Mountain & Desert Thunderstorms

Their Formation & Field-Forecasting Guidelines

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The author…who is this guy anyway?

Basically I am a lifelong student of weather, educated in physical science. I have undergraduate degrees in physics and in geology, a masters degree in geology, and advanced courses in atmospheric science. I served as a NOAA ship's officer using weather information operationally, and have taught meteorology as part of wildfire-behavior courses for firefighters. But most of all, I love to watch the sky, to try understand what is going on there, and I've been observing and learning about the weather since childhood.

It is my hope that this description of thunderstorms will increase your own enjoyment and understanding of what you see in the sky, and enable you to better predict it. It emphasizes what you can see. You need not absorb all the quantitative detail to get something out of it, but it will deepen your understanding to consider it.

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Summer storm examples

High on the spine of the White Mountains in California you have hiked and worked all week in brilliant sunshine and clear skies, with a few pretty afternoon cumulus clouds to accent the summits of the White Mtns. and the Sierra Nevada to the west. The late-summer morning begins clear, the skies above are deep blue, as you hike up and set about your work on the high ridges. Hardly noticed, a transient shred of cloud appears over a nearby peak just before mid-morning. As the morning wears on friendly cumulus clouds arise across the range…a glorious day in the mountains. By lunch time the sky seems largely cloud-covered, with some darker cloud bases…hmmm, might need that warm shirt. A couple of hours later, intent on your work, you are surprised by the low rumble of thunder. You look up to see dark sky overhead, massive clouds over the Sierras, and a bright wall of clouds over the desert ranges to the east. As you wonder whether you'll get finished in time a few scattered raindrops fall. You press ahead to get the last observations done. But your decision is forced as the sharp crack of thunder follows closely on the heels of a brilliant lightning flash. It is time to retreat from the exposed ridge, and you pack your gear, put on your jacket and head down in a hurry. Within minutes you are drenched by heavy rain then pelted by hailstones, as lightning crackles all around. Visibility is poor, and the footing is wet and slippery. Wow, this is not fun anymore, and you are driven on by real concern about being so exposed. Fortunately you reach the shelter of your car, soaking wet, but otherwise unharmed. What happened? How was today different, and how could you have noticed sooner?

On a July vacation you plan to hike up a lovely canyon, cut into beautiful, colorful sandstones of the Colorado Plateau. The weather report said something about widely scattered showers. Off you go, hiking in perfect weather, anticipating a day in a spectacular slot canyon. The only feature in a deep blue sky is a handful of small white clouds over distant mesas. You enter the canyon, and the visible sky is just a ribbon between the high canyon rims. By lunch time the sky seems whiter, mostly covered by diffuse high cloud. The cloud seems to be drifting in a direction from the highlands upstream toward the lower end of the canyon. Oh well, no rain in sight, no sound of thunder. On you go. An hour later the cloud overhead is denser, sunlight diminished, and now covers all of the sky you can see. And you glimpse a few lobe-like shapes on the underside of the cloud. You hear the low rumble of distant thunder, think that maybe it would be best to turn around and head back, but no rain yet so you press on for a while. A strong wind gust from up the canyon hits and off goes your hat, but it is soon past and you continue to explore. Thunder is louder now, more frequent, large drops are falling into the canyon. OK, time to go back. Then you hear a low rumble that continues longer than the thunder, getting louder. It soon sounds like water sloshing against the canyon walls. Uh oh. Better get up off the canyon floor, so you climb up into a short tributary gulch. The muddy torrent appears below you, cutting off your way home. After several wet, cold hours, the flood recedes and you once again enter the canyon for a muddy slog back out. Where did that come from?...how could you have seen it in time?

All of those things could have happened during a hike in the high country, or while you are camping in the mountains on your summer vacation, even at lower elevations. It can happen anywhere in the mountains and deserts of the western US. For that matter, it could happen when you are visiting other parts of the US or the world, such as the mountains or deserts of South America, Europe, Africa, or Asia. This description of thunderstorms is a relevant introduction to similar processes throughout the world.

Application of this paper is relevant to all thunderstorms, and to cumulus clouds

Though this paper focuses on mountain and desert thunderstorms, the information is very applicable to other clouds. Much of it describes cloud processes that also occur in thunderstorms that develop with frontal systems or over the plains…they differ mainly in the lifting mechanisms and the overall storm organization (such as large complexes of thunderstorms), especially the rotation that characterizes supercell thunderstorms of the US Great Plains. The formation of cloud droplets is the same in other kinds of cumulus clouds, and even in stratiform clouds. Processes that produce precipitation in thunderstorms are also important in other continental rain clouds.

An overview of thunderstorm development, to be more fully elaborated

Air rises buoyantly above the summits, cooling as it ascends. When it cools to its 'dew point temperature' water droplets form and cloud appears. Further ascent results in more condensation and the cloud top rises, ever colder, deepening the cloud mass to several thousands of meters. Some droplets freeze, a critical step. They then grow quickly, mostly by stealing water from liquid water droplets. The growing ice particles begin to fall downward through the updraft, gaining mass rapidly by collision with smaller droplets in their path. As the falling graupel (ice particles onto which droplets have frozen) collides with tiny ice crystals, electrical charges separate in the cloud. When the cloud reaches sufficient depth and maturity, precipitation and lightning can occur at the ground. A downdraft of dense, cold air can spread out as a strong gusty wind.

The thunderstorm process proceeds with observable signs all along the way…to be described in detail below. Noticing the progression of cloud development certainly raises one's awareness and leads to better decisions about avoiding thunderstorm hazards. But a nice additional benefit is the pleasure of enjoying the beautiful and dramatic spectacle in the light of better understanding and fuller appreciation of what is going on. It is wonderful fun to watch.

Setting the Stage

Two atmospheric conditions are needed for typical mountain thunderstorms. First, an air mass that will allow deep convection, air rising buoyantly for several kilometers (1 kilometer is about 10% more than 3000 feet, 3280 feet or 0.62 miles). Such a condition is called "unstable", and it basically requires an atmospheric environment that is warm enough at the bottom compared to cooler temperatures aloft. Second, sufficient moisture to produce a cloud that is on the order of 4 km (13,000 ft) in depth or more, rising from a base at or below roughly 6 km (~20,000 ft) altitude (in mountains of the western US). Condensation of cloud droplets also contributes to the buoyancy of the rising air. In fact, without the extra warming of condensation and freezing, dry air currents would be limited in their daily rise to a fraction of the depth that a thundercloud reaches.

To get things started, the air needs to be warmed at the bottom. That occurs daily as the sun heats the mountains, which then stand as elevated warm areas surrounded by cooler air, making them the source of the highest-rising air currents. Other processes can also impel or encourage upward motion, such as airflow against the slopes deflecting upward, influx of cooler air aloft (which makes rising columns more buoyant), and dynamically driven convergence of low-level air and/or divergence of air aloft. But the main impetus for a typical summer thunderstorm is the heating of the mountains by the sun. Warming of the slopes and ridges by the sun can be assumed for any summer day, the initial impetus is there, unless reduced by cloud cover. Usually, cloud growth slows when the sun goes down. But if the motions of the atmosphere are producing low-level convergence, high-level divergence, or cold air influx aloft thunderstorms can continue all night.

