Thunderstorms In some storms, convection produces lightning and thunder. Although storm electrification can occur in a variety of circumstances, most thunderstorms develop under atmospheric conditions with warm air at low levels, with relatively cold air aloft. In such situations, termed *conditional instability,* if low-level air has sufficient moisture and is lifted by some atmospheric process, such as a front, to its *lifting condensation level* and beyond, it can reach a level (called the *level of free convection*) above which is becomes warmer than the air into which it is rising. Like a hot air balloon, this low-level air is positively buoyant above the level of free convection and can continue to rise without further energy being supplied to lift it. Buoyancy continues to accelerate the air upward until it once again becomes cooler than its surroundings. The point where the rising air's temperature again equals that of its surroundings after having been positively buoyant is called the *equilibrium level*, above which its rising motion is slowed and eventually stopped by negative buoyancy. The air then settles back to the equilibrium level, spreading out as it does so. {*see* Conditional and Convective Instability}

The visible manifestation of this process is a *cumulonimbus cloud*, often called a *thunderhead*. Such clouds are not always visible to observers on the ground because they can be obscured by other clouds and atmospheric haze, but their presence is made evident by lightning and thunder. Because such clouds can be very deep, with tops as high as 16 to 20 kilometers, they absorb a large proportion of the sunlight, so an observer sees a dark cloud base. The crisply-defined, cauliflower-like part of a visible cumulonimbus corresponds to the rising air, or *updraft*, within the thunderstorm. Cloud material accumulates at the equilibrium level, forming the spreading cumulonimbus *anvil*. As air rises through the equilibrium level before settling back into the anvil, it can form a cloud dome above the anvil, called an *overshooting top*. The rise and fall of overshooting tops is associated with intermittent rising surges of low-level air. Each such surge comprises a thunderstorm *cell*, and the typical thunderstorm is made up of several such cells.

The fact that thunderstorms are made up of cells was discovered during the Thunderstorm Project, carried out in Florida and Ohio shortly after World War II. The importance of thunderstorms to aviation had become especially apparent during the war, so a major research program was begun under the direction of Horace R. Byers and Roscoe R. Braham. By using the newly-developed observing tool, radar, as well as extensive surface and aircraft observations, the researchers documented the cellular nature of thunderstorms for the first time.

Thunderstorm cells have a distinct life cycle, beginning with a *towering cumulus stage*, when the cell is dominated by updraft and any precipitation that develops is being retained aloft. As the precipitation falls to the Earth, its drag on the air and the cooling from its evaporation combine to develop a downdraft that eventually reaches the ground and spreads out as *outflow*, with a *gust front* at its leading edge. As this outflow develops, the cell is made up of both updraft and downdraft, so the cell is said to be in its *mature stage*. During the mature stage, the cell attains its greatest strength, with the strongest updraft and downdraft, the heaviest precipitation, and the most frequent lightning. Finally, the cell's updraft diminishes, and the cell becomes dominated by downdraft as the remaining precipitation falls out. The cell has now entered the *dissipating stage*, and all the effects associated with the it gradually wane. A typical cell completes its life cycle in about 20 to 40 minutes, corresponding to the time it takes for a parcel of air to rise from near the surface to the storm top. At any given time, a thunderstorm usually contains several cells in different stages of their life cycles.

About 90 percent of all thunderstorms are benign, producing beneficial rains and few other effects. Some thunderstorms produce little or no rain but their lightning can set destructive fires. Only about 10 percent of thunderstorms become severe, producing hazardous weather that may include large hailstones 2 or more centimeters in diameter, damaging surface winds of at least 25 meters per second, or tornadoes. Although not officially classified as severe events, large amounts of small hail, heavy rains that create flash floods, and frequent cloud-to-ground lightning flashes can also be serious hazards. Any thunderstorm can be quite dangerous to aviation, especially when aircraft encounter intense localized downdrafts called microbursts during take-off or landing. The occurrence of microbursts, even in relatively benign-appearing thunderstorms, has only recently been recognized, in part through the pioneering studies of T. Theodore Fujita. {*see* Aviation; Weather Hazards}

