Fig. 7-1. Mamma hanging down from the underside of the anvil of a cumulonimbus with rain in the distance over Cheyenne, WY 12 Jun 2016. Jan Curtis.

Fig. 7-2. Severe thunderstorm with cirrus at the edge of the anvil, a dark shelf cloud and rain fall streaks south of Cheyenne, WY 21 Jul 2023, Jan Curtis.

Fig. 7-3. Underlit arcus of an impending hailstorm over Cheyenne, WY at sunset 18 Jun 2021. Pastel colors belie the storm's fury. Jan Curtis.

Wonders of the Atmosphere
Chapter 7: Thunderstorms

Started 17 Aug 2024

7.1 Thunderstorm Facts and Statistics

Cumulonimbus, the monarch of the sky, is the thunderstorm cloud. It metamorphoses from cauliflower-topped cumulus congestus that bubbles up into a stable layer high in or at the top of the troposphere. Then, like a butterfly spreading its wings for the first time, the cumulonimbus sprouts an anvil top, perhaps underlain by mamma (Fig. 7-1). From a distance, as in Fig. 4-8, Fig. 7-2, Fig. 6-19, it is an impressive, even awesome sight that dwarfs mountains and can be a thing of great beauty, graced by rainbows (Chapter 9). From below, it can also be an awesome sight (Fig. 7-3), but a terror, led by an arcus cloud then pelting rain, deadly hail, furious winds, flashing lightning (Chapter 8), deafening, earth-shaking thunder, and tornadoes that sweep all into ruin. No wonder, the thunderstorm god, the hurler of thunderbolts was the king of the Gods in so many ancient religions.

The power of an average thunderstorm is 1 trillion watts, enough to power 40 million homes during the time it lasts. Unfortunately, it is only possible to tap a minue fraction of this energy.

Thunderstorms are narrow, towering storms. Typical features are;

Height, 8 – 16 km.
Width, 8 – 40 km not counting the anvil.
Updraft Speed, 5 – 20 m/s.
Duration, 10 – 30 minutes.

Typically, the storm's intensity rises to a quick peak, with cold, gusty winds, intense lightning and potentially torrential precipitation for about 10-15 minutes before gradually subsiding.

Most thunderstorms pass by without causing significant damage or death. Violent downbursts, large hail, and tornadoes are almost exclusively confined to severe, organized thunderstorms. Each year in the United States thunderstorms kill an average of about

15 people due to Lightning. (Americans have wised up.)
50 people due to Tornadoes
200 people due to Flash Floods.

Thunderstorms are as common as popcorn. Globally, there are about

2000 at any moment
45000 per day
16 million per year.

The global map of lightning flashes (a good proxy for *thunder*storms) measured by satellite (Fig. 7-4) shows that thunderstorms occur most frequently in the tropics, where sunlight is intense all year. Thunderstorms are also much more frequent over land, which the Sun heats more rapidly than water. Thus the saying, "Convection craves continents and lightning loves land!" Central Equatorial Africa is the world thunderstorm capital, and their electrical effects are conducted around the world. Java and Maracaibo have equal or even greater peaks but over smaller areas. In the United States central Florida is the thunderstorm capital due to the boost to convection given by converging sea breezes from both the Atlantic Ocean and the Gulf of Mexico.

In most of the middle latitudes, thunderstorms are most common in late spring and summer and least common in winter.Thunderstorms are uncommon at Polar latitudes, and almost nonexistent over the Greenland and Antarctic Ice Caps. Even in mid latitudes, thunderstorms are uncommon in places where they are suppressed by