The stability and moisture of clear, cloud-free air are impossible to judge in the field just by looking, though the evidence of that will unfold throughout the day, and there are sometimes early signs. Guidance beforehand on the potential for thunderstorms is best gleaned from the weather forecast. The forecast might hint at thunderstorms with comments on such things as monsoon moisture, south or southeast flow aloft, or deep instability. Explicit predictions of thunderstorms are of course meaningful, including "isolated" or "scattered" thunderstorms, and there have been some very thundery days with a forecasted probability-of-precipitation of no more than 20% (see Glossary). The lightning activity level (LAL) given in the fire-weather forecast is also helpful and embodies the scale shown below in Figure 1. Any LAL of 2 or higher should be taken as an indicator of thunderstorm potential that can affect a mountaineer.

Sometimes the presence of adequate moisture and instability is suggested by altocumulus castellanus clouds. These are patches of cloud in the mid-levels of the troposphere that have usually drifted in from elsewhere, and are not necessarily associated with high elevations of the terrain, nor with afternoon heat. The tops of the patches sprout small turrets, like miniature cumulus clouds growing from a broader base, arising not from the ground but at the cloud top itself (Figure 2). Their presence signifies that the air at middle-altitudes is sufficiently moist and unstable to encourage upward motion of buoyant cloud columns. Any cumulus clouds that grow that day will benefit from those conditions of instability and moisture when they reach that altitude, conditions that favor thunderstorms.

Watching the drift of altocumulus, or cirrus, clouds can reveal the direction of the mid-level and upper winds. That is an important clue to the source of the airmass that is approaching, and whether it is bringing significant moisture.

Lightning Activity Level (LAL)	
Is a scale which describes lightning activity. Values are labeled 1-6:	
LAL 1	No thunderstorms
LAL 2	Isolated thunderstorms. Light rain will occasionally reach the ground. Lightning is very infrequent, 1 to 5 cloud to ground strikes in a five minute period.
LAL 3	Widely scattered thunderstorms. Light to moderate rain will reach the ground. Lightning is infrequent, 6 to 10 cloud to ground strikes in a 5 minute period.
LAL 4	Scattered thunderstorms. Moderate rain is commonly produced Lightning is frequent, 11 to 15 cloud to ground strikes in a 5 minute period.
LAL 5	Numerous thunderstorms. Rainfall is moderate to heavy. Lightning is frequent and intense, greater then 15 cloud to ground strikes in a 5 minute period.
LAL 6	Dry lightning (same as LAL 3 but without rain). This type of lightning has the potential for extreme fire activity and is normally highlighted in fire weather forecasts with a Red Flag Warning.

Figure 1. Lightning activity level. LAL is used largely in fire weather forecasting, but can be a very useful guide to the potential for thunderstorm development.

Figure 2. Altocumulus castellanus (Acc) clouds. The clouds are at atmospheric mid-levels, not necessarily over elevated terrain, and often already present when the sun rises. The convective turrets that sprout from the cloud base (2 shown by arrows) are driven by infrared radiation warming the bottoms and cooling the tops, and the release of heat-of-condensation, but are not dependent on currents arising from heating of the ground. The presence of Acc clouds is evidence of moisture and instability in the middle troposphere, and those conditions favor thunderstorms.

Early indications…small cumulus clouds

All night long heat is lost by radiation, very effectively in the thin, dry air of the mountains (including desert ranges). Dawn comes with the higher terrain surrounded by cold air. The sun rapidly heats the ground, making the higher terrain effectively warm islands in a sea of cold air. Buoyant blobs of air rise invisibly. At first the rising columns don't get very far before mixing with the surrounding air and losing their buoyancy. But as warming continues they extend ever higher. As air rises it cools by expansion (even though it remains warmer than the surrounding air…or else it would not be buoyant), at a rate of about 1^{o}C per 100 meters (5.4^{o}F per 1000 ft). The condition that allows air to rise is that the overall environment is enough cooler with height that the rising parcels of air, though cooling, are still warmer than the surrounding air…a condition described as 'unstable'. Eventually the tops of the columns cool to the dew point temperature of the rising air, and cloud droplets condense on tiny airborne particles that act as nuclei. Small, transient clouds appear, usually first above the highest topographic points. They are often just ragged shreds that soon vanish. The sooner and lower they appear, the moister is the air. It is common to see the first small cumulus clouds by midmorning on a day with thunderstorm potential, and the sign inherent in clouds forming in the morning should not be ignored.

Figure 3. The first cumulus cloud of the day forms as air rising above the sun-heated ground reaches the altitude at which condensation takes place. It is usually an indicator of further cloud development to come, and when it appears early in the day it commonly heralds the development of thunderstorms.

The rising columns of air penetrate further upward as the day progresses. Condensation of cloud droplets releases heat that helps the rising air maintain its loft. The developing cumulus clouds can deepen, become more numerous, and spread out into larger cloud patches. Just how high the cloud tops rise, at what altitude they spread out, depends on where they encounter layers that either suppress or favor upward motion—where the air is stable (which resists rising columns) or unstable (which accelerates rising columns). The flat cloud bases mark the altitude where air cools to its dew point temperature (see Glossary), and that altitude depends on the difference between the surface air temperature and the dew point…larger difference means higher cloud bases.

A sign that the clouds are quite limited in their vertical growth (by a relatively stable layer) is that they are wider than they are tall. Columns that are capped by stable air flatten out and aggregate into flat, wide clouds, with all of the column-tops being at about the same altitude (Figure 4, left). The cloud tops are not bright white and crisp, because the edges are mixing readily with surrounding clear air, rather than pushing strongly into it. The bases are not very dark, because the sunlight is not attenuated very much in passing through the shallow cloud. In contrast, columns that are rising vigorously in unstable air are taller than they are wide (Figure 4, right), and they aggregate into clouds that are vertically extended, at least as deep as they are broad, showing bright white tops and distinctly darker bases.

Fresh columns often extend above the older columns nearby, as we'll discuss in the next section, 'Further cumulus development'.

Figure 4. Left panel shows cumulus clouds (Cumulus humilus) over Mono Domes in broad patches, limited in their vertical growth by stable air. The cloud tops are not especially bright white and the bases are not especially dark. The right panel, in contrast, shows a vigorously rising column (or thermal), taller than it is wide, in unstable air. The cloud behind the thermal also has a column rising at its left end.

So what is there in a small cumulus cloud? (Figure 5) That lovely white cloud floating above the landscape is a mass of tiny water droplets condensed from the rising air, with updrafts on the order of 1-3 m/sec (a m/sec is 2.24 mi/hr). The droplets number in hundreds per cm^3, and are most frequently several to about 15 microns (μm, micrometers) in diameter, roughly the size of cells in your body. There is only modest variation in droplet size. Liquid water content is no more than 1 g/m^3, most commonly about 0.3 g/m^3. Droplet fall speeds are on the order of mm/sec, and they are easily suspended by even weak currents of rising air. On the cloud edges, where cloudy air mixes with the drier surrounding air it quickly evaporates, giving rise to ragged edges and shreds of cloud. Slowly some drops grow larger, to maybe as much as 80 μm diameter. At most a very few drizzle or small-rain drops will form, but they'd not get far below the cloud before evaporating. Not much else happens. More water for further condensation is lacking for lack of continued upward growth. No precipitation falls. If all stays at that stage, the day will be fine. But keep your eyes on the clouds for signs of renewed or further growth.