The most characteristic property of thunderstorms is the lightning that produces the thunder. Lightning represents an electrical discharge between regions of different electrical charge; a giant spark. Surprisingly, relatively little is known for certain about how cumulonimbus clouds become electrified, but laboratory experiments suggest that air's breakdown voltage (the voltage necessary to allow the charged regions to equalize by allowing a spark between them) is measured in millions of volts per meter. Most lightning flashes begin and end within the cloud, but some extend between the cloud and the ground. Of those that reach the ground, the great majority lower negative charge to the Earth, but a small fraction lowers positive charge to the ground. It is not well understood why a few flashes bring down positive charge, but it appears that at least some severe storms have an unusually high proportion of positive flashes; thus, this is an important topic of current research. Recently, cloud-to-ground lightning flash detection networks have become widespread throughout the United States, and it is becoming possible to develop better knowledge of the distribution of thunderstorms. {*see* Atmospheric Electricity; Global Electric Circuit; Lightning}

Present knowledge about the distribution of thunderstorms has been developed mainly from surface observations, satellite images, and radar data. The implementation of new radars that include Doppler capability, permitting them to sense air motion in thunderstorms, is an important recent development that should eventually lead to improved understanding and prediction of thunderstorms. {*see* Radar}

Generally, thunderstorms are most frequent during the afternoon and early evening, when the Sun's radiation has warmed the low levels and the atmosphere's conditional instability is the greatest; however, over a large section of the central North American plains in the summer, thunderstorms are most frequent at night. Many of these nocturnal thunderstorms actually develop during the afternoon and persist well into the night, aided by a low-level poleward wind speed maximum that tends to develop soon after dark over the plains east of the Rocky Mountains. This low level wind speed maximum brings warm, moist air into the thunderstorms, prolonging their existence into the nighttime hours and sometimes into the following morning.

Thunderstorms usually are more frequent and intense over continental land masses than over the open oceans. The main reason for the concentration of thunderstorms over land, rather than over water, is that most ground surfaces warm more rapidly than water surfaces, given equal amounts of sunshine. This is the result of the high heat capacity of water; that is, its temperature changes relatively slowly as heat is added. The heated land surface transfers its heat to the low-level air, producing conditional instability more readily than a water surface. One exception to this occurs over warm ocean-surface currents such as the Gulf Stream. Another exception to this rule is associated with frequent thunderstorms that develop within the Intertropical Convergence Zone, which lies generally near the equator. This atmospheric convergence zone lifts the warm, moist air of the tropics and produces thunderstorms over both land and sea. The thunderstorms that form over the ocean in this zone are often in clusters associated with westward-moving disturbances. Occasionally, these disturbances can organize into tropical cyclones.

Just as many thunderstorms tend to follow the daily solar heating cycle, their overall timing also reflects the seasonal cycle. In many parts of the United States, conditional instability is at its highest during the warmest part of the year, but during the summer, the lifting processes needed to initiate thunderstorms are often missing. The mechanisms that initiate thunderstorms are usually found within the traveling weather systems that tend to follow the jet streams of middle latitudes, which move far poleward during the summer. Important exceptions to this general rule occur in Florida and southern Texas, where sea and land breeze fronts may initiate thunderstorms nearly every afternoon. The mountain-valley circulations in the western United States act similarly to set off nearly daily thunderstorms in the summer. This is why thunderstorm frequency maps show Florida and Colorado with the most frequent thunderstorm occurrence, generally in the summer. Apart from these exceptions, thunderstorms are most common in the late spring, when conditional instability is high and traveling weather systems are still relatively strong; these conditions are also important ingredients for creating severe thunderstorms. The peak in thunderstorm frequency generally tends to move poleward during the spring and, to a lesser extent, equatorward in the fall. In order to understand this asymmetry in the distribution of thunderstorms between spring and fall, the role of thunderstorms in the atmosphere must be considered.

