{-2} (more than 1 min to fall 1 m)
100 μm	7.2 10^{-1}
1 mm	6.5
2.5 mm	9.1

Droplets of different size will be moving relative to each other within a cloud, with small droplets moving upwards relative to large drop.



The problem is that the collision efficiency is very small for droplets smaller than about 20 μm. Because of their small inertia, such small droplets end to move with the airstream around an approaching larger drop.

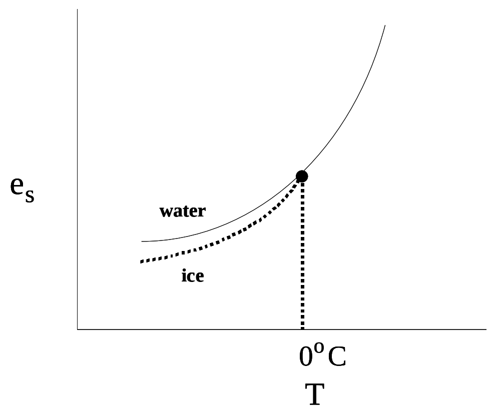
In warm, moist clouds, it is possible for droplets to grow by condensation sufficiently large that the collision/coalescence process can continue their growth. However, in colder climates, such as in the mid and high latitudes, there is insufficient moisture that growth to sizes in excess of 20 μm takes too long.

Bergeron three-phase process (also known as the Bergeron-Findeisen process)

This process refers to the three-phases of water (vapor, liquid, and ice) which must occur together within the cloud.

Two facts are important for this process:

a) The saturation vapor pressure over ice is less than over water (difference of 0.3 mb at –12 ^oC).



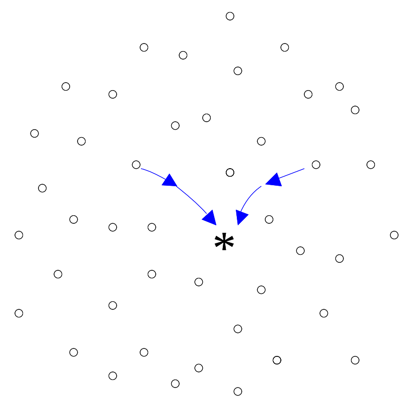
This difference exists because the crystalline structure of solid ice binds molecules of water to the surface more strongly than does liquid water.

b) Ice crystals will not from unless freezing nuclei are present. Ice nuclei in the atmosphere are much less abundant than condensation nuclei – typically 1/liter compared with 10^5/litter. The most abundant icing nuclei in the atmosphere are particles of kaolinite (a clay), which are most effective when temperatures are about –9 ^oC. Thus, supercooled water droplets are common in the atmosphere in clouds, at least between o 0C and about –20 ^oC.

$T > -10\ ^oC$	clouds are mostly water
$-10\ ^oC > T > -20\ ^oC$	clouds consist of water and ice
$T < -20\ ^oC$	clouds are mostly ice

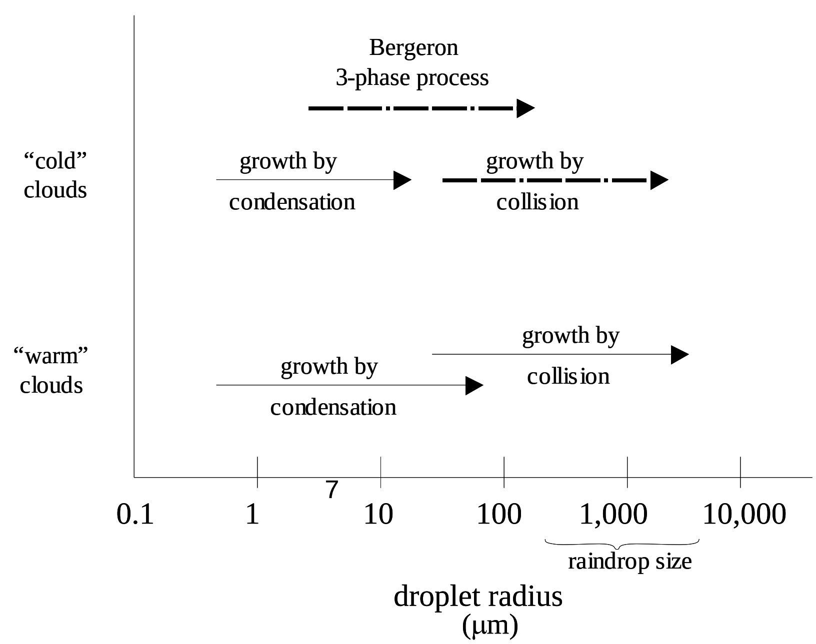
When supercooled water droplets and ice crystals coexist in a cloud, the large number of liquid drops will maintain a relative humidity close to that for water in equilibrium with vapor. However, because e_s (water) > e_s (ice), this will be a state of supersaturation as far as the smaller number of ice crystals is concerned.

Thus, the ice crystals will grow at the expense of the liquid water droplets. Instead of a large number of droplets competing for available water vapor and growing slowly, a small number of ice crystals grow quickly to sizes where the collision/coalescence process takes over.



This is the Bergeron three-phase profess. In mid and high latitudes, most rainfall from “cold” clouds has involved the ice phase but melting occurs as snow or ice pellets fall through the cloud or in the warmer air at lower levels beneath the cloud.

The following diagram summarizes the combination of these growth processes for both “warm” and “cold” clouds.



In “cold” clouds with temperatures substantially below 0 ^oC, it is the Bergeron 3-phase process which bridges the gap so that ice crystals grow preferentially to sizes large enough to take part in the collision/coalescence mechanism.