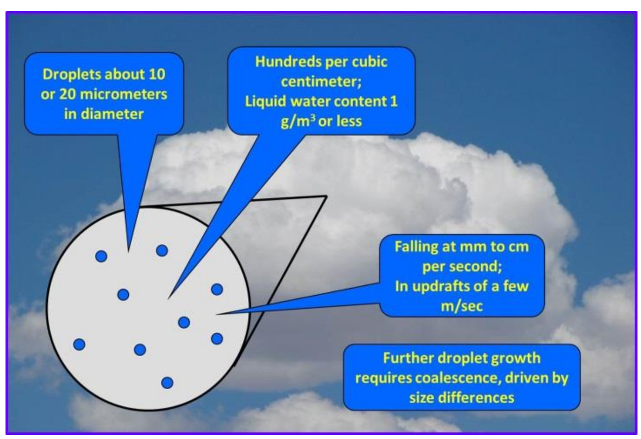

Figure 5. A typical cumulus cloud, with characteristic composition and motions shown as a "magnified" inset.

Where'd those cloud droplets come from?

Water vapor is a gas, with widely separated water molecules flying around. No sooner do a few of them gather together as a tiny drop of liquid than they are jostled by other rapidly jiggling air or water molecules and they fly apart. To condense into a liquid droplet they need a nucleus to gather on, to reduce their tendency to evaporate. The most effective droplet nuclei are soluble bits that dissolve as the water molecules gather on the surface. The dissolved salt reduces the tendency of the water molecules to evaporate, and in sufficient concentration allows the droplet to grow to the critical size to be stable and capable of further growth. That incipient-droplet radius is between about 0.1 μm and 1 μm. Droplets on too-small nuclei cannot grow bigger and remain "haze droplets". Droplets on adequate nuclei can grow larger. Further growth in the updraft (growth slows down as the droplets get bigger) will produce droplets tending toward 15 μm το 20 μm diameter. Some droplets get bigger, but overall not much changes.

Further cumulus development

It is very common for the upward growth of the clouds to take place in stages as the day progresses, moderated by variations in stability with height, rather than steadily. When cumulus growth is not strongly capped by a resistant stable layer, the continual heating of the ground pushes the rising columns higher, deepening the clouds. Fresh columns will surge above the general level of the cloud tops, bright white turrets against the sky (Figure 6). "Turrets" are the tops of convective columns/towers, and are typically 1 to 3 km in diameter; "tufts" are the smaller, rounded bumps on a turret, and typically 100 to 200 meters in diameter.

Often the new turret will slow down as it becomes less buoyant, and will mix out into the surrounding air (which is drier) and be dissipated. Other turrets rise and in their turn fade away, their complete dissipation indicating that they are composed of small water droplets, not of ice. But as time goes on, the air is being moistened by the water being transported upward in rising turrets, and new turrets have a better chance of persisting. The tops of the cumulus clouds come to define a new cloud-top, higher than the old one.

Figure 6. Rise of a new turret above an earlier cloud-top level. Time progresses from left to right, and is on the order of minutes. Red arrows mark the original upper limit of convection and the new upper limit. After it stops rising the new turret mixes with the surrounding air and fades away, with only a small cloud remnant remaining in the last panel. The quickly-dissipating remnants are composed of small liquid water droplets.

Rise of successive turrets deepens the cumulus clouds, and commonly much of the sky over the mountains gradually becomes full of moderately deep cumulus clouds, cumulus mediocris (Figure 7, right). The individual clouds tend to be about as deep as they are wide, but it is not always obvious what is "a cloud" and what is a group of them. We can view such a cloud as being a group of several contiguous columns or turrets, each individual column being taller than it is wide.

Figure 7. Deeper cumulus cloud (Cumulus mediocris). Compare this figure to Figure 4, left panel. The individual clouds here tend to be about as deep as they are wide. "A cloud" (example on left side) can be thought of as a contiguous group of several columns or turrets, each individual column being taller than it is wide. And the fresh turrets have clean, sharp, bright edges. The cloud bases are darker than for the shallower cumulus that existed

previously, because the deeper clouds more effectively shade their own bases. In both panels there are also cloud patches that have not yet deepened. Right panel is later in the day in the same area shown in Figure 3.

The fresh turrets have clean, sharp, bright edges. The numerous small droplets formed in rapidly ascending new turrets scatter sunlight very well and make the cloud bright white. The cloud bases are darker than for the shallower cumulus, simply because the deeper clouds under bright turrets more effectively shade their own bases.

The total mass of liquid water in these taller clouds is larger than in the shallow cumulus clouds, and the spread in droplet sizes is a little greater. But still precipitation does not occur…myriad tiny droplets hang suspended in the updrafts.

Onward and upward to cumulonimbus

If turrets rise still further, becoming ever colder as they do, they reach temperatures well below freezing. Figure 8 shows a surge of growth above the previous level, and is a continuation of the cloud sequence shown in Figure 6. Three separate stages, or altitudes reached by the cloud over the course of the day, are visible (red arrows). The uppermost stage is showing signs of ice formation (blue arrow)…a critically important step in the formation of precipitation and lightning, as discussed below in 'Ice formation'.

Sometimes, when intermediate stable layers are not limiting upward growth the tall clouds can surge all the way up without pausing, Figure 9. Within these towering cumulus clouds updraft speeds are perhaps reaching 10m/s, and liquid water content is typically on the order of 1 or a bit over 2 g/m^3.

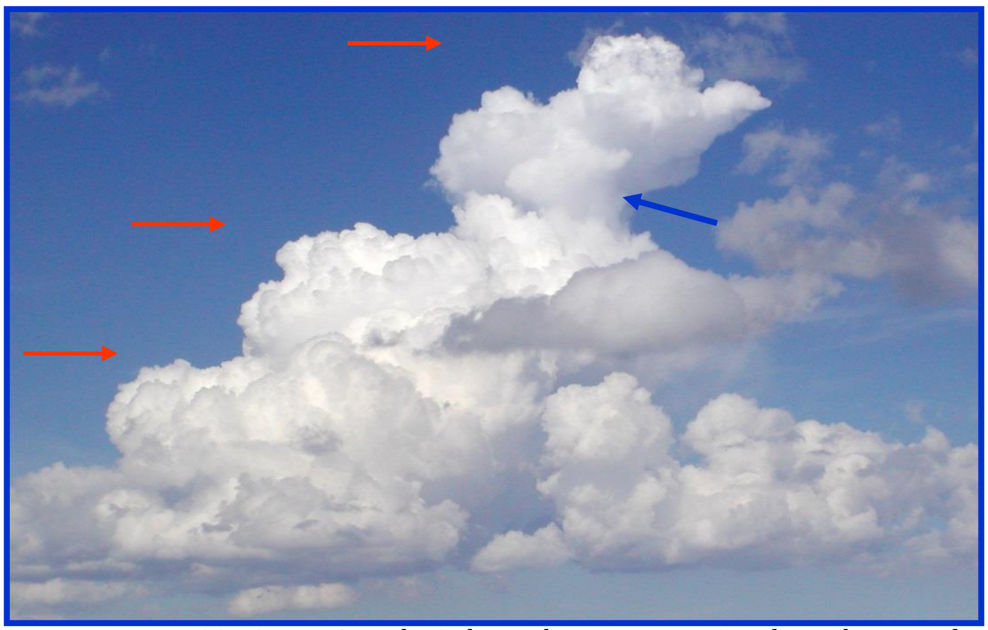

Figure 8. Cumulus congestus transitioning to Cumulonimbus calvus. Turrets rise above the second stage, with arrows marking 3 stages or levels of cloud development. Even though the tops of fresh turrets are bright white and sharp-edged, composed of supercooled water droplets, signs of ice formation are present. The blue arrow indicates an area that is 'glaciating', becoming composed of ice particles. The clear, high-contrast outlines of tufts and turrets are here becoming less clear, less bright white, more diffuse, with a 'silky' texture (see 'Ice formation' below).