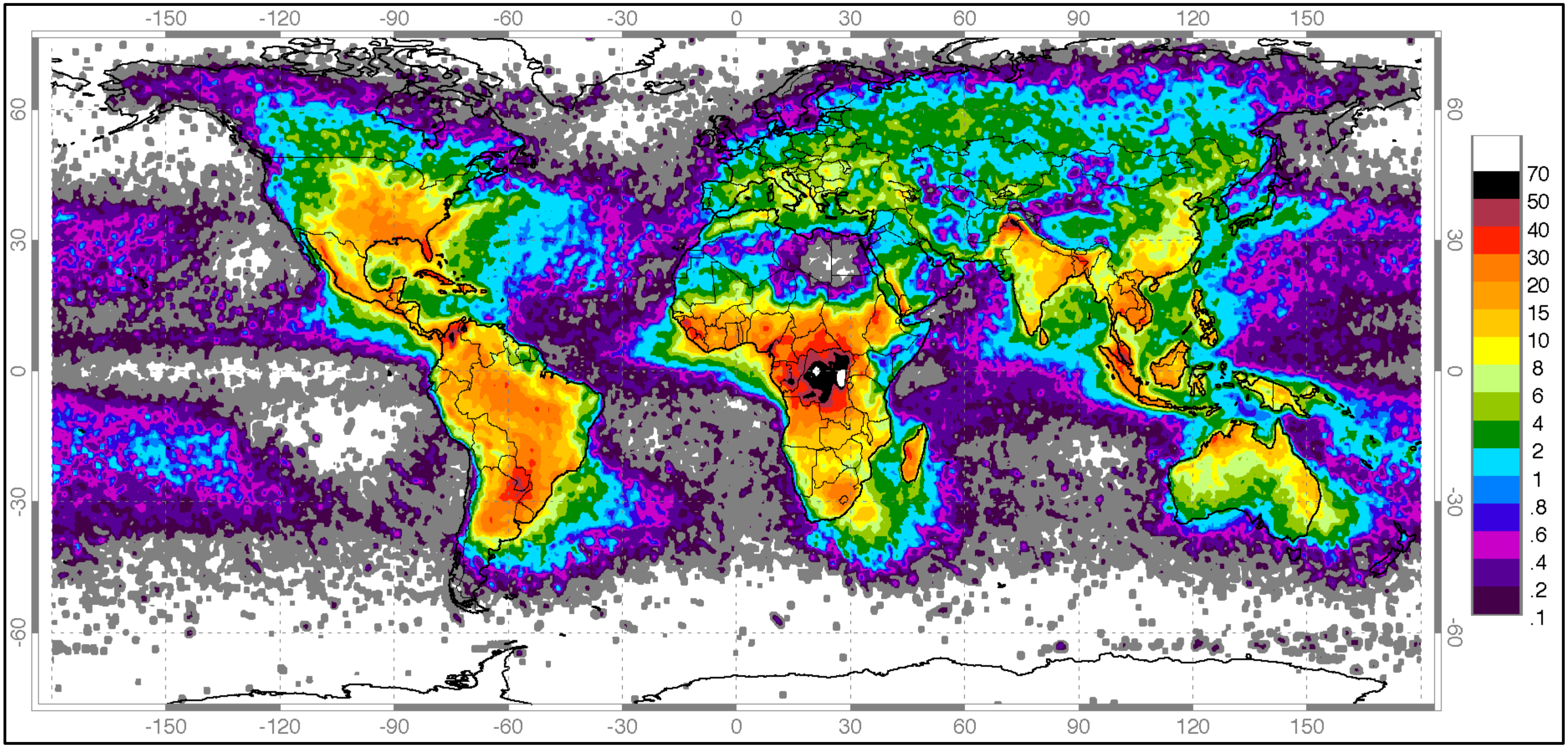

Fig. 7-4. Global map of annual lightning flash frequency per km^2. Concentrations are greatest over land and in the tropics, almost absent over the Poles. NASA.

cold ocean currents such as the west coast of the United States and Maine and the Maritime Provinces of Canada (due to the Labrador Current).

Thunderstorms also have a strong diurnal cycle. In many inland locations peak time is late afternoon, shortly after the hottest time of the day. But as the land cools at night, most thunderstorms fade away or move down from mountain ranges towards valleys, following the convergence of mountain-valley breezes, or form over warm coastal waters, where they are aided by land breezes,.

7.2 Thunderstorm Structure and Features

All thunderstorms share four core features, namely,

1. A deep layer with a conditionally unstable lapse rate.
2. A lifting mechanism.
3. Strong updrafts of buoyant warm, moist air.
4. Cold, precipitation laden downdrafts.

All thunderstorms undergo a similar life cycle and have the same basic structural features. In youth they consist of buoyant updrafts. As droplets and ice condense in the rising air they weigh the air down. In maturity a precipitation laden downdraft lies side by side with the updraft (Fig. 7-5). Evaporating rain cools the air and accelerates the downdraft, sometimes causing a rain gush and downburst, which splays out on hitting the ground, as in the video,

https://www.youtube.com/watch?v=a_G2KRzha7o

Nothing good lasts forever. Old age encroaches when the supply of nearby warm air is exhausted. This occurs sooner for air mass storms because they can only draw from the nearby, local supply of hot air, which the shading of sunlight by the anvil helps to reduce. The more severe squall line and supercell thunderstorms last longer because they are embedded in larger scale flow that provides a large and protracted supply of humid hot air.

Once the hot air supply is exhausted the updraft dies, usually from bottom up sp that the anvil is the last remnant of many storms. Without an updraft the production of liquid water and ice ends. That, in turn, weakens the downdraft, which persists a little while longer with only light rain. Remnants of the anvil gradually blow downwind, detach from the dying storm, and evaporate to produce humid layers aloft that may later recondense as sheets of Altocumulus.