As a manifestation of convection, a thunderstorm can be thought of as a giant heat engine, transporting latent and sensible heat upward to alleviate conditional and convective instability. The heated air at low levels rises in updrafts and is replaced by downdraft air that is cool and relatively dry. Although the thunderstorm updraft does not cover a large area, its rising motion is on the order of 10 meters per second or more, much faster than the larger but weaker vertical motions of the large-scale traveling weather disturbances. Therefore, thunderstorms can rapidly process large amounts of air and carry aloft large amounts of moisture in a short time. A single updraft averaging 10 meters per second in vertical speed and covering an area of 100 square kilometers (a circular updraft about 5.6 kilometers in radius), is lifting about one million kilograms of air per second. If that air has a water vapor content of 10 grams of water vapor per kilogram of air, that means a vertical ascent of 10 million grams (or 10,000 kilograms) of water vapor per second. For the most part, the energy required to perform this feat is derived from latent heat release associated with the condensation of the transported water vapor.

We can get a feeling for how much this represents if we assume that this hypothetical storm lasts for 2,000 seconds (about 30 minutes), so that 20 million kilograms of water are processed. If all of that water vapor condenses, this produces roughly 1.2 x 10^{13} calories of released latent heat. The explosion of 1 kiloton of TNT corresponds to about 10^{12} calories, so the thunderstorm releases heat roughly equivalent to a 12-kiloton bomb (about half the yield of the first atomic explosion). Of course, this comparison is somewhat misleading, because the thunderstorm spreads its energy release over 2000 seconds, whereas a bomb releases its heat in a tiny fraction of one second. Nonetheless, the comparison at least suggests the enormous energies involved in even a fairly weak thunderstorm. Severe storms can be substantially more energetic.

The net effect of thunderstorms in the overall heat budget of the Earth is quite significant. They are important in transferring the heat received daily from the Sun upward into the atmosphere, especially during the warm season in each hemisphere, and in the tropics during much of the year. If thunderstorms act to transfer heat upward, thereby mitigating conditional and convective instability, then the asymmetry between spring and fall, mentioned earlier, can be easily explained. During the spring, the upper atmosphere tends to be relatively cold, in part because the increasing solar heat input at the surface has not yet been transferred upward. Solar heating warms the low levels increasingly during the spring but because the upper atmosphere is still relatively cold, conditional instability is high. In addition, the strong weather systems of spring produce conditions very favorable for thunderstorms. In the fall, however, thunderstorms have been operating through the spring and summer to reduce instability by depositing heat into the upper atmosphere. Thus fall conditions are generally more stable than in spring and summer, and fall thunderstorms typically are correspondingly less frequent and intense. Naturally, exceptions to this rule occur occasionally. The atmosphere does not know anything about the calendar and if sufficient conditional instability is produced, then thunderstorms will develop to alleviate it.

About 1500 thunderstorms are occurring worldwide, on the average, at any given time. The equilibrium level in a few thunderstorms (often the more severe ones) can be into the stratosphere, so these thunderstorms deposit considerable amounts of water substance into the stratosphere in the form of ice. These stratospheric ice clouds from thunderstorms can be an important factor in the atmosphere's radiation and heat balance. Not only are thunderstorms important in the heat and water balance of the Earth; their lightning also acts to fix atmospheric nitrogen into forms that can be used by plants. The lightning also maintains the Earth's overall negative charge with respect to the atmosphere, the so-called *fair weather electric field*, because the vast majority of cloud-to-ground lightning flashes lower negative charge to the surface. On the whole, despite the damage they sometimes cause, thunderstorms are an important and mostly beneficial component of the processes sustaining life on the Earth.

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Figures

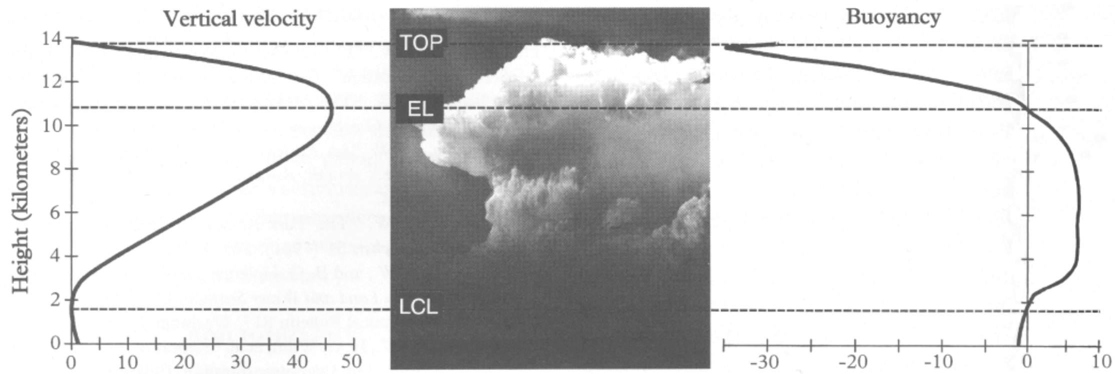

Figure 1. Schematic vertical profiles of the vertical motion (left) and the buoyancy (right) associated with an actual thunderstorm (center). On the diagrams, the lifting condensation level is denoted by LCL and the equilibrium level by EL. Values shown for buoyancy and vertical motion are only qualitative and do not necessarily reflect the actual values for the thunderstorm shown.

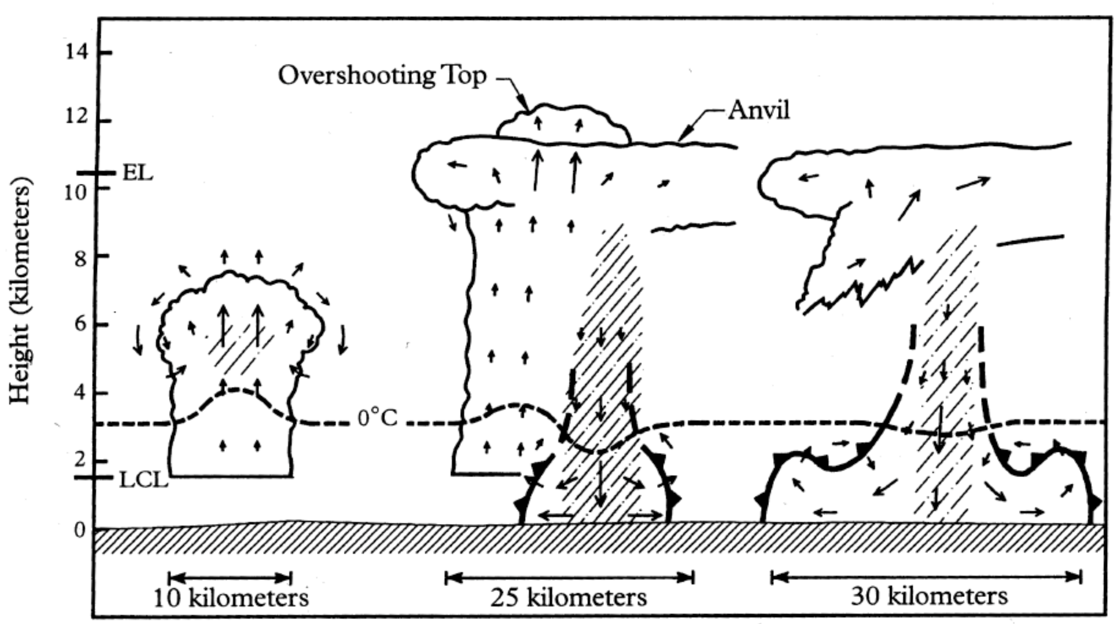

Figure 2. Stages in the life cycle of a single thunderstorm cell, show air motions (arrows), precipitation (hatching), cloud outlines, and the freezing level (dashed line, labeled 0˚C): from left to right, towering cumulus stage, mature stage, and dissipating stage. The gust front is denoted by a thick line with cold front symbols.