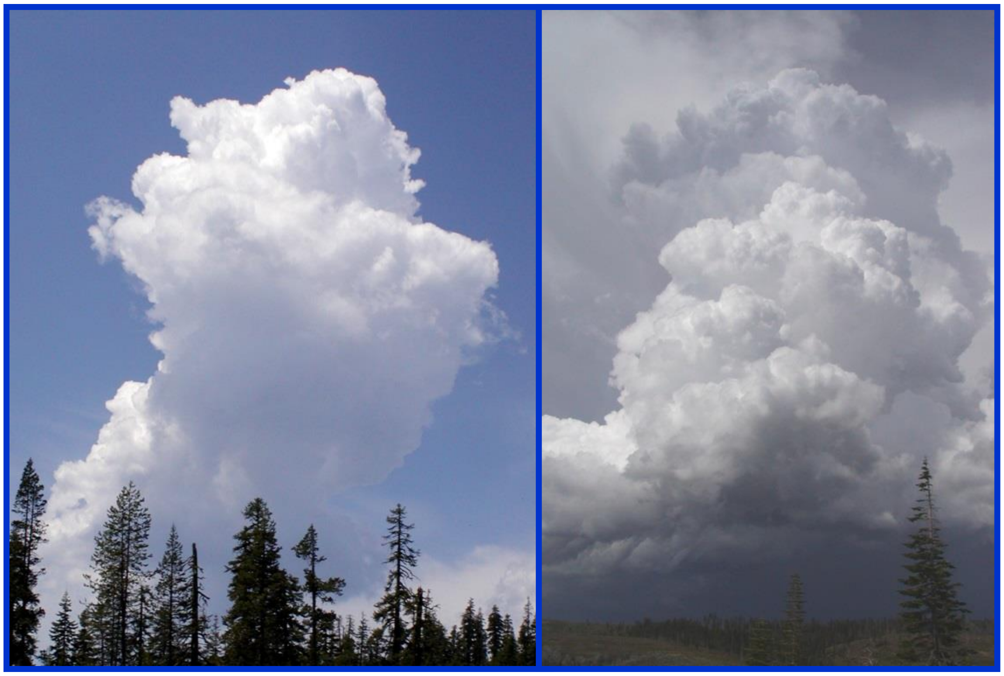

Figure 9. Towering cumulus (Cumulus congestus). When there is deep instability the upward rise of convective columns is vigorous and continuous, resulting in tall, powerful columns. The vertical cumulus development in such cases does not "pause" at lower altitudes before continuing.

Ice formation, an interesting story and an important development

Cloud droplets don't freeze as soon as they are cooled below 0^oC (32^oF)…they become supercooled. It takes sub-freezing temperatures and an appropriate 'ice nucleus' to trigger droplet freezing or to initiate the direct crystallization of ice particles from water vapor. The concentration of potential ice nuclei increases as temperature drops further below freezing. An extremely small number of nuclei, fewer than 1 in a liter, can initiate freezing at -4^oC (25^oF). When the temperature drops to -15^oC (5^oF) there are perhaps one or a few ice nuclei per liter, or there can be as many as of order a hundred ice nuclei in a liter of air (while there are hundreds of thousands of supercooled droplets in the same liter of air). Ice nuclei are solid, with molecular patterns a close match for the ice crystal lattice, unlike droplet nuclei which are predominantly soluble.

Until the temperature in a continental cumulus cloud falls to about -10^oC (14^oF) there are essentially no ice particles in it. At cloud temperatures in the range -10^oC to -20^oC (14^oF to -4^oF), the rapid increase of ice particle numbers can take place. Ice formation begins in small regions at the very tops of the highest turrets, where the temperatures are the coldest in the cloud, and where cloud mixes with clear air. Most of the water droplets there are no more than 10 or 15 μm in diameter, and a small but important %-age are 2 or 3 times that big. Some of the supercooled water droplets at least 20 μm in diameter are induced to freeze, by ice nuclei that are contained within them or that contact them.

By now the concentration of ice particles (frozen droplets and ice crystals) might be on the order of one to ten, or even several dozen, per liter. It depends on the composition of the ice nuclei (solids, commonly clay particles, with crystal lattice dimensions close to that of ice are best), average size of the nuclei (bigger is better), and relative humidity and temperature.

Until very recently it was thought that "ice enhancement" amplified ice particle numbers greatly by various processes that increased the number of ice particles by fragmentation. But it has been found recently that much of the apparent increase in ice-particle concentrations was due to collisions of the supercooled droplets and ice particles with the sampling apparatus on research aircraft.

Many questions remain, and ice formation is an active area of research in cloud microphysics. Whatever the detailed processes of its formation, that small frozen-particle fraction will lead to great changes—heavy precipitation, electrification, and accelerated upward growth of the cloud.

Ice cloud textures are distinctive and can be discerned in the cloud visually (early, though not at the very moment of first ice production). Because ice particles evaporate only slowly in clear (subsaturated) air they can spread out and present a more diffuse, less bright, 'silky', and less cleanly-outlined appearance (Figure 10). In contrast, water droplets evaporate quickly in subsaturated air. The ragged shreds often visible at the edges of water cloud look different, and will dissipate in a minute or two, while ice cloud textures are smoother, and persist for long times. Watching a wisp or shred for a short time will quickly show its tendency to persist (ice) or dissipate (liquid). Tufts and turrets lose their clear, ‘cauliflower’ shapes as ice develops. Often the highest turrets, just as they are reaching their maximum height, exhibit small blunt “spikes” jutting out from the rounded form…perhaps these are tufts within which ice formation has just begun. Seeing evidence of the transition to ice in a cloud should alert you to the rapid and significant progress toward both showers and electrification within the cloud.

Figure 10. Ice textures. Left panel: on the lower-left is ice cloud and on the upper right is liquid-water cloud. Right panel: much of the cloud appears diffuse, lacks clear turrets, and is glaciating, while the two bright white turrets rising at upper right are still supercooled water droplets. Ragged droplet edges dissipate rapidly; ice persists.

The glaciation (transition to ice) of the cloud also provides additional buoyancy and commonly induces a significant increase in the rate at which the top of the cloud rises. Cloud tops might rise roughly only halfway to the tropopause over several hours, and then when glaciation begins tops can surge the rest of the way to the tropopause in 30 minutes or so. At the tropopause the ice particles spread out under the base of the very stable stratosphere, forming the classic ‘anvil cloud’ typical of mature thunderstorms (Figure 11). Upper-level winds will spread the anvil downwind, which often indicates the direction that the storm is moving in. A strong column can temporarily surge above the tropopause and into the lower stratosphere, often showing as a low dome above the anvil top, which soon settles back.

Figure 11. Anvil top, cumulonimbus. The updraft spreads out under the stable base of the stratosphere, and the ice particles carried up in the updraft spread out to form the flat-topped anvil-shaped cloud. The ice particles settle slowly downward having descended farther nearest the main cloud and least at the outer edges. Being ice, the anvil has a soft-edged, diffuse texture.

Showers

Cumulonimbus means a raining cumulus cloud, even if the showers have not reached the ground. Towering cumulus clouds that have begun to show signs of ice are properly called cumulonimbus. Cumulonimbus clouds are characterized by updrafts on the order of 20 to 30 m/sec, and liquid water contents of 1½ to over 4 g/m^3.