Despite this basic plan and life cycle, there are enough differences to divide thunderstorms into several distinct types, which, in order of increasing severity, are,

1. Single cell, air mass thunderstorms.
2. Multicell, air mass thunderstorms.
3. Squall-line thunderstorms.
4. Supercell thunderstorms.

Air mass storms are the least intense form of thunderstorms because they form with little organization and little vertical wind shear (change of wind speed and/or direction with height). Their anvils tend to be nearly circular since there is no driving wind aloft to stretch them.

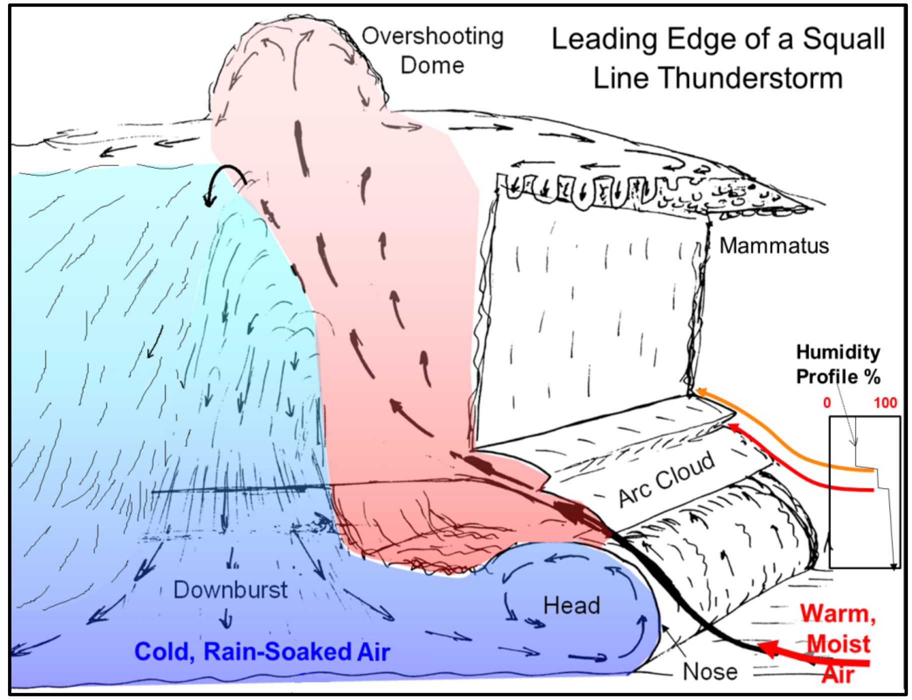

Fig. 7-5. Structure at front end of a mature squall line thunderstorm with attendant features including an overshooting dome, mammatus, an arc or shelf cloud, and a downburst with a vortex ring at its head. SDG.

Severe thunderstorms, squall line storms and supercells, form in settings with

1. Marked instability
2. Sustained warm air supplies
3. Ahead of cold fronts or below jet stream troughs
4. Significant vertical wind shear.

Vertical wind shear adds to a thunderstorm's intensity by tilting the updraft so that condensed water and ice do not fall back into it, weigh it down, and choke it on its own precipitation. (Wind shear too large

Fig. 7-6. A tornadic supercell thunderstorm on 23 Jun 2023, 75 miles SE of Cheyenne, WY with Ci streamers and mamma lined up under the anvil. Jan Curtis.

will shred the updraft.) The downdrafts increase the strength of the updrafts by undercutting them and wedging them aloft. The video,

https://www.youtube.com/watch?v=Ur4k8cAuQUY

animates many motions of severe thunderstorms' features.

The main structural features of squall line thunderstorms are illustrated in Fig. 7-5. A long-lasting supply of warm, moist air (pink) enters the updraft, tilted by the vertical wind shear. Precipitation forms and falls to the side of the updraft, weighing the air down and cooling it by evaporation to produce a downdraft (blue). The downdraft splays out on striking the ground, moving ahead of the cloud and forces the warm air aloft, often before it is buoyant. This leads to a convex plow-shaped arcus cloud at the leading edge of the squall line thunderstorm. The rising air soon becomes buoyant and results in an updraft of great intensity.

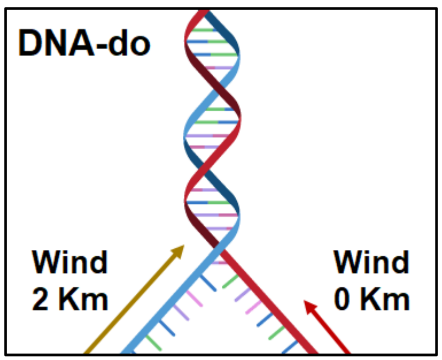

Fig. 7-7. Helical flow approