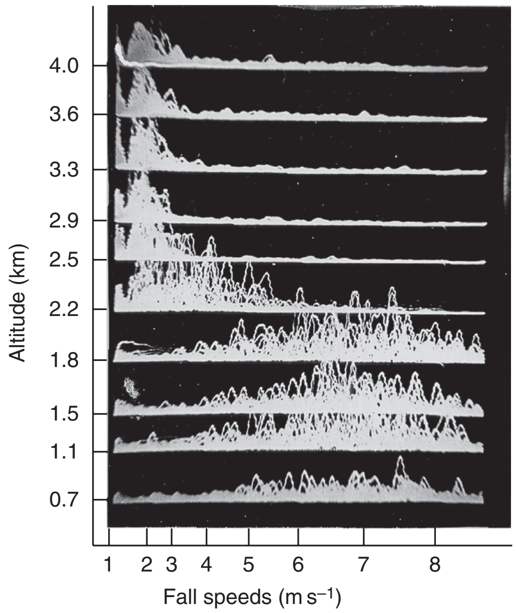


Fig. 6.46 Spectra of Doppler fall speeds for precipitation particles at ten heights in the atmosphere. The melting level is at about 2.2 km. [Courtesy of Cloud and Aerosol Research Group, University of Washington.]

particles is reduced. These changes result in a sharp decrease in radar reflectivity below the melting band.

The sharp increase in particle fall speeds produced by melting is illustrated in Fig. 6.46, which shows the spectrum of fall speeds of precipitation particles measured at various heights with a vertically pointing Doppler radar.[37] At heights above 2.2 km the particles are ice with fall speeds centered around 2 m s^{-1}. At 2.2 km the particles are partially melted, and below 2.2 km there are raindrops with fall speeds centered around 7 m s^{-1}.

6.5.5 Classification of Solid Precipitation

The growth of ice particles by deposition from the vapor phase, riming, and aggregation leads to a very wide variety of solid precipitation particles. A relatively simple classification into 10 main classes is shown in Table 6.2.

6.6 Artificial Modification of Clouds and Precipitation

As shown in Sections 6.2–6.5, the microstructures of clouds are influenced by the concentrations of CCN and ice nuclei, and the growth of precipitation particles is a result of instabilities that exist in the microstructures of clouds. These instabilities are of two main types. First, in warm clouds the larger drops increase in size at the expense of the smaller droplets due to growth by the collision-coalescence mechanism. Second, if ice particles exist in a certain optimum range of concentrations in a mixed cloud, they grow by deposition at the expense of the droplets (and subsequently by riming and aggregation). In light of these ideas, the following techniques have been suggested whereby clouds and precipitation might be modified artificially by so-called *cloud seeding*.

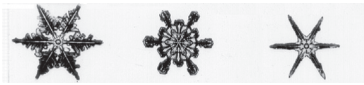
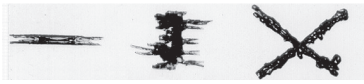
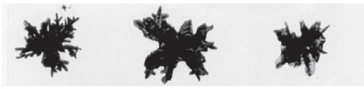
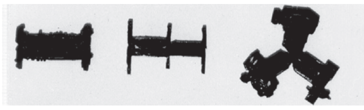
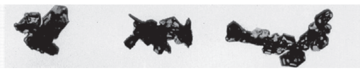
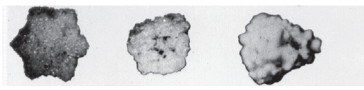
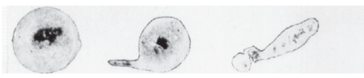
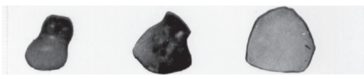
- Introducing large hygroscopic particles or water drops into warm clouds to stimulate the growth of raindrops by the collision-coalescence mechanism.
- Introducing artificial ice nuclei into cold clouds (which may be deficient in ice particles) to stimulate the production of precipitation by the ice crystal mechanism.
- Introducing comparatively high concentrations of artificial ice nuclei into cold clouds to reduce drastically the concentrations of supercooled droplets and thereby inhibit the growth of ice particles by deposition and riming, thereby dissipating the clouds and suppressing the growth of precipitable particles.

6.6.1 Modification of Warm Clouds

Even in principle, the introduction of water drops into the tops of clouds is not a very efficient method for producing rain, since large quantities of water

[37] Doppler radars, unlike conventional meteorological radars, transmit coherent electromagnetic waves. From measurements of the difference in frequencies between returned and transmitted waves, the velocity of the target (e.g., precipitation particles) along the line of sight of the radar can be deduced. Radars used by the police for measuring the speeds of motor vehicles are based on the same principle.

Table 6.2 A classification of solid precipitation[a,b,c]

Typical forms	Symbol	Graphic symbol
	F1	
	F2	
	F3	
	F4	
	F5	
	F6	
	F7	
	F8	
	F9	
	F10	

[a] Suggested by the International Association of Hydrology's commission of snow and ice in 1951. [Photograph courtesy of V. Schaefer.]
[b] Additional characteristics: *p*, broken crystals; *r*, rime-coated particles not sufficiently coated to be classed as graupel; *f*, clusters, such as compound snowflakes, composed of several individual snow crystals; *w*, wet or partly melted particles.
[c] Size of particle is indicated by the general symbol D. The size of a crystal or particle is its greatest extension measured in millimeters. When many particles are involved (e.g., a compound snowflake), it refers to the average size of the individual particles.

are required. A more efficient technique might be to introduce small water droplets (radius $\simeq 30\ \mu$m) or hygroscopic particles (e.g., NaCl) into the base of a cloud; these particles might then grow by condensation, and then by collision-coalescence, as they are carried up and subsequently fall through a cloud.

In the second half of the last century, a number of cloud seeding experiments on warm clouds were carried out using water drops and hygroscopic particles. In some cases, rain appeared to be initiated by the seeding, but because neither extensive physical nor rigorous statistical evaluations were carried out, the results were inconclusive. Recently, there has been somewhat of a revival of interest in seeding warm clouds with hygroscopic nuclei to increase precipitation but, as yet, the efficacy of this technique has not been proven.

Seeding with hygroscopic particles has been used in attempts to improve visibility in warm fogs. Because the visibility in a fog is inversely proportional to the number concentration of droplets and

Description
A plate is a thin, plate-like snow crystal the form of which more or less resembles a hexagon or, in rare cases, a triangle. Generally all edges or alternative edges of the plate are similar in pattern and length.
A stellar crystal is a thin, flat snow crystal in the form of a conventional star. It generally has 6 arms but stellar crystals with 3 or 12 arms occur occasionally. The arms may lie in a single plane or in closely spaced parallel planes in which case the arms are interconnected by a very short column.
A column is a relatively short prismatic crystal, either solid or hollow, with plane, pyramidal, truncated, or hollow ends. Pyramids, which may be regarded as a particular case, and combinations of columns are included in this class.
A needle is a very slender, needle-like snow particle of approximately cylindrical form. This class includes hollow bundles of parallel needles, which are very common, and combinations of needles arranged in any of a wide variety of fashions.
A spatial dendrite is a complex snow crystal with fern-like arms that do not lie in a plane or in parallel planes but extend in many directions from a central nucleus. Its general form is roughly spherical.
A capped column is a column with plates of hexagonal or stellar form at its ends and, in many cases, with additional plates at intermediate positions. The plates are arranged normal to the principal axis of the column. Occasionally, only one end of the column is capped in this manner.
An irregular crystal is a snow particle made up of a number of small crystals grown together in a random fashion. Generally the component crystals are so small that the crystalline form of the particle can only be seen with the aid of a magnifying glass or microscope.
Graupel, which includes soft hail, small hail, and snow pellets, is a snow crystal or particle coated with a heavy deposit of rime. It may retain some evidence of the outline of the original crystal, although the most common type has a form that is approximately spherical.
Ice pellets (frequently called sleet in North America) are transparent spheroids of ice and are usually fairly small. Some ice pellets do not have a frozen center, which indicates that, at least in some cases, freezing takes place from the surface inward.
A hailstone[d] is a grain of ice, generally having a laminar structure and characterized by its smooth glazed surface and its translucent or milky-white center. Hail is usually associated with those atmospheric conditions that accompany thunderstorms. Hailstones are sometimes quite large.

[d] Hail, like rain, refers to a number of particles, whereas hailstone, like raindrop, refers to an individual particle.

to their total surface area, visibility can be improved by decreasing either the concentration or the size of the droplets. When hygroscopic particles are dispersed into a warm fog, they grow by condensation (causing partial evaporation of some of the fog droplets) and the droplets so formed fall out of the fog slowly. Fog clearing by this method has not been widely used due to its expense and lack of dependability. At the present time, the most effective methods for dissipating warm fogs are "brute force" approaches, involving evaporating the fog droplets by ground-based heating.

6.6.2 Modification of Cold Clouds

We have seen in Section 6.5.3 that when supercooled droplets and ice particles coexist in a cloud, the ice particles may increase to precipitation size rather rapidly. We also saw in Section 6.5.1 that in some situations the concentrations of ice nuclei may be less than that required for the efficient initiation of the ice crystal mechanism for the formation of precipitation. Under these conditions, it is argued, clouds might be induced to rain by seeding them with artificial ice nuclei or some other material that might increase the concentration of ice particles. This idea was the basis for most of the cloud seeding experiments carried out in the second half of the 20th century.

A material suitable for seeding cold clouds was first discovered in July 1946 in Project Cirrus, which was carried out under the direction of Irving Langmuir.[38] One of Langmuir's assistants, Vincent Schaefer,[39] observed in laboratory experiments that when a small piece of dry ice (i.e., solid carbon dioxide) is dropped into a cloud of supercooled droplets, numerous small ice crystals are produced and the cloud is glaciated quickly. In this transformation, dry ice does not serve as an ice nucleus in the usual sense of this term, but rather, because it is so cold ($-78\,°C$), it causes numerous ice crystals to form in its wake by homogeneous nucleation. For example, a pellet of dry ice 1 cm in diameter falling through air at $-10\,°C$ produces about 10^{11} ice crystals.

The first field trials using dry ice were made in Project Cirrus on 13 November 1946, when about 1.5 kg of crushed dry ice was dropped along a line about 5 km long into a layer of a supercooled altocumulus cloud. Snow was observed to fall from the base of the seeded cloud for a distance of about 0.5 km before it evaporated in the dry air.

Because of the large numbers of ice crystals that a small amount of dry ice can produce, it is most suitable for *overseeding* cold clouds rather than producing ice crystals in the optimal concentrations ($\sim$1 liter^{-1}) for enhancing precipitation. When a cloud is overseeded it is converted completely into ice crystals (i.e., it is glaciated). The ice crystals in a glaciated cloud are generally quite small and, because there are no supercooled droplets present, supersaturation with respect to ice is either low or nonexistent. Therefore, instead of the ice crystals growing (as they would in a mixed cloud at water saturation) they tend to evaporate. Consequently, seeding with dry ice can dissipate large areas of supercooled cloud or fog (Fig. 6.47). This technique is used for clearing supercooled fogs at several international airports.

Fig. 6.47 A γ-shaped path cut in a layer of supercooled cloud by seeding with dry ice. [Photograph courtesy of General Electric Company, Schenectady, New York.]

Following the demonstration that supercooled clouds can be modified by dry ice, Bernard Vonnegut,[40] who was also working with Langmuir, began searching for artificial ice nuclei. In this search he was guided by the expectation that an effective ice nucleus should have a crystallographic structure similar to that of ice. Examination of crystallographic tables revealed that silver iodide fulfilled this requirement. Subsequent laboratory tests showed that silver iodide could act as an ice nucleus at temperatures as high as $-4\,°C$.

The seeding of natural clouds with silver iodide was first tried as part of Project Cirrus on 21 December 1948. Pieces of burning charcoal impregnated with silver iodide were dropped from an aircraft into about 16 km^2 of supercooled stratus cloud 0.3 km thick at a temperature of $-10\,°C$. The cloud was converted into ice crystals by less than 30 g of silver iodide!

[38] **Irving Langmuir** (1881–1957) American physicist and chemist. Spent most of his working career as an industrial chemist in the GE Research Laboratories in Schenectady, New York. Made major contributions to several areas of physics and chemistry and won the Nobel Prize in chemistry in 1932 for work on surface chemistry. His major preoccupation in later years was cloud seeding. His outspoken advocacy of large-scale effects of cloud seeding involved him in much controversy.

[39] **Vincent Schaefer** (1906–1993) American naturalist and experimentalist. Left school at age 16 to help support the family income. Initially worked as a toolmaker at the GE Research Laboratory, but subsequently became Langmuir's research assistant. Schaefer helped to create the Long Path of New York (a hiking trail from New York City to Whiteface Mt. in the Adirondacks); also an expert on Dutch barns.

[40] **Bernard Vonnegut** (1914–1997) American physical chemist. In addition to his research on cloud seeding, Vonnegut had a lifelong interest in thunderstorms and lightning. His brother, Kurt Vonnegut the novelist, wrote "My longest experience with common decency, surely, has been with my older brother, my only brother, Bernard . . . We were given very different sorts of minds at birth. Bernard could never be a writer and I could never be a scientist." Interestingly, following Project Cirrus, neither Vonnegut nor Schaefer became deeply involved in the quest to increase precipitation by artificial seeding.

Many artificial ice nucleating materials are now known (e.g., lead iodide, cupric sulfide) and some organic materials (e.g., phloroglucinol, metaldehyde) are more effective as ice nuclei than silver iodide. However, silver iodide has been used in most cloud seeding experiments.

Since the first cloud seeding experiments in the 1940s, many more experiments have been carried out all over the world. It is now well established that the concentrations of ice crystals in clouds can be increased by seeding with artificial ice nuclei and that, under certain conditions, precipitation can be artificially initiated in some clouds. However, the important question is: under what conditions (if any) can seeding with artificial ice nuclei be employed to produce significant increases in precipitation on the ground in a predictable manner and over a large area? This question remains unanswered.

So far we have discussed the role of artificial ice nuclei in modifying the microstructures of cold clouds. However, when large volumes of a cloud are glaciated by overseeding, the resulting release of latent heat provides added buoyancy to the cloudy air. If, prior to seeding, the height of a cloud were restricted by a stable layer, the release of the latent heat of fusion caused by artificial seeding might provide enough buoyancy to push the cloud through the inversion and up to its level of free convection. The cloud top might then rise to much greater heights than it would have done naturally. Figure 6.48 shows the explosive growth of a cumulus cloud that may have been produced by overseeding.

Seeding experiments have been carried out in attempts to reduce the damage produced by hailstones. Seeding with artificial nuclei should tend to increase the number of small ice particles competing for the available supercooled droplets. Therefore, seeding should result in a reduction in the average size of the hailstones. It is also possible that, if a hailstorm is overseeded with extremely large numbers of ice nuclei, the majority of the supercooled droplets in the cloud will be nucleated, and the growth of hailstones by riming will be reduced significantly. Although these hypotheses are plausible, the results of experiments on hail suppression have not been encouraging.

Exploratory experiments have been carried out to investigate if orographic snowfall might be redistributed by overseeding. Rimed ice particles have relatively large terminal fall speeds ($\sim 1 \text{ m s}^{-1}$), therefore they follow fairly steep trajectories as they fall to the ground. If clouds on the windward side of a mountain are artificially over-seeded, supercooled droplets can be virtually eliminated and growth by riming significantly reduced (Fig. 6.49). In the absence of riming, the ice

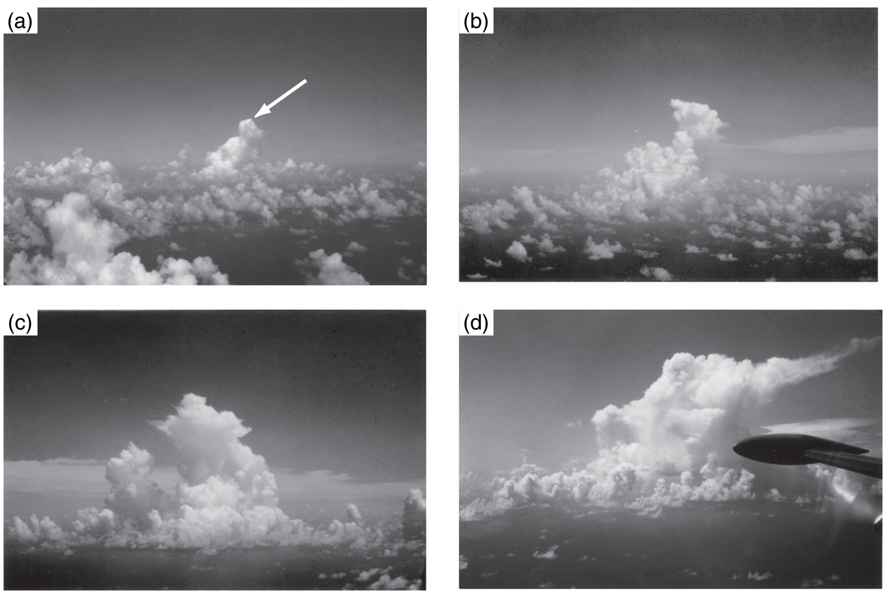


Fig. 6.48 Causality or chance coincidence? Explosive growth of cumulus cloud (a) 10 min; (b) 19 min; 29 min; and 48 min after it was seeded near the location of the arrow in (a). [Photos courtesy of J. Simpson.]

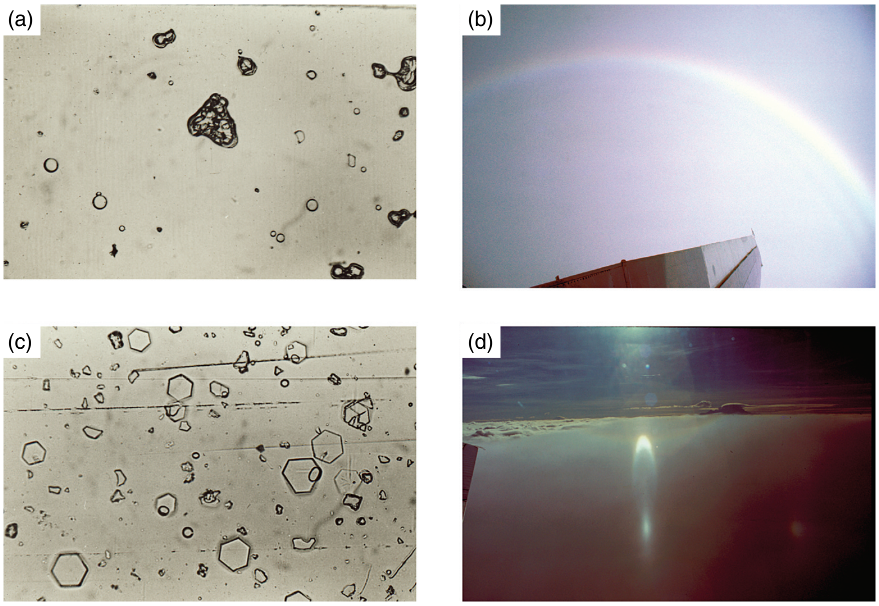


Fig. 6.49 (a) Large rimed irregular particles and small water droplets collected in unseeded clouds over the Cascade Mountains. (b) Cloud bow produced by the refraction of light in small water droplets. Following heavy seeding with artificial ice nuclei, the particles in the cloud were converted into small unrimed plates (c) which markedly changed the appearance of the clouds. In (d) the uniform cloud in the foreground is the seeded cloud and the more undulating cloud in the background is the unseeded cloud. In the seeded cloud, optical effects due to ice particles (portion of the 22° halo, lower tangent arc to 22° halo, and subsun) can be seen. [Photographs courtesy of Cloud and Aerosol Research Group, University of Washington.]

particles grow by deposition from the vapor phase and their fall speeds are reduced by roughly a factor of 2. Winds aloft can then carry these crystals farther before they reach the ground. In this way, it is argued, it might be possible to divert snowfall from the windward slopes of mountain ranges (where precipitation is often heavy) to the drier leeward slopes.

6.6.3 Inadvertent Modification

Some industries release large quantities of heat, water vapor, and cloud-active aerosol (CCN and ice nuclei) into the atmosphere. Consequently, these effluents might modify the formation and structure of clouds and affect precipitation. For example, the effluents from a single paper mill can profoundly affect the surrounding area out to about 30 km (Fig. 6.50). Paper mills, the burning of agricultural wastes, and forest fires emit large numbers of CCN ($\sim 10^{17}$ s^{-1} active at 1% supersaturation), which can change droplet concentrations in clouds downwind. High concentrations of ice nuclei have been observed in the plumes from steel mills.

Fig. 6.50 The cloud in the valley in the background formed due to effluents from a paper mill. In the foreground, the cloud is spilling through a gap in the ridge into an adjacent valley. [Photograph courtesy of C. L. Hosler.]

Large cities can affect the weather in their vicinities. Here the possible interactions are extremely complex since, in addition to being areal sources of aerosol, trace gases, heat, and water vapor, large cities modify the radiative properties of the Earth's surface, the moisture content of the soil, and the surface roughness. The existence of urban "heat islands," several degrees warmer than adjacent less populated regions, is well documented. In the summer months increases in precipitation of 5–25% over background values occur 50–75 km downwind of some cities (e.g., St. Louis, Missouri). Thunderstorms and hailstorms may be more frequent, with the areal extent and magnitude of the perturbations related to the size of the city. Model simulations indicate that enhanced upward air velocities, associated with variations in surface roughness and the heat island effect, are most likely responsible for these anomalies.

6.4 Holes in Clouds

Photographs of holes (i.e., relatively large clear regions) in thin layers of supercooled cloud, most commonly altocumulus, date back to at least 1926. The holes can range in shape from nearly circular (Fig. 6.51a) to linear tracks (Fig. 6.51b). The holes are produced by the removal of supercooled droplets by copious ice crystals ($\sim$100–1000 per liter) in a similar way to the formation of holes in supercooled clouds by artificial seeding (see Fig. 6.41). However, the holes of interest here are formed by natural seeding from above a supercooled cloud that is intercepted by a fallstreak containing numerous ice particles (see Fig. 6.45) or by an aircraft penetrating the cloud.

In the case of formation by an aircraft, the ice particles responsible for the evaporation of the supercooled droplets are produced by the rapid expansion, and concomitant cooling, of air in the vortices produced in the wake of an aircraft (so-called *aircraft produced ice particles* or APIPs). If the air is cooled below about -40 °C, the ice particles are produced by homogeneous nucleation (see Section 6.5.1). With somewhat less but still significant cooling, the ice crystals may be nucleated heterogeneously (see Section 6.5.2). The crystals so produced are initially quite small and uniform in size, but they subsequently grow fairly uniformly at the expense of the supercooled droplets in the cloud (see Fig. 6.36). The time interval between an aircraft penetrating a supercooled cloud and the visible appearance of a clear area is $\sim$10–20 min.

APIPs are most likely at low ambient temperatures (at or below -8 °C) when an aircraft is flown at maximum power but with gear and flaps extended; this results in a relatively low airspeed and high drag. Not all aircraft produce APIPs.

Fig. 6.51 (a) A hole in a layer of supercooled altocumulus cloud. Note the fallout of ice crystals from the center of the hole. [Copyright A. Sealls.] (b) A clear track produced by an aircraft flying in a supercooled altocumulus cloud. [Courtesy of Art Rangno.]

The shape of the hole in a cloud depends on the angle of interception of the fallstreak or the aircraft flight path with the cloud. For example, if an aircraft descends steeply through a cloud it will produce a nearly circular hole (Fig. 6.51a), but if the aircraft flies nearly horizontally through a cloud it will produce a linear track (Fig. 6.51b).

6.7 Thunderstorm Electrification

The dynamical structure of thunderstorms is described in Chapter 10. Here we are concerned with the microphysical mechanisms that are thought to be responsible for the electrification of thunderstorms and with the nature of lightning flashes and thunder.

6.7.1 Charge Generation

All clouds are electrified to some degree.[41] However, in vigorous convective clouds sufficient electrical charges are separated to produce electric fields that exceed the dielectric breakdown of cloudy air ($\sim$1 MV m^{-1}), resulting in an initial *intracloud* (i.e., between two points in the same cloud) lightning discharge.

The distribution of charges in thunderstorms has been investigated with special radiosondes (called altielectrographs), by measuring the changes in the electric field at the ground that accompany lightning flashes, and with instrumented aircraft. A summary of the results of such studies, for a relatively simple cloud, is shown in Fig. 6.52. The magnitudes of the lower negative charge and the upper positive charge are $\sim$10–100 coulombs (hereafter symbol "C"), or a few nC m^{-3}. The location of the negative charge (called the *main charging zone*) is rather well defined between the -10 °C and about -20 °C temperature levels. The positive charge is distributed in a more diffuse region above the negative charge. Although there have been a few reports of lightning from warm clouds, the vast majority of thunderstorms occur in cold clouds.

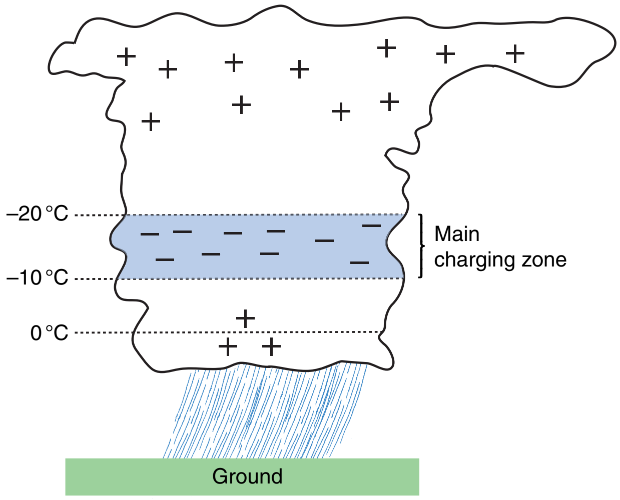


Fig. 6.52 Schematic showing the distribution of electric charges in a typical and relatively simple thunderstorm. The lower and smaller positive charge is not always present.

An important observational result, which provides the basis for most theories of thunderstorm

[41] Benjamin Franklin, in July 1750, was the first to propose an experiment to determine whether thunderstorms are electrified. He suggested that a sentry box, large enough to contain a man and an insulated stand, be placed at a high elevation and that an iron rod 20–30 ft in length be placed vertically on the stand, passing out through the top of the box. He then proposed that if a man stood on the stand and held the rod he would "be electrified and afford sparks" when an electrified cloud passed overhead. Alternatively, he suggested that the man stand on the floor of the box and bring near to the rod one end of a piece of wire, held by an insulating handle, while the other end of the wire was connected to the ground. In this case, an electric spark jumping from the rod to the wire would be proof of cloud electrification. (Franklin did not realize the danger of these experiments: they can kill a person—and have done so—if there is a direct lightning discharge to the rod.) The proposed experiment was set up in Marly-la-Ville in France by d'Alibard[42], and on 10 May 1752 an old soldier, called Coiffier, brought an earthed wire near to the iron rod while a thunderstorm was overhead and saw a stream of sparks. This was the first direct proof that thunderstorms are electrified. Joseph Priestley described it as "the greatest discovery that has been made in the whole compass of philosophy since the time of Sir Isaac Newton." (Since Franklin proposed the use of the lightning conductor in 1749, it is clear that by that date he had already decided in his own mind that thunderstorms were electrified.) Later in the summer of 1752 (the exact date is uncertain), and before hearing of d'Alibard's success, Franklin carried out his famous kite experiment in Philadelphia and observed sparks to jump from a key attached to a kite string to the knuckles of his hand. By September 1752 Franklin had erected an iron rod on the chimney of his home, and on 12 April 1753, by identifying the sign of the charge collected on the lower end of the rod when a storm passed over, he had concluded that "clouds of a thundergust are most commonly in a negative state of electricity, but sometimes in a positive state—the latter, I believe, is rare." No more definitive statement as to the electrical state of thunderstorms was made until the second decade of the 20th century when C. T. R. Wilson[43] showed that the lower regions of thunderstorms are generally negatively charged while the upper regions are positively charged.

[42] **Thomas Francois d'Alibard** (1703–1779) French naturalist. Translated into French Franklin's *Experiments and Observations on Electricity*, Durand, Paris, 1756, and carried out many of Franklin's proposed experiments.

[43] **C. T. R. Wilson** (1869–1959) Scottish physicist. Invented the cloud chamber named after him for studying ionizing radiation (e.g., cosmic rays) and charged particles. Carried out important studies on condensation nuclei and atmospheric electricity. Awarded the Nobel Prize in physics in 1927.

electrification, is that the onset of strong electrification follows the occurrence (detected by radar) of heavy precipitation within the cloud in the form of graupel or hailstones. Most theories assume that as a graupel particle or hailstone (hereafter called the *rimer*) falls through a cloud it is charged negatively due to collisions with small cloud particles (droplets or ice), giving rise to the negative charge in the main charging zone. The corresponding positive charge is imparted to cloud particles as they rebound from the rimer, and these small particles are then carried by updrafts to the upper regions of the cloud. The exact conditions and mechanism by which a rimer might be charged negatively, and smaller cloud particles charged positively, have been a matter of debate for some hundred years. Many potentially promising mechanisms have been proposed but subsequently found to be unable to explain the observed rate of charge generation in thunderstorms or, for other reasons, found to be untenable.

Exercise 6.6 The rate of charge generation in a thunderstorm is $\sim 1\ \mathrm{C\,km^{-3}\,min^{-1}}$. Determine the electric charge that would have to be separated for each collision of an ice crystal with a rimer (e.g., a graupel particle) to explain this rate of charge generation. Assume that the concentration of ice crystals is $10^5\ \mathrm{m^{-3}}$, their fall speed is negligible compared to that of the rimer, the ice crystals are uncharged prior to colliding with the rimer, their collision efficiency with the rimer is unity, and all of the ice crystals rebound from the rimer. Assume also that the rimers are spheres of radius 2 mm, the density of a rimer is $500\ \mathrm{kg\ m^{-3}}$, and the precipitation rate due to the rimers is 5 cm per hour of water equivalent.

Solution: If $\frac{dN}{dt}$ is the number of collisions of ice crystals with rimers in a unit volume of air in 1 s, and each collision separates q coulombs (C) of electric charge, the rate of charge separation per unit volume of air per unit time in the cloud by this mechanism is

$$\frac{dQ}{dt} = \frac{dN}{dt} q \tag{6.39}$$

If the fall speed of the ice crystals is negligible, and the ice crystals collide with and separate from a rimer with unit efficiency,

$$\begin{aligned}\frac{dN}{dt} &= \text{(volume swept out by one rimer in 1 s)}\\ &\quad \text{(number of rimers per unit volume of air)}\\ &\quad \text{(number of ice crystals per unit volume of air)}\\ &= (\pi r_H^2 v_H)\,(n_H)\,(n_I)\end{aligned} \tag{6.40}$$

where, r_H, v_H, and n_H are the radius, fall speed, and number concentration of rimers and n_I the number concentration of ice crystals.

Now consider a rain gauge with cross-sectional area A. Because all of the rimers within a distance v_H of the top of the rain gauge will enter the rain gauge in 1 s, the number of rimers that enter the rain gauge in 1 s is equal to the number of rimers in a cylinder of cross-sectional area A and height v_H; that is, in a cylinder of volume $v_H A$. The number of rimers in this volume is $v_H A n_H$. Therefore, if each rimer has mass m_H, the mass of rimers that enter the rain gauge in 1 s is $v_H A n_H m_H$, where $m_H = (4/3)\pi r_H^3 \rho_H$ and ρ_H is the density of a rimer. When this mass of rimers melt in the rain gauge, the height h of water of density ρ_l that it will produce in 1 s is given by

$$hA\rho_l = v_H A n_H \left(\frac{4}{3}\pi r_H^3 \rho_H\right)$$

or

$$v_H n_H = \frac{3h}{4\pi}\frac{\rho_l}{\rho_H}\frac{1}{r_H^3} \tag{6.41}$$

From (6.39)–(6.41)

$$q = \frac{4\rho_H r_H}{3h\rho_l n_I}\frac{dQ}{dt}$$

Substituting,

$\frac{dQ}{dt} = \frac{1}{60 \times 60}\ C\ \mathrm{km^{-3}\,s^{-1}}$, $h = \frac{5 \times 10^{-2}}{60 \times 60}\ \mathrm{m\,s^{-1}}$, $\rho_l = 10^3\ \mathrm{kg\ m^{-3}}$, $n_I = 10^5\ \mathrm{m^{-3}}$, $\rho_H = 500\ \mathrm{kg\ m^{-3}}$ and $r_H = 2 \times 10^{-3}$ m, we obtain $q = 16 \times 10^{-15}\ C$ per collision or 16 fC per collision. ■

We will now describe briefly a proposed mechanism for charge transfer between a rimer and a colliding ice crystal that appears promising, although it remains to be seen whether it can withstand the test of time.

Laboratory experiments show that electric charge is separated when ice particles collide and rebound. The magnitude of the charge is typically about 10 fC per collision, which, as we have seen in Exercise 6.6, would be sufficient to explain the rate of charge generation in thunderstorms. The sign of the charge received by the rimer depends on temperature, the liquid water content of the cloud, and the relative rates of growth from the vapor phase of the rimer and the ice crystals. If the rimer grows more slowly by vapor deposition than the ice crystals, the rimer receives negative charge and the ice crystals receive the corresponding positive charge. Because the latent heat released by the freezing of supercooled droplets on a rimer as it falls through a cloud will raise the surface temperature of the rimer above ambient temperatures, the rate of growth of the rimer by vapor deposition will be less than that of ice crystals in the cloud. Consequently, when an ice crystal rebounds from a rimer, the rimer should receive a negative charge and the ice crystal a positive charge, as required to explain the main distribution of charges in a thunderstorm.

The charge transfer appears to be due to the fact that positive ions move through ice much faster than negative ions. As new ice surface is created by vapor deposition, the positive ions migrate rapidly into the interior of the ice, leaving the surface negatively charged. During a collision material from each of the particles is mixed, but negative charge is transferred to the particle with the slower growth rate.

In some thunderstorms, a relatively weak positive charge is observed just below the main charging zone (Fig. 6.52). This may be associated with the charging of solid precipitation during melting or to mixed-phase processes.

6.7.2 Lightning and Thunder

As electrical charges are separated in a cloud, the electric field intensity increases and eventually exceeds that which the air can sustain. The resulting dielectric breakdown assumes the form of a lightning flash that can be either (1) within the cloud itself, between clouds, or from the cloud to the air (which we will call *cloud flashes*) or (2) between the cloud and the ground (a *ground flash*).

Ground flashes that charge the ground negatively originate from the lower main negative charge center in the form of a discharge, called the *stepped leader*, which moves downward toward the Earth in discrete steps. Each step lasts for about 1 μs, during which time the stepped leader advances about 50 m; the time interval between steps is about 50 μs. It is believed that the stepped leader is initiated by a local

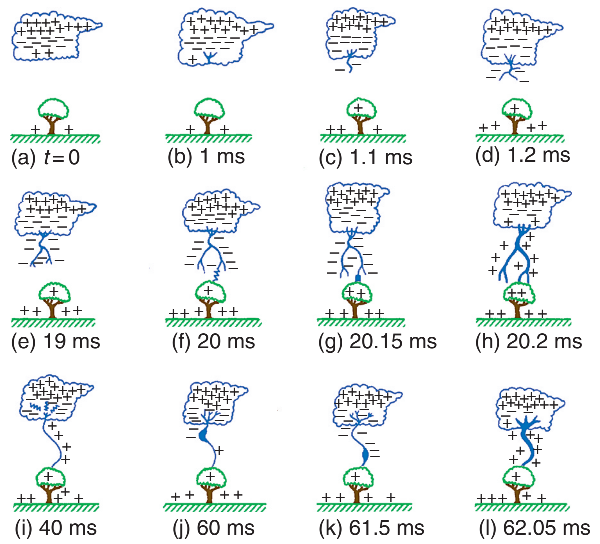


Fig. 6.53 Schematics (not drawn to scale) to illustrate some of the processes leading to a ground flash that charges the ground negatively. (a) cloud charge distribution, (b) preliminary breakdown, (c–e) stepped leader, (f) attachment process, (g and h) first return stroke, (i) K and J processes, (j and k) the dart leader, and (1) the second return stroke. [Adapted from M. Uman, *The Lightning Discharge*, Academic Press, Inc., New York, 1987, p. 12, Copyright 1987, with permission from Elsevier.]

discharge between the small pocket of positive charge at the base of a thundercloud and the lower part of the negatively charged region (Fig. 6.53b). This discharge releases electrons that were previously attached to precipitation particles in the negatively charged region. These free electrons neutralize the small pocket of positive charge that may be present below the main charging zone (Fig. 6.53c) and then move toward the ground (Fig. 6.53c–e). As the negatively charged stepped leader approaches the ground, it induces positive charges on the ground, especially on protruding objects, and when it is 10–100 m from the ground, a discharge moves up from the ground to meet it (Fig. 6.53f). After contact is made between the stepped leader and the upward connecting discharge, large numbers of electrons flow to the ground and a highly luminous and visible *lightning stroke* propagates upward in a continuous fashion from the ground to the cloud along the path followed by the stepped leader (Fig. 6.53g and 6.53h). This flow of electrons (called the *return stroke*) is responsible for the bright channel of light that is observed as a lightning stroke. Because the stroke moves upward so quickly (in about 100 μs), the whole return stroke channel appears to the eye to brighten simultaneously. After the downward flow of electrons, both the return stroke and the ground, to which it is linked, remain positively charged in response to the remainder of the negative charge in the main charging zone.

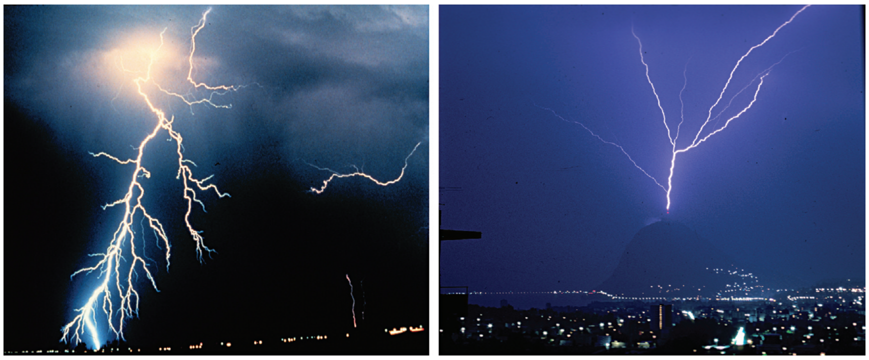
Following the first stroke, which typically carries the largest current (average 30,000 A), subsequent strokes can occur along the same main channel, provided that additional electrons are supplied to the top of the previous stroke within about 0.1 s of the cessation of current. The additional electrons are supplied to the channel by so-called *K* or *J streamers*, which connect the top of the previous stroke to progressively more distant regions of the negatively charged area of the cloud (Fig. 6.53i). A negatively charged leader, called the *dart leader*, then moves continuously downward to the Earth along the main path of the first-stroke channel and deposits further electrons on the ground (Figs. 6.53j and 6.53k). The dart leader is followed by another visible return stroke to the cloud (Fig. 6.53l). The first stroke of a flash generally has many downward-directed branches (Fig. 6.54a) because the stepped leader is strongly branched; subsequent strokes usually show no branching, because they follow only the main channel of the first stroke.

Most lightning flashes contain three or four strokes, separated in time by about 50 ms, which can remove 20 C or more of charge from the lower region of a thundercloud. The charge-generating mechanisms within the cloud must then refurbish the charge before another stroke can occur. This they can do in as little as 10 s.

In contrast to the lightning flashes described earlier, most flashes to mountain tops and tall buildings are initiated by stepped leaders that start near the top of the building, move upward, and branch toward the base of a cloud (Fig. 6.54b). Lightning rods[44] protect tall structures from damage by routing the strokes to the ground through the rod and down conductors rather than through the structure itself.

A lightning discharge within a cloud generally neutralizes the main positive and negative charge centers. Instead of consisting of several discrete strokes, such a discharge generally consists of a single, slowly moving spark or leader that travels between the positively and the negatively charged regions in a few tenths of a second. This current produces a low but continuous luminosity in the cloud upon which may be superimposed several brighter pulses, each lasting about 1 ms. Tropical thunderstorms produce about 10 cloud discharges for every ground discharge, but in temperate latitudes the frequencies of the two types of discharge are similar.

The return stroke of a lightning flash raises the temperature of the channel of air through which it passes to above 30,000 K in such a short time that the air has no time to expand. Therefore, the



(a) (b)

Fig. 6.54 (a) A time exposure of a ground lightning flash that was initiated by a stepped leader that propagated from the cloud to the ground. Note the downward-directed branches that were produced by the multibranched stepped leader. [Photograph courtesy of NOAA/NSSL.] (b) A time exposure of a lightning flash from a tower on a mountain to a cloud above the tower. This flash was initiated by a stepped leader that started from the tower and propagated upward to the cloud. In contrast to (a), note the upward-directed branching in (b). [Photograph courtesy of R. E. Orville.]

[44] The use of lightning rods was first suggested by Benjamin Franklin in 1749, who declined to patent the idea or otherwise profit from their use. Lightning rods were first used in France and the United States in 1752. The chance of houses roofed with tiles or slate being struck by lightning is reduced by a factor of about 7 if the building has a lightning rod.

pressure in the channel increases almost instantaneously to 10−100 atm. The high-pressure channel then expands rapidly into the surrounding air and creates a very powerful shock wave (which travels faster than the speed of sound) and, farther out, a sound wave that is heard as *thunder*.[45] Thunder is also produced by stepped and dart leaders, but it is much weaker than that from return strokes. Thunder generally cannot be heard more than 25 km from a lightning discharge. At greater distances the thunder passes over an observer's head because it is generally refracted upward due to the decrease of temperature with height.

Although most ground lightning flashes carry negative charge to the ground, about 10% of the lightning flashes in midlatitude thunderstorms carry a positive charge to the ground. Moreover, these flashes carry the largest peak currents and charge transfers. Such flashes may originate from the horizontal displacement by wind shear of positive charge in the upper regions of a thunderstorm (as depicted in Fig. 6.52) or, in some cases, from the main charge centers in a thunderstorm being inverted from normal.

6.7.3 The Global Electrical Circuit

Below an altitude of a few tens of kilometers there is a downward-directed electric field in the atmosphere during fair weather. Above this layer of relatively strong electric field is a layer called the *electrosphere*, extending upward to the top of the ionosphere in which the electrical conductivity is so high that it is essentially at a constant electric potential. Because the electrosphere is a good electrical conductor, it serves as an almost perfect electrostatic shield.

The magnitude of the fair weather electric field near the surface of the Earth averaged over the ocean $\sim$130 V m^{-1}, and in industrial regions it can be as high as 360 V m^{-1}. The high value in the latter case is due to the fact that industrial pollutants decrease the electrical conductivity of the air because large, slow-moving particles tend to capture ions of higher mobility. Because the vertical current density (which is equal to the product of the electric field and electrical conductivity) must be the same at all levels, the electric field must increase if the conductivity decreases. At heights above about 100 m, the conductivity of the air increases with height and therefore the fair weather electric field decreases with height. The increase in electrical conductivity with height is due to the greater ionization by cosmic rays and diminishing concentrations of large particles. Thus, at 10 km above the Earth's surface the fair weather electric field is only 3% of its value just above the surface. The average potential of the electrosphere with respect to the Earth is $\sim$250 kV, but most of the voltage drop is in the troposphere.

The presence of the downward-directed fair weather electric field implies that the electrosphere carries a net positive charge and the Earth's surface a net negative charge. Lord Kelvin, who in 1860 first suggested the existence of a conducting layer in the upper atmosphere, also suggested that the Earth and the electrosphere act as a gigantic spherical capacitor, the inner conductor of which is the Earth, the other conductor the electrosphere, and the (leaky) dielectric the air. The electric field is nearly constant despite the fact that the current flowing in the air (which averages about 2 to 4 $\times$ 10^{-12} A m^{-2}) would be large enough to discharge the capacitor in a matter of minutes. Thus, there must be an electrical generator in the system. In 1920, C. T. R. Wilson proposed that the principal generators are thunderstorms and electrified shower clouds, and this idea is now almost universally accepted. As we have seen, thunderstorms separate electric charges in such a way that their upper regions become positively charged and their bases negatively charged. The upper positive charges are leaked to the base of the electrosphere through the relatively highly conducting atmosphere at these levels. This produces a diffuse positive charge on the electrosphere, which decreases with height (as does the fair weather electric field) with a scale height of $\sim$5 km. Below a thunderstorm the electrical conductivity of the air is low. However, under the influence of the very large electric fields, a current of positive charges, the *point discharge current*,[47] flows upwards from the Earth (through trees and other pointed obstacles). Precipitation particles are polarized by the fair weather electric field, and by the electric field

[45] This explanation for thunder was first given by Hirn[46] in 1888.

[46] **Gustave Adolfe Hirn** (1815–1890) French physicist. One of the first to study the theory of heat engines. Established a small network of meteorological stations in Alsace that reported observations to him.

[47] Point discharges at mastheads, etc., are know as *St. Elmo's fire*.

beneath thunderstorms, in such a way that they tend to preferentially collect positive ions as they fall to the ground. A positive charge equivalent to about 30% of that from point discharges is returned to the Earth in this way. Finally, ground lightning flashes transport negative charges from the bases of thunderstorms to the ground.

A schematic of the main global electrical circuit is shown in Fig. 6.55. A rough electrical budget for the Earth (in units of C km^{-2} year^{-1}) is 90 units of positive charge gained from the fair weather conductivity, 30 units gained from precipitation, 100 units of positive charge lost through point discharges, and 20 units lost due to the transfer of negative charges to the Earth by ground lightning flashes.

Monitoring of lightning flashes from satellites (Fig. 6.56) shows that the global average rate of ground flashes is ~12–16 s^{-1}, with a maximum rate of ~55 s^{-1} over land in summer in the northern hemisphere. The global average rate of total lightning flashes (cloud and ground flashes) is 44 ± 5 s^{-1}, with a maximum of 55 s^{-1} in the northern hemisphere summer and a minimum of 35 s^{-1} in the northern hemisphere winter. About 70% of all lightning occurs between 30 °S and 30 °N, which reflects the high incidence of deep, convective clouds in this region. Over the North American continent ground flashes occur about 30 million times per year!

Over the United States there is a ground network that detects ground flashes. By combining counts of ground flashes from this network with counts of total flashes from satellite observations, the ratio of cloud flashes to ground cloud can be derived. This ratio varies greatly over the United States, from a maximum of ~10 over Kansas and Nebraska, most of Oregon, and parts of northwest California to a ratio of ~1 over the Appalachian Mountains, the Rockies, and the Sierra Nevada Mountains.

Because lightning is associated with strong updrafts in convective clouds, measurements of lightning can serve as a surrogate for updraft velocity and severe weather.

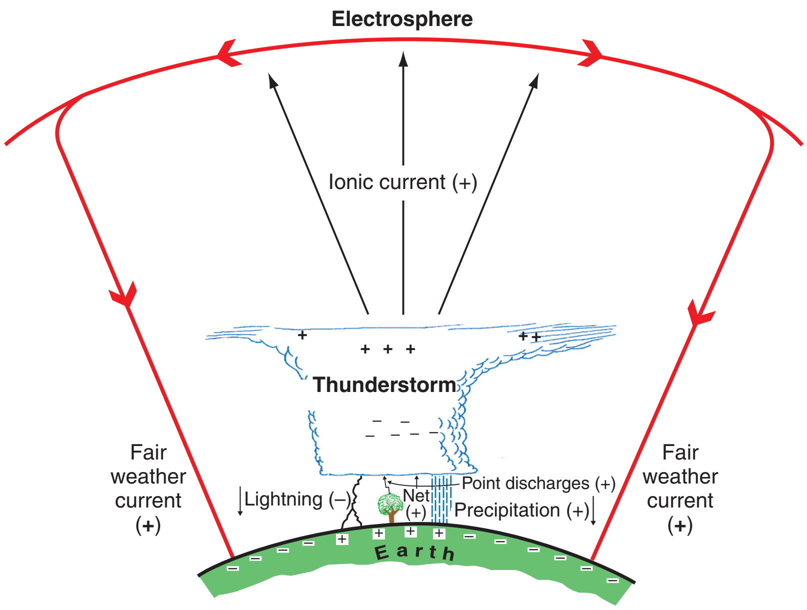


Fig. 6.55 Schematic (not drawn to scale) of the main global electrical circuit. The positive and negative signs in parentheses indicate the signs of the charges transported in the direction of the arrows. The system can be viewed as an electrical circuit (red arrows) in which electrified clouds are the generators (or batteries). In this circuit positive charge flows from the tops of electrified clouds to the electrosphere. Thus, the electrosphere is positively charged, but it is not at a sharply defined height. In fact most of the positive charge on the electrosphere is close to the Earth's surface. The fair-weather current continuously leaks positive charge to the Earth's surface. The circuit is completed by the transfer of net positive charge to the bases of electrified clouds due to the net effect of point discharges, precipitation, and lightning. In keeping with the normal convention, the current is shown in terms of the direction of movement of positive charge, but in fact it is negative charge in the form of electrons that flows in the opposite direction. See text for further details.

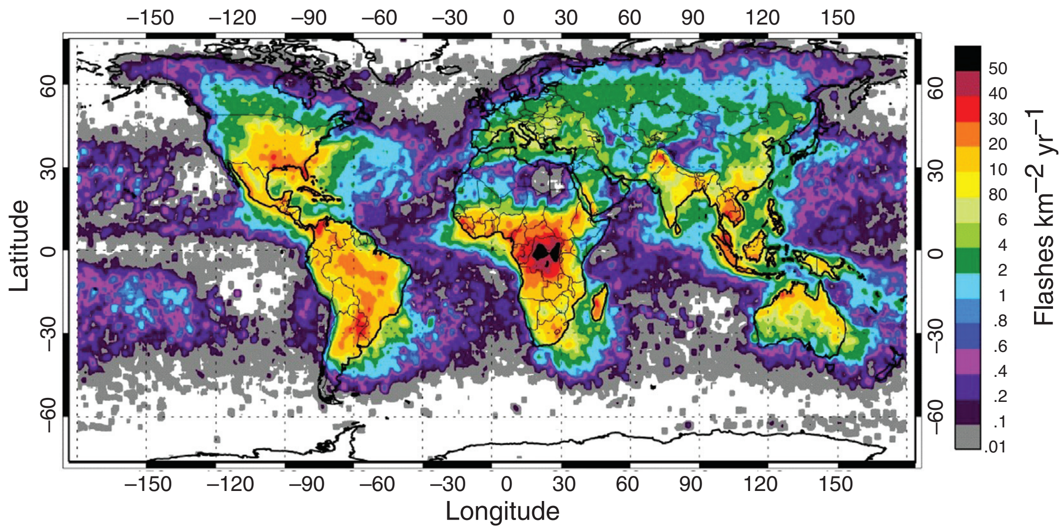


Fig. 6.56 Global frequency and distribution of total lightning flashes observed from a satellite. [From H. J. Christian et al., "Global frequency and distribution of lightning as observed from space by the Optical Transient Detector," *J. Geophys. Res.* **108**(D1), 4005, doi:10.1029/2002JD002347 (2003). Copyright 2003 American Geophysical Union. Reproduced by permission of American Geophysical Union.]

6.5 Upward Electrical Discharges

In 1973 a NASA pilot, in a surveillance aircraft flying at 20 km, recorded the following: "*I approached a vigorous, convective turret close to my altitude that was illuminated from within by frequent lightning. The cloud had not yet formed an anvil. I was surprised to see a bright lightning discharge, white-yellow in color, that came directly out of the center of the cloud at its apex and extended vertically upwards far above my altitude. The discharge was very nearly straight, like a beam of light, showing no tortuosity or branching. Its duration was greater than an ordinary lightning flash, perhaps as much as five seconds.*"

Since then numerous types of lightning-related, transient luminous phenomena in the stratosphere and mesosphere have been documented, which go under the names of *sprites, elves*, and *blue jets* (Fig. 6.57).

Sprites are luminous flashes that last from a few to a few hundred milliseconds. Sprites may extend from ~90 km altitude almost down to cloud tops and more than 40 km horizontally. They are primarily red, with blue highlights on their lower regions; they can sometimes be seen by eye. Sprites are believed to be generated by an electric

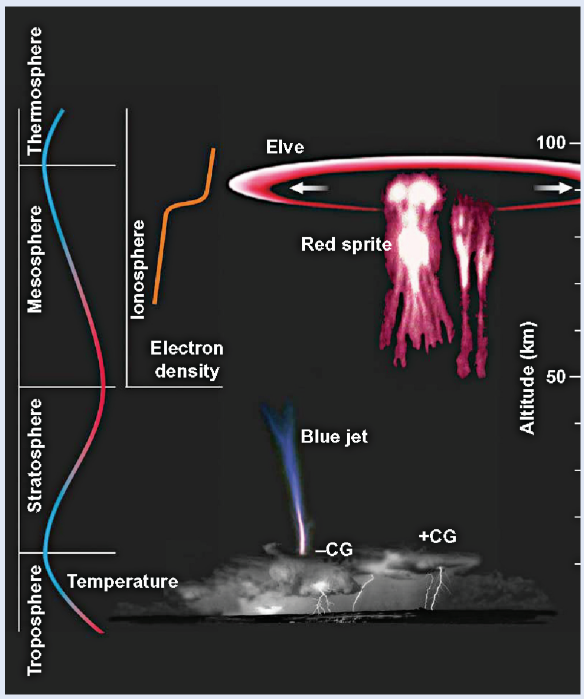


Fig. 6.57 Transient luminous emissions in the strato-sphere and mesosphere. [Reprinted with permission from T. Neubert, "On Sprites and their exotic Kin." *Science* **300**, 747 (2003). Copyright 2003 AAAS.]

Continued on next page

6.5 Continued

field pulse when particularly large amounts of positive charge are transferred from a thunderstorm to the ground by a lightning stroke, often from the stratiform regions of large mesoscale convective systems discussed in Section 8.3.4. In contrast to the fully ionized channels of a normal lightning stroke, sprites are only weakly ionized.

Elves are microsecond-long luminous rings located at ~90 km altitude and centered over a lightning stroke. They expand outward horizontally at the speed of light and are caused by atmospheric heating produced by the electromagnetic pulse generated by a lightning stroke. They are not visible by eye.

Blue jets are partially ionized, luminous cones that propagate upward from the tops of thunderstorms at speeds of ~100 km s^{-1} and reach altitudes of ~40 km. On occasions, blue jets trigger sprites, thereby creating a direct, high-conductivity electrical connection from a thunderstorm to the ionosphere. These rare events do not appear to be directly associated with cloud-to-ground lightning flashes. They last only ~100–200 ms and are difficult to see by eye even at night.

Other less well-documented upward propagating discharges have been reported. Figure 6.58 shows an upward-extending column of white light, about 1 km in length, from the top of a thunderstorm.

Fig. 6.58 Upward discharge from a thunderstorm near Darwin, Australia. There is a blue "flame" at the top of the white channel that extends upward another kilometer or so. [From *Bull. Am. Meteor. Soc.* **84**, 448 (2003).]

These various phenomena likely play a role in the global electrical circuit and perhaps also in the chemistry of the stratosphere and mesosphere in ways yet to be elucidated.

6.8 Cloud and Precipitation Chemistry[48]

In Chapter 5 we discussed trace gases and aerosols in the atmosphere. This section is concerned with the roles of clouds and precipitation in atmospheric chemistry. We will see that clouds serve as both sinks and sources of gases and particles, and they redistribute chemical species in the atmosphere. Precipitation scavenges particles and gases from the atmosphere and deposits them on the surface of the Earth, the most notable example being *acid precipitation* or *acid rain*.

6.8.1 Overview

Some important processes that play a role in cloud and precipitation chemistry are shown schematically in Fig. 6.59. They include the transport of gases and particles, nucleation scavenging, dissolution of gases into cloud droplets, aqueous-phase chemical reactions, and precipitation scavenging. These processes, and their effects on the chemical composition of cloud water and precipitation, are discussed in turn in this section.

6.8.2 Transport of Particles and Gases

As depicted on the left side of Fig. 6.59, gases and particles are carried upward on the updrafts that feed clouds. Some of these gases and particles are transported to the upper regions of the clouds and are ejected into the ambient air at these levels. In this way, pollutants from near the surface of the Earth (e.g., SO_2, O_3, particles) are distributed aloft. Solar radiation

[48] See footnote 1 in Chapter 5.