It's not that easy to turn zillions of tiny cloud droplets into precipitation that can fall from a cloud. It takes a million or more cloud droplets collected to make a decent raindrop. Somehow a relatively few particles have to collect the water from a lot of small droplets. The distribution of droplet sizes must broaden to include larger ones that can fall down through smaller ones, colliding and growing as they go. A number of processes advance the broadening of the droplet size spectrum, including: differences in nucleus sizes, random collisions, partial evaporation. Given enough time droplets big enough to fall can appear in most clouds. After a few 10s of minutes, even in clouds that do not reach the freezing level, small drizzle or raindrops can fall. Such rain is light, and easily evaporated as it falls. In fact it would take hours for them to reach the ground, even if they did not evaporate. But in thunderclouds, deep clouds (kilometers deep), with strong updrafts (tens of m/sec), things are different and ice is a key factor.

Cloud droplets are constantly losing as well as gaining molecules from the water vapor in the air—an energetic one flies off, and a slower one sticks. When the air is saturated they can grow, the balance a little in favor of droplets gaining vs. losing molecules. Growth slows as the droplet gets bigger, flattening out at a diameter of about 80 μm. A small fraction of the droplets contain, or collide with, an appropriate ice nucleus. Instantly that droplet freezes. Also, some ice crystals have begun to form on ice nuclei (commonly clay minerals, but even bacteria). The fraction of ice particles is small, ~1/1000th, but important. When ice appears things change dramatically.

Ice grips water molecules more tightly than does liquid water, and can lower the concentration of water vapor below that required for maintaining liquid droplets. A water molecule that leaves a water droplet is more likely to stick to an ice crystal and not return. Therefore the gain-vs-loss balance of water molecules shifts in favor of ice, and ice particles grow rapidly by deposition at the expense of water droplets…few ice particles gain while many water droplets lose. The frozen droplets grow large enough (~60 μm diam.), and ice crystals become plates big enough (~1 mm across), to settle downward at an appreciable rate. They begin to fall through the smaller cloud droplets, collecting them as they go, becoming graupel (ice pellets) …getting larger, falling faster, collecting more…in the strong updrafts and deep cloud The process is called coalescence or accretion, and it accelerates the transfer of water to the larger particles. You can sometimes see young showers as they were developing, when high-rising towers stall, mix out, and dissipate, leaving strands of the ice that was forming within them visible (Figure 12).

Growing ice particles become precipitation about 1 to 3 mm in diameter and showers develop in the cloud—within 30 minutes or so after ice first appears. The precipitation, falling at meters-per-second, can reach the ground in roughly 10 minutes after showers begin to form up in the cloud (Figure 12), often as graupel. If the originally-frozen precipitation falls a significant distance through air above 0^{o}C (32^{o}F) it melts and reaches the ground as rain. If strong updrafts allow the graupel to continue to grow by gathering droplets, hailstones can form (ice particles greater than 5 mm in diameter are called hail), and hailstones can fall a long way in air above freezing temperature without melting. In general, deeper clouds and stronger updrafts mean larger hail or raindrops. Raindrops don't grow as big as hailstones because they break up when they get to be about 8 or 10 mm in diameter.

Figure 12. An evaporating cloud tower. Ice showers that were forming within this convective tower remain as the water droplets in the tower dissipate, appearing as diffuse strands that trail downward.

The first and strongest showers are of the type described above, and our main focus here. But it can happen that a complex of strong convection cells, which have put a lot of droplets and ice into the air, weakens over hours and evolves into a deep layer of nimbostratus cloud. Ice at high altitudes can drift slowly down through the moist, cloudy air, growing slowly into flakes or drops. Light, more widespread rain can continue after the initial strong showers end.

Showers drive strong downdrafts, by mechanical drag and by evaporative cooling (the dominant influence) that can hit the ground hard and spread laterally as strong, gusty winds. Such wind gusts often arrive just before the rain or hail begins. They can be very strong, with 40 mi/hr or higher winds. They tend to be strongest where channeled by the terrain (cold, dense airflows follow slopes and drainages), and/or on the side of the storm toward which it is moving (usually the side toward which the anvil cloud is extended).

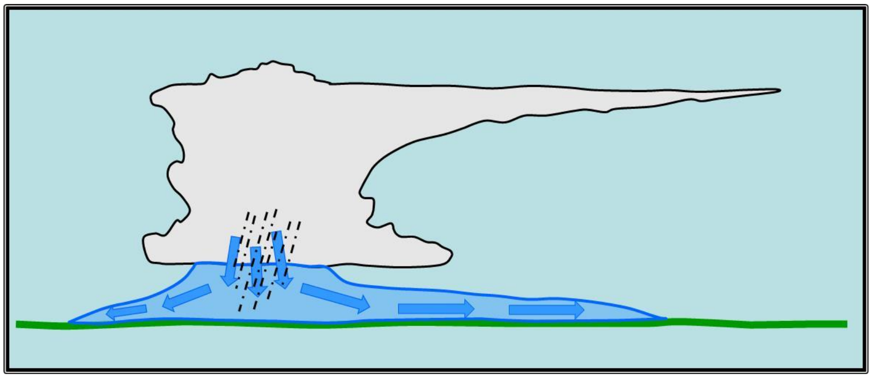

Figure 13 Diagram of thunderstorm downdraft and outflow winds. Precipitation drives the downdraft, mostly by cooling as rain evaporates beneath the cloud. The downdraft spreads out along the ground as the outflow.

The production of showers requires several things: enough water condensed in the cloud, the creation of some larger particles (in thunderstorms, primarily by ice formation) that can fall and accumulate droplets, and a long enough fall distance to grow large. Then the falling precipitation must survive all the way to the ground and not evaporate away on the way down.

All of that is possible in clouds that are deep enough from base to top. The minimum depth for shower formation in cumulus clouds over land is often observed to be about 4 to 4½ km (~13,000 to 15,000 ft). That observation is for cumulonimbus clouds that develop showers of fairly large drops or ice particles within about a half hour, as seen on radar, with cloud-top height tracked visually. Over the oceans, and even for shallow cumulus clouds over land, the required cloud depth for showers can be less. The drops are much smaller and the showers are lighter.

As will be discussed in ‘Gauging cloud heights’, you can sometimes estimate the cloud depth and whether it is sufficient for showers—it is not a hard and fast rule, but a helpful indication of the likelihood that showers are forming in the growing cloud. Making careful observations, estimating cloud depth, and applying a guideline will improve your accuracy in judging the potential for showers.

Figure 14. Showers fall from the base of a thundercloud. Large shaft of precipitation on the right probably contains hail. Newer showers are emerging from the cloud base center and left. Cloud- to-ground lightning commonly begins

*about when showers emerge from the cloud base, and often near the fringes of showers—**but always assume that lightning could hit the ground anywhere under or near (even a few miles away) a thundercloud.***.

Electrification and lightning

Not only are showers forming as the ice phase begins within a cumulonimbus cloud, the ice particles are also instrumental to its electrification. Electrification is seen to begin in a volume of cloud in which graupel, supercooled droplets, and ice particles all coexist. The rate at which lightning occurs is roughly proportional to the cloud radius, to the volume of space containing ice, and is strongly dependent on updraft speed (the 6th power of updraft speed). It takes a cloud depth of about 5 km to 8 km (16,000 ft to 26,000 ft) to produce much lightning.

Within the mid-levels of the cloud, water droplets, ice crystals, and graupel pellets all coexist simultaneously. At the level where temperatures are about -10°C to -20°C (14°F to -4°F) collisions between graupel and ice crystals leave a negative charge on the graupel and a positive charge on the ice crystals. The larger graupel (with its slightly greater negative charge) falls downward while the tiny ice crystals (with their slightly positive net charge) are swept upward in the updraft, to eventually form the anvil. Lower down, where temperatures are warmer, the charge transfer between colliding graupel and ice crystals reverses, leaving the graupel positively charged, but that contributes only a minor pocket of positive charge.

The cloud becomes electrically stratified, with a negative-charge layer some kilometer or so thick centered at the -15°C (5°F) level, a positive charge in the upper cloud, and also a (smaller) positive charge near the cloud base. Lightning rarely occurs before the cloud top has reached the -15°C to -20°C level, and strong electrification occurs only after graupel or hail can be detected in the cloud with radar.

While not all details are known, cloud electrification as described above includes at least two important processes. Both involve charge transfer as particles collide. The first depends on charge distribution that is influenced by the differences in mobility of protons vs. larger anions within ice. The second depends on charge distribution that is produced by polarization of particles falling within the growing electric field of the cloud. See Figure 15.

Protons (hydrogen nuclei, H^+) are tiny and very nimble within the ice-crystal lattice, and they diffuse rapidly through it. Anions dissolved in the droplets (such as SO_4^{-2}, OH^-, or Cl^-) are larger and much less mobile in ice and get segregated into the last-freezing liquid bits as graupel grows, leaving the outer surface of the graupel with net positive charge. On ice crystals, H^+ ions move away from the surface as the crystal grows, and accumulated anions tend to get left on the surface. As graupel particles fall and collide with ice crystals, briefly in contact, the exchange of surface charges leaves the graupel slightly negatively charged and the ice crystals slightly positively charged. Positive charge, being on the smaller particles, is lofted to the upper reaches of the cloud and negative charge, being on the larger particles, is carried down.

As an overall electric field grows, positive above and negative below, the charges on a falling particle are induced to move—leaving negative on top (attracted by the positive upper cloud) and positive on the bottom (attracted by the negative mid-lower cloud). As a falling graupel approaches an ice crystal its slightly positive lower side faces the slightly negative upper side of the crystal. A collision will transfer a bit of negative charge to the falling particle, and positive charge to the rising particle. This mechanism grows in importance as the cloud becomes more electrified.

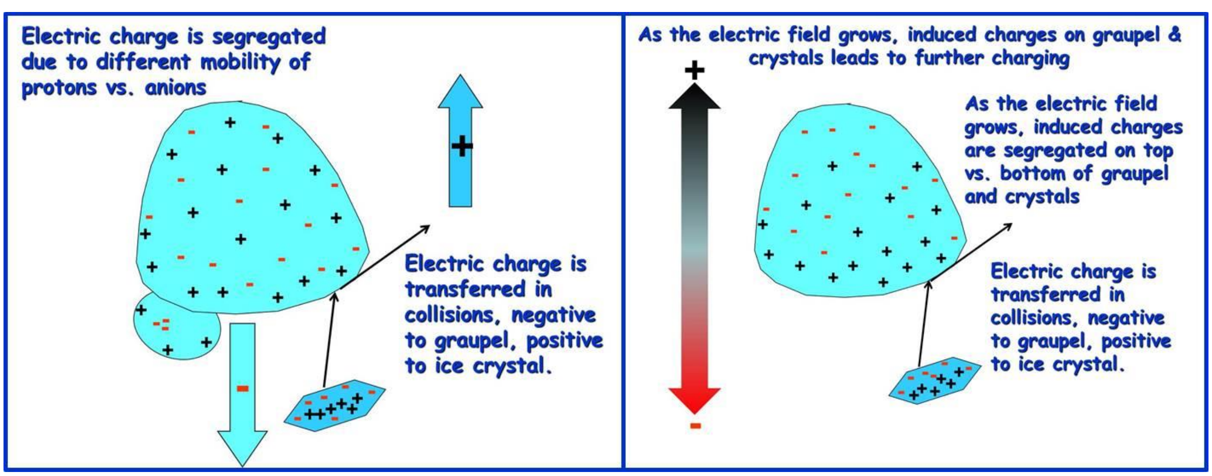

Figure 15. Two mechanisms for charge separation dominate the electrification of a thundercloud. The one on the left is most important early on, with the one on the right becoming more important as the electric field builds up.

When the voltage difference becomes great enough, lightning discharges occur between oppositely charged portions of the cloud, and between the cloud and the ground (mainly between the negative layer and the ground). The first lightning is typically intracloud (between the main charge centers within the cloud), and can occur within minutes of shower formation in the cloud. Cloud-to-ground flashes begin soon after the first intracloud discharges, often when the shower emerges from the cloud base. Lightning can strike the ground anywhere beneath the cloud and even several miles from the cloud. But the first strikes commonly occur near the outer zone of the shower curtain.

Lightning can obviously be fatal, but there are many more injuries than deaths. Take no comfort in knowing that not all lightning strikes are fatal. Those injuries are often severe and permanent. It is a real danger in the high mountains, and awareness and caution are called for. Lightning-safety guidelines are below…read them. Lightning is a very real hazard. The following is excerpted (with minor edits of nonessential material) from materials published by the National Oceanic and Atmospheric Administration (NOAA). Check the NOAA Lightning Safety website for the latest advice http://www.lightningsafety.noaa.gov/safety.shtml.

Lightning Safety Guidelines

The lightning safety community reminds you that there is NO safe place to be outside in a thunderstorm. If you absolutely can't get to safety, this section is designed to help you lessen the threat of being struck by lightning while outside. Don't kid yourself--you are NOT safe outside.

The SAFEST location during lightning activity is a large enclosed building, not a picnic shelter or shed. The second safest location is an enclosed metal vehicle, car, truck, van, etc., but NOT a convertible, bike or other topless or soft top vehicle.

Being stranded outdoors when lightning is striking nearby is a harrowing experience. Your first and only truly safe choice is to get to a safe building or vehicle. If you are engaged in outdoor activities and cannot get to a safe vehicle or shelter, follow these last resort tips. These will not prevent you from being hit, just *slightly* lessen the odds.

- Do **NOT** seek shelter under tall isolated trees. The tree may help you stay dry but will significantly increase your risk of being struck by lightning. Rain will not kill you, but the lightning can!
- Do **NOT** seek shelter under partially enclosed buildings
- Stay away from tall, isolated objects. Lightning typically strikes the tallest object. That may be you in an open field or clearing.
- Know the weather patterns of the area. For example, in mountainous areas, thunderstorms typically develop in the early afternoon, so plan to hike early in the day and be down the mountain by noon.
- Know the weather forecast. If there is a high chance of thunderstorms, curtail your outdoor activities.
- Do not place your campsite in an open field on the top of a hill or on a ridge top. Keep your site away from tall isolated trees or other tall objects. If you are in a forest, stay near a lower stand of trees. If you are camping in an open area, set up camp in a valley, ravine, or other low area. A tent offers NO protection from lighting.
- Wet ropes can make excellent conductors. This is BAD news when it comes to lightning activity. If you are mountain climbing and see lightning, and can do so safely, remove unnecessary ropes extended or attached to you. If a rope is extended across a mountain face and lightning makes contact with it, the electrical current will likely travel along the rope, especially if it is wet.
- Stay away from metal objects, such as fences, poles and backpacks. Metal is an excellent conductor. The current from a lightning flash will easily travel for long distances.

If lightning is in the immediate area, and there is no safe location nearby, stay at least 15 feet apart from other members of your group so the lightning won't travel between you if hit. Keep your feet together and sit on the ground out in the open. If you can possibly run to a vehicle or building, DO so. Sitting or crouching on the ground is not safe and should be a last resort if a enclosed building or vehicle is not available.

Gauging cloud heights…advanced field observations

This section describes ways of estimating the heights of cloud base and top, and cloud depth. It isn't always practical, and it is not necessary to monitoring thunderstorm development. It is not possible for clouds that are directly overhead, and best done looking at clouds in the distance. But when it can be done it provides some interesting information, and helps you gain a more refined sense of cloud dimensions and the potential for thundershowers.

As was mentioned above in 'Showers', the minimum cloud depth required for showers to develop in tall cumulus clouds in continental settings is about 4 to 4½ km (~13,000 to 15,000 feet). It is also interesting to note both the cloud base height (as a measure of the water content of the air) and the top height (as it relates to temperature and the freezing level). The cloud depth is the distance between the cloud base and its top. The top/base heights, and cloud depth, can be estimated by comparing them to a baseline distance scaled against terrain features.

The clouds have to be about the same distance away as the terrain features, best seen over adjacent mountains. With clouds seen growing over particular mountains, the distance scale can be derived from those mountains. Sometimes points of known elevation can provide a vertical scale directly, but often more accurate distances can be scaled horizontally between known points and then applied to the vertical. You can "measure" the apparent angular separation between two points with any convenient object held at arms' length, your fingers, hand, pencil, etc.

Figure 16 shows thunderstorms building over the White Mountains as seen looking east from Sherwin Grade, with White Mtn. Peak on the left and Mt. Barcroft in the center. The apparent distance between White Mtn. Peak and Mt. Barcroft from this vantage point is about 5.6 km—for our estimating let's call it 6 km (~20,000 ft). Upending the scale to touch Mt. Barcroft (elev. 4 km, 13,000 feet) provides a scale for judging the cloud base and cloud top heights, and cloud depth. You can shift such a scale up or down to fit the feature you are scaling. Cloud base and top are marked in blue.

The base is about $1/7^{th}$ of 6 km, some 0.9 km (3000 ft), above Mt. Barcroft, an altitude of approximately 4.9 km (16,000 ft). The highest cloud top happens to be at the top of the scale, about 6 km above Mt. Barcroft, an altitude of approximately 10 km (33,000 ft). The cloud depth is roughly $6/7^{th}$ of 6 km, 5 km or so…deep enough for shower formation. On this day the 0^{o}C altitude was at about 5 km, and the -15^{o}C altitude at about 7.6 km (as derived from weather balloon soundings from Las Vegas and Reno). Try scaling those levels on the photo below.

You can also estimate the height of the cloud base from the surface air temperature and dew point. Rising (clear) air cools, and approaches the dew point at about 8^{o}C per km rise (4.4 ^{o}F per 1000 ft rise). Divide the difference between surface & dew point temperatures (^{o}C) by 8 for cloud-base height (above the surface) estimate in km.

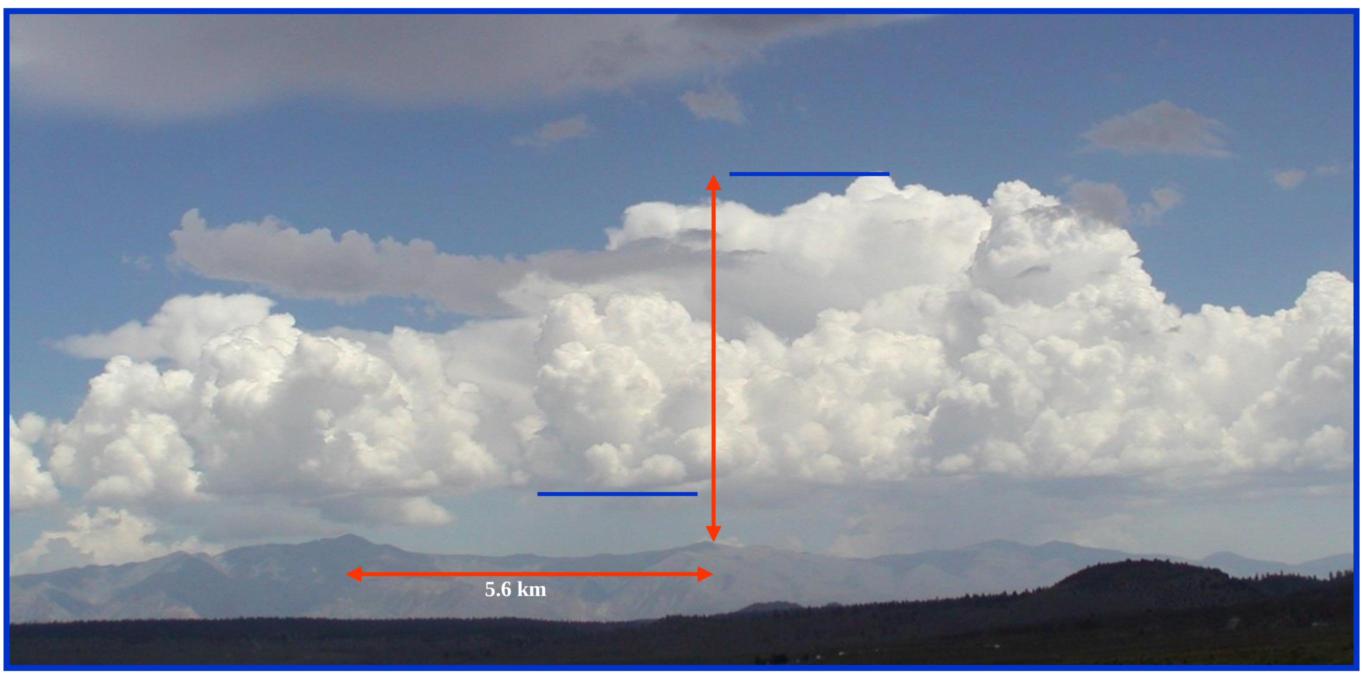

Figure 16. Thunderstorms over the White Mountains. The distance between White Mtn. Peak on the left and Mt. Barcroft in the center is about 5.6 km. Vertical red scale is also 5.6 km. Blue lines mark cloud base and top. Showers are not visible, but are probably forming in the deeper cloud masses.

Summary: Recounted here are the stages described above for mountain thunderstorm development, and the field observations you can make to monitor their development.

- <u>Favorable conditions</u>: Deep unstable layer to permit convection, sufficient moisture for cloud development. Note the forecast of thunderstorm potential, including LAL, and the presence of altocumulus castellanus clouds.

- <u>First cumulus clouds</u>: Small fragments of cloud appearing in the morning, above the higher terrain. Earlier and lower appearance of such clouds indicates more water and/or instability available for cumulus development.

- Cumulus growth: Potential for further growth is indicated by turrets rising above general cloud-top level, by individual cloud columns that are taller than wide, and by cumulus clouds that are at least as high as they are wide.

- Towering cumulus: Large clouds showing multiple turrets on top and sides surge upward rapidly, and in overall shape are taller than they are wide. Powerful towers under gray skies are especially telling forerunners.

- Glaciation: Ice forms in the high, cold cloud tops, initiating shower formation, the electrification that leads to lightning, and a surge in cloud growth. Visual indicators include softening of cloud edges, less bright white, silky texture, diffuse veils and streaks. You can assume ice formation when the tops reach the -10^{o}C level and colder.

- Shower formation: When ice forms, showers develop in the cloud, within about a half hour. Evidence can sometimes be seen in the diffuse streaks that remain when a recently-grown tower dissipates. Graupel, rain, or hail can reach the ground in the next 10 minutes or so after shower formation begins within the cloud.
- Lightning: Electrification arises from the precipitation process and updraft, and can reach discharge potential in minutes. First lightning usually occurs within the cloud, and strikes to the ground follow within minutes. **Lightning can hit the ground even miles outside of the cloud base.**

Figure 17 shows cumulonimbus clouds growing over the Sierras, and captures several stages in thunderstorm development. Wind is from right to left. The younger clouds, and newer towers within clouds, appear on the right with the older ones to the left. The older sections are glaciating, and some ice showers are visible. Try to pick out some new vigorously rising towers, towers reaching their maximum height and just beginning to glaciate, well glaciated portions, and the beginnings of anvil cloud.

Figure 17. Cumulonimbus growing over the Sierras, showing stages in development ranging from vigorous convective towers to glaciated areas.

Glossary

Altocumulus cloud Cloud in the midlevels of the troposphere, not generated by air currents rising from the ground. Motions within altocumulus clouds are driven by combinations of infrared radiative warming of the bases and cooling of the tops, heat released by condensation, and by wind shear. Castellanus (or castellatus) refers to altocumulus that have small turrets rising from the cloud mass, driven mostly by the heat released as condensation takes place.

Anvil top The flat-topped ice cloud formed as ice particles are carried aloft in the updraft spread outwards at the tropopause, and slowly settle out, leaving a cloud that is thickest near the center and thinning toward its edges.

Coalescence The capture of smaller droplets by larger droplets or ice particles falling down through them, and a key mechanism for creating precipitation. It becomes very efficient and the dominant precipitation process when the larger particles come to be at least 60 μm in diameter and are falling through droplets about 20 μm in diameter.

Convection Movement of a fluid (including air) that is predominantly vertical. "Free convection", the common use of the term, is driven by differences in density (buoyancy). In the atmosphere that takes the form of buoyantly rising columns of air that are warmer than the surrounding air (sinking air if cooler than surroundings). Even though rising air is warmer than the surrounding air, clear air is cooled by expansion at 9.8^{o}C per km rise (5.4^{o}F per 1000 ft rise). If the air is cloudy the rate of cooling is less, about 6.6^{o}C per km rise (3.6^{o}F per 1000 ft rise).

Cumulonimbus cloud A cumulus cloud that is producing showers. Often a tall cumulus that is glaciating is also called cumulonimbus on the assumption that showers are developing in the cloud even if they are not yet seen. Calvus refers to cumulonimbus that are just beginning to glaciate.

Cumulus cloud Clouds that form in convection currents that rise from the ground, and therefore have their bases in the lower troposphere. Humilis refers to cumulus that are not deep, much broader than deep, and tend to not be especially bright white on top. Mediocris refers to cumulus that have deepened to the point that they are roughly as deep as they are wide, and with some bright white turrets on top. Congestus refers to cumulus that are very deep, taller than they are wide, with fresh bright turrets, and often capable of generating showers.

Dew point temperature For a particular concentration of water vapor (a gas) in the air, it is the temperature at which that vapor will begin to condense as liquid (on a flat water surface). For example (at mountain elevations), for a water vapor concentration of about 6 g/kg the dew point temperature will be 2^{o}C (36^{o}F). The higher the concentration of water vapor the higher is the dew point—a concentration of 8 g/kg would have a dew point of 6^{o}C (43^{o}F) at similar elevation.

Electrification Electrification refers to the separation of electric charges (negative and positive) into different volumes of the cloud. Updrafts carry smaller particles with one charge upward, while heavier particles of opposite charge fall downward. While several charge-separation processes may contribute, two mechanisms dominate, and both involve collisions between falling graupel and rising ice crystals: one is due to asymmetrical charge distribution on particles caused by differences in ion mobility, and the other by differences induced by the overall electric field in the cloud. The detailed charge-transfer processes are still imperfectly understood, and long-standing questions remain to be answered with further research.

Graupel Ice particles collect supercooled cloud droplets as they collide with them, and the water droplet freezes onto the ice particle. The ice particle has bubbles and voids, and forms a frozen pellet called graupel. **Hail** refers to ice particles greater than 5 mm in diameter.

Probability-of-precipitation (PoP) The probability, expressed as a %-age, that measurable precipitation (0.01" or more) will fall at a randomly chosen point in the forecast area during the forecast period. The terms "slight chance" and "isolated" correspond to a PoP of 10-20%; "chance" and "scattered" to PoP 30-50%; "likely" and "numerous" to POP 60-70%; and 80-100% PoP is just stated as the forecasted weather ("rain", "thunderstorms", etc.) without qualifiers.

Relative humidity The concentration of water vapor in the air as a %-age of the saturation concentration (see Saturation below) at that temperature. For each 10.5^{o}C (19^{o}F) change in air temperature RH changes by a factor of about 2.

Saturation The condition in which the air contains the maximum concentration of water vapor that will remain a gas, in equilibrium with a flat water surface, at that temperature. Any lowering of temperature will cause condensation of liquid, if a suitable surface or nucleus is available to condense on. Saturation corresponds to 100% relative humidity.

Stable air Air in which convection is precluded or rapidly damped out. The vertical temperature distribution in stable air is warm enough with height so that rising air, as it cools, is not warmer than the surrounding air and cannot remain buoyant.

Stratosphere The major layer above the troposphere. Temperature is nearly constant with height in the lower stratosphere and then cools with height in the upper stratosphere. It is very stable, resistant to convection.

Subsaturation The condition in which the air contains less than the maximum concentration of water vapor that will remain a gas at that temperature. Liquid water will evaporate, such as where cloud mixes with clear air. Subsaturation corresponds to relative humidities less than 100%.

Supersaturation The condition in which the air contains more than the maximum concentration of water vapor that will remain a gas at that temperature. Water vapor will condense. Supersaturation corresponds to relative humidities greater than 100%. The (liquid water) supersaturation levels in clouds are typically only a fraction of 1% above 100% RH (and for ice can be on the order of 10% or 20%).

Tropopause The top of the troposphere, base of the stratosphere, below which temperature declines with altitude and above which it does not. It is higher in the tropics and lower near the poles, averaging about 11 km altitude in the midlatitudes. It can be visualized as the surface coinciding with the top of the anvil cloud on a thunderstorm.

Troposphere The lowest major layer of the atmosphere, in our latitudes about 11 km deep (though somewhat variable), and overall warmer at the surface and cooler upward. It is in the troposphere that convective mixing, storms, and precipitation…most of what we call 'weather'…occur.

Tuft A smaller, rounded mound on the surface of a turret, where much of the mixing of cloud and clear air takes place, commonly 100 to 300 meters in diameter.

Turret The top of a rising convection column (column, tower, thermal, and updraft are all equivalent terms in describing cumulus convection), commonly 1 to 3 km in diameter.

Unstable air Air in which free convection is possible. The vertical temperature distribution in unstable air is cool enough with altitude so that rising air (though it is cooling as it rises) is always warmer than its surroundings and therefore remains buoyant. If cloud is condensing in the rising air the requirement for instability can be met with a lower rate of environmental cooling with altitude, because condensation gives the cloudy convection column a thermal boost.

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