I
Clouds and Cloud Formation

Cloud Classification and Occurrence

Clouds on Earth appear in seemingly endless variety, from wisps of fog or steam over lakes to huge and imposing thunderstorm anvils. To classify them may seem nearly impossible, but in 1803 the English naturalist Luke Howard (1772–1864) published a classification scheme based on appearance and height. It was by no means the first, but it had such logic and simplicity that it met with immediate and wide-ranging success and remains to this day the basis of cloud classification. Howard's contribution demonstrated that meteorological phenomena are not just random.

Some major cloud types retain the Latin names that Howard gave them (see Figure 2). Cirrus (Latin for "curl," or "hair") are generally thin and wispy, frequently exhibiting a feathery or filamentary appearance. They are the highest clouds. Cumulus ("heap") clouds have a piled-up look. They are cauliflower-like systems, often consisting of roughly spherical bubbles with flat bases. Stratus ("layer") clouds are sheet-like, with little or no internal structure; they are frequently associated with a dull grey sky.

Howard's classification system subdivides these cloud forms by height. Low-lying, sheet-like clouds that sometimes almost touch the ground are stratus. Those at midaltitude are altostratus. (They may show the Sun or Moon as a bright, diffuse glow.) The highest ones are cirrostratus.

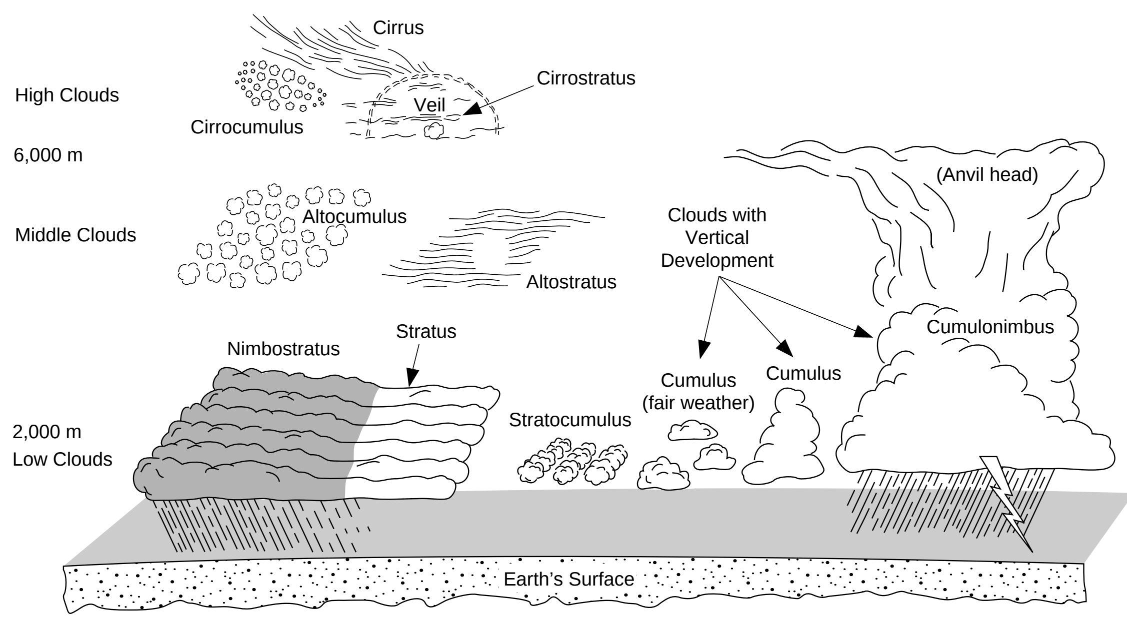

Figure 2. The major cloud types.

In the 1960s, following the launch of the first meteorological satellites, views from space showed that clouds often congregate into huge systems thousands of kilometers in extent, and that some regions of the globe tend to be more cloudy than others. Even with the breadth provided by satellite views, though, compilation of atlases showing cloudiness patterns has proven extremely difficult. A major problem is that from any angle our view of clouds is incomplete. Looking down from high above the atmosphere we see only the top layer of clouds; those beneath are hidden from our view.

Figure 3 shows two kinds of global cloud map. Large-scale patterns are readily apparent in both. One notable feature is the persistent cloud bands in the middle and high latitudes. We see more or less the same pattern in both the Northern and Southern hemispheres. These great bands of cloudiness migrate poleward in summer and toward the equator in winter. The dearth of clouds at latitudes around 30 degrees, the belt where we find the great deserts, is associated with large-scale sinking motions of dry air in the atmosphere.

These are some of the main cloud patterns on our planet. Appendix I discusses cloud patterns on other planets.

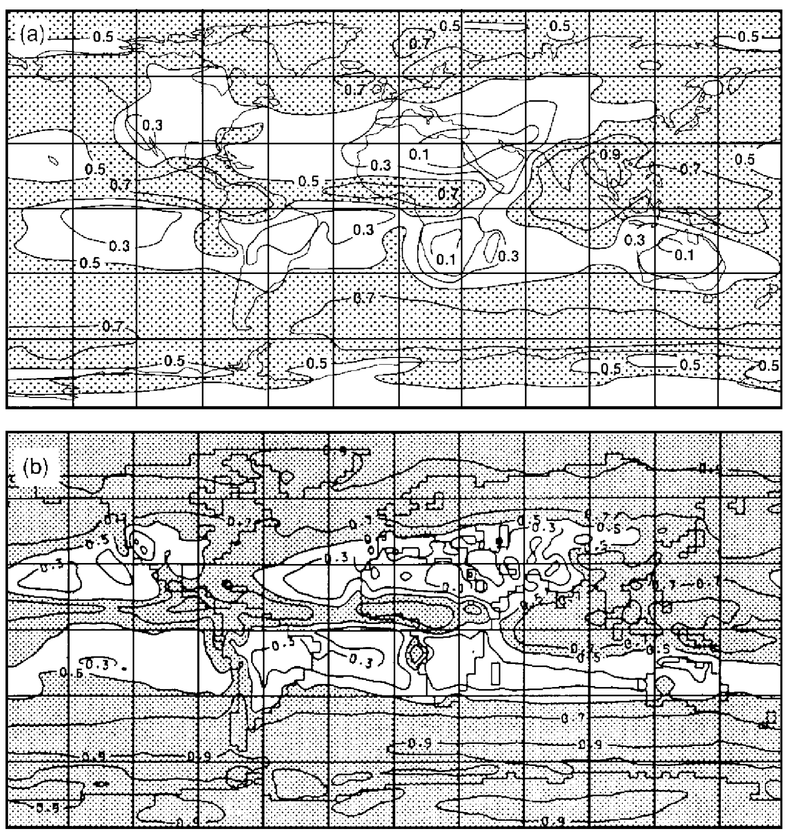

Figure 3. Cloud coverage (in tenths of the sky covered with cloud). A: Observed by satellite. B: Calculated with a general circulation model. From A. Slingo, R.C. Wilderspin, and R.N.B. Smith, 1989: Effect of improved physical parameterizations on simulations of cloudiness and the the Earth's radiation budget. Journal of Geophysical Research, *94. Reprinted by permission.*

Cloud Composition

In 1672, the German physicist Otto von Guericke, perhaps inadvertently, put forward the idea that clouds were made of tiny suspended bubbles when he called the small particles he produced in a crude cloud chamber (see page 7) *bullulae*, or bubbles. The bubble misconception persisted for two centuries. The droplets, such as those caught on a spider web on a foggy morning (see Figure 4), do look like bubbles, but it's an illusion.

In 1846, it was found that fog particles did not burst on impact, as bubbles would. And around 1884, cloud droplets were collected and studied under a microscope, finally settling the matter. Clouds consist of water droplets.

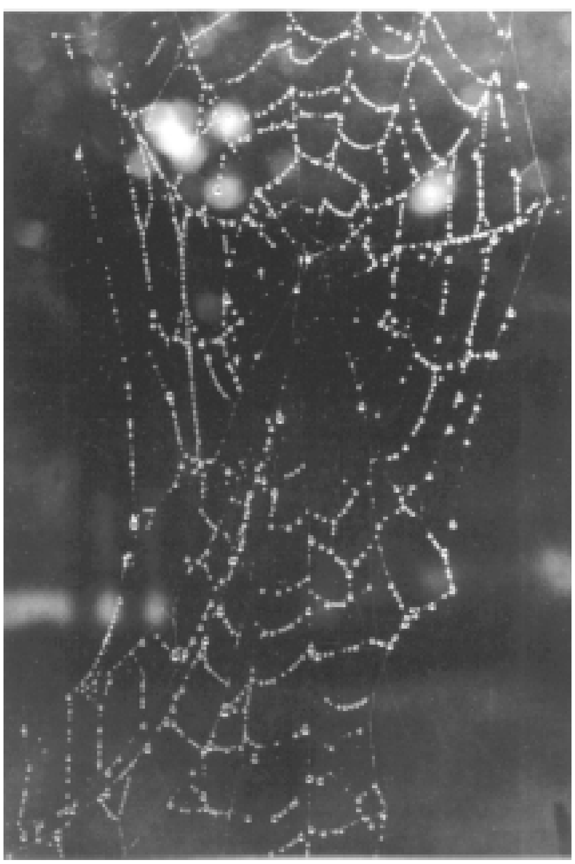

Figure 4. Water droplets on a spider web. From The Anatomy of Nature, by Andreas Feininger, Crown Publishers, 1956. Photograph by Andreas Feininger (copyrighted). Reprinted by permission.

When clouds become very cold, the water vapor condenses to form tiny six-sided crystals of ice, many of them like the snowflakes in Figure 5. Some clouds contain both water droplets and ice crystals. Water droplets do not freeze instantly when the temperature drops below freezing but supercool to varying extents first. Supercooled liquid water is water at a temperature below freezing but still in the liquid state. As the temperature continues to drop, the fraction of frozen droplets increases until they all freeze at –40°C. The exact distribution of frozen to liquid droplets is not constant for all clouds but depends on the prevalence of trace atmospheric constituents called ice nuclei.

The Underlying Physics of Cloud Formation

The effect of clouds on climate or climate on clouds depends on the physics of cloud formation. There are several concepts essential to understanding cloud-climate interactions.

Atmospheric Moisture: Evaporation and Condensation

If you pour some water into a jar and close it with a lid, the water begins to evaporate as water molecules leave the liquid surface and become airborne. (The level of liquid water in the jar will drop imperceptibly.) Molecules of liquid water are loosely bound to each other by electric forces, but they are mobile, being constantly knocked about and trading places. The airborne water molecules, in the gaseous or vapor phase, are essentially flying around loose in a state of frantic motion, colliding with each other and with air molecules billions of times a second and racing back and forth between collisions at a speed of about a kilometer a second (about the speed of a modern jet fighter).

If evaporation continues, the water dries up. But it is not a one-way process. The constant collisions of airborne water molecules exert a small but measurable force on the water surface and the interior of the jar: the gas or vapor pressure. As more and more water evaporates, the vapor pressure in the jar builds up, at first rapidly but later on more slowly. After a long while it approaches a constant value: the saturation vapor pressure. When this point is reached, the relative humidity is 100%. The gas (water vapor) and liquid are in equilibrium.

This does not mean that water molecules cease to evaporate, but that evaporation is balanced by another process: condensation. Some of the myriads of molecules in the gas phase, speeding around above the water surface, smash into it and adhere. At equilibrium, equal numbers of molecules in a given surface area travel from water phase to gas phase as from gas phase to water phase in a set amount of time. In other words, evaporation and condensation rates are equal. If the vapor pressure builds up enough, more molecules on average enter the water than leave, and water condenses.

It takes energy to tear a molecule away from a body of water, so the water cools slightly each time that happens. Evaporation has a cooling effect. But if you add energy in the form of heat,

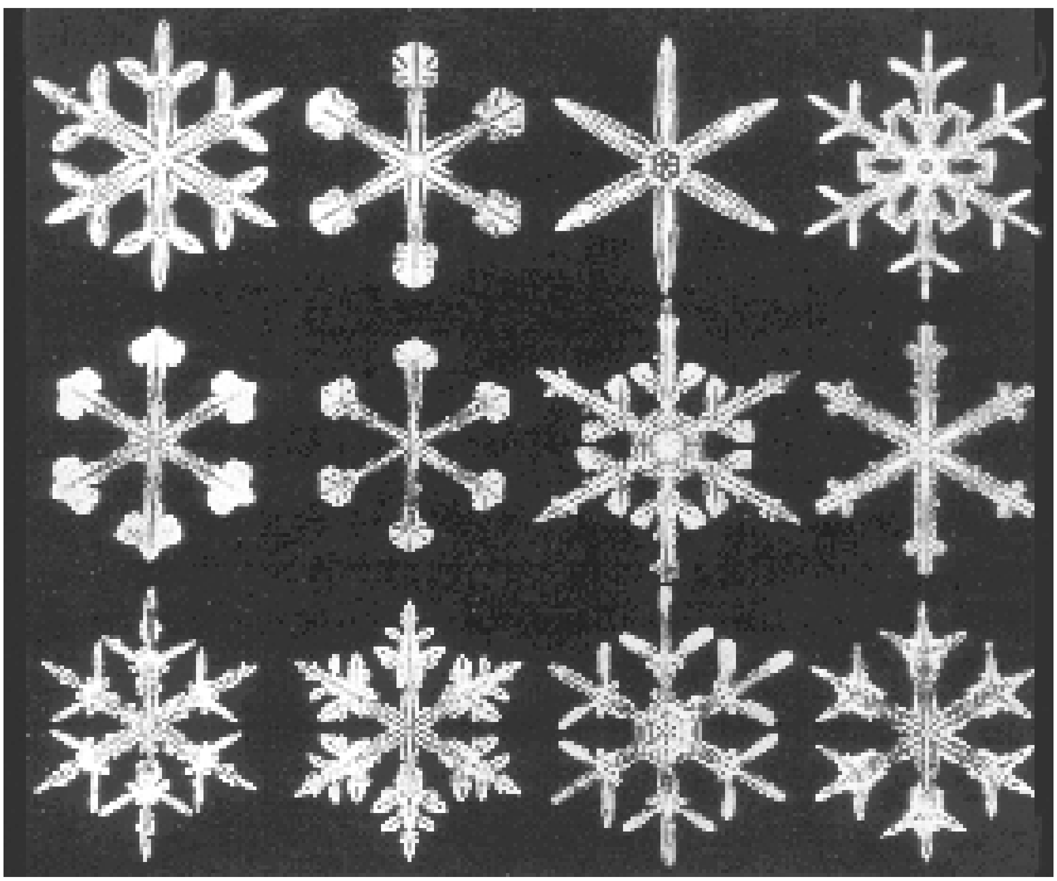

Figure 5. Snowflake forms showing hexagonal structure. From Snow Crystals, by W.A. Bentley and W.J. Humphreys, Dover Publications, 1962. Reprinted by permission.

the molecules move faster (the heat energy has become kinetic energy), and more get kicked out of the liquid into the air. So as the temperature rises, water evaporates faster. Because more gas molecules must be knocked down into the water to replenish the increased numbers that are bumped out, saturation vapor pressure (which we have defined as the pressure needed to maintain equilibrium) also increases. Remember, though, that the water vapor exerts this pressure in all directions. It presses not only against the water surface and the walls of the jar but against the surrounding air, which has its own pressure: atmospheric pressure. At room temperature saturation vapor pressure is only about 1/30 of atmospheric pressure. But at 100° C the molecules are moving so fast that saturation vapor pressure equals atmospheric pressure and the water boils. Table l lists the vapor pressure of water at different temperatures.

To sum up this discussion:

1. Heat dislodges molecules from a water surface and injects them into the atmosphere (evaporation).

2. Water molecules in the gas (vapor) phase, in their chaotic thermal motion, occasionally strike the water surface and adhere (condensation).

3. If the air is saturated, the evaporation rate (water to gas) and the condensation rate (gas to water) are equal, and increase with increasing temperature. The increase isn't linear with temperature; this subtlety is a key point in climate studies.

4. At any given temperature there is a critical vapor pressure, called the saturation vapor pressure. If the vapor pressure exceeds this value, the condensation rate is greater than the evaporation rate and water vapor condenses; below this value the evaporation rate is faster than the condensation rate and water evaporates.

A familiar measure of moisture content in the atmosphere is relative humidity, the ratio of the existing vapor pressure to saturation vapor pressure. At a relative humidity of unity (sometimes expressed as 100%), the air is saturated with moisture, or, more precisely, the water vapor pressure equals the saturation vapor pressure.

Table 1
Vapor Pressure (in Millibars) of Water at Different Temperatures

Temperature °C	°F	Pressure
–40	–40	0.189
–20	–4	1.25
0	32	6.10
20	68	23.4
40	104	73.8
100	212	1,000

Atmospheric pressure is approximately equal to 1,000 mb. Thus, water vapor pressure at 20°C (68°F) is about 1/40 that of the atmosphere.

The Supersaturated State

From the above, it should be clear that evaporation is the favored process when the air is unsaturated (the vapor pressure is below saturation) and that when the air is supersaturated (vapor pressure is higher than the equilibrium value), water will condense. So supersaturation is necessary for cloud formation. How does air become supersaturated? Standing water will humidify air, but only up to 100% relative humidity (saturation). Remember, though, that the saturation vapor pressure is lower for lower temperatures. We can supersaturate air by humidifying it (exposing it for a long time to a body of water), then quickly cooling it. This two-step process is the usual way of reaching a state of supersaturation.

At the turn of the century, two Scottish scientists, both inspired by the clouds that constantly form and evaporate on the moors, but working independently, conducted “cloud in a bottle” experiments that led the way to understanding how clouds form. C.T.R. Wilson, working at Cambridge University’s Cavendish Laboratory in England, and John Aitken (Figure 6), an Aberdeen, Scotland, marine engineer, introduced water into a closed chamber, allowed it to humidify, and then cooled it by rapidly expanding it into another chamber. (Air cools when it expands and heats up when compressed; this is why a bicycle pump becomes warm when you’re inflating a tire.) This brought the humid air into a state of supersaturation and, indeed, the water condensed out and formed a tiny cloud. (See Appendix III to learn how to perform a similar experiment.) Wilson and Aitken correctly surmised that this must be how clouds form in the atmosphere.

The Nuclei of Cloudy Condensation

Wilson and Aitken discovered something else: that it is more difficult to form a cloud after one or two expansion cycles. In fact, if they waited for the cloud droplets to settle between expansions, after several expansions no cloud formed at all.

They surmised that cloud droplets must form on invisible particles of dust in the air and that each cloud that settles out takes some of the dust with it. After several cloud-forming cycles, the dust would all be cleared out of the air and no more condensation could occur. We now know they were right. Some type of solid surface, called a cloud condensation nucleus, is necessary to initiate the condensation of water droplets. In subsequent experiments, Wilson demonstrated that clouds could still form in cleaned-out air, but only with extreme supersaturation corresponding to a relative humidity of 400%.

In the free atmosphere, although it is still necessary to exceed 100% relative humidity for clouds to form, such extreme supersaturations are not necessary. Atmospheric supersaturations are usually less than 1% (101% relative humidity). And there must be plenty of cloud condensation nuclei everywhere, because even in the extremely clean air over oceans or polar ice sheets, clouds seem to have no trouble forming.

Creation of the Supersaturated State in Nature

Supersaturation in nature happens the same way as in a bottle: through high humidity coupled with cooling. When warm, moist air blows over a cool surface it becomes chilled. When it is chilled below the dew point (the

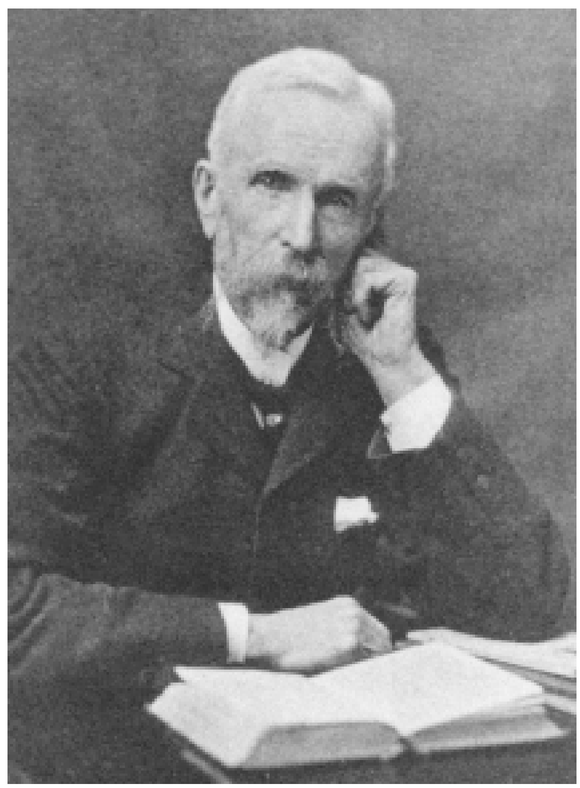

Figure 6. John Aitken, who from 1888 to 1892 performed a variety of experiments showing that clouds nucleate on motes of dust. From The Collected Papers of John Aitken, L.L.D., F.R.S. Edited by Cargill G. Knott, Cambridge University Press, 1923.

temperature at which water vapor begins to condense), a fog forms. On the west coast of the United States, warm, moist air from the Pacific blows over the cold California Current and then onshore to produce the familiar fogs of San Francisco.

When, on the other hand, cool air moves over warm water, it chills humid air rising from the water, condensing it into filamentary clouds that look like steam. Hunters, campers, and naturalists know that steam fog is rather commonly found over lakes in early morning.

When humidity is high and skies are clear, nighttime fogs may form at the bottom of valleys or on low-lying plains as the heat that the ground absorbed during the day radiates away. Radiation fogs usually dissipate within a few hours after sunrise as sunshine warms the air to above its dew point.

Air forced to flow over a mountain or hill expands—and cools—as it rises. Low-lying and very persistent clouds form in this way along windward coasts. A good example is the cloud bank over Hilo, Hawaii, when the warm, moist air of the trade winds encounters the rising terrain of the large volcanic mountains.

Clouds may form like a string of beads on the crests of atmospheric waves created when winds blow over mountain peaks. These clouds also form by cooling; the air is coldest at the top of the wave. Saucer- or lens-shaped wave clouds (Figure 7) are frequently seen just to the east of the Rocky Mountains and on the lee-ward sides of other mountain ranges.

Figure 7. Lenticular clouds form on the crests of atmospheric waves on the lee side of a mountain. Photo courtesy of the National Center for Atmospheric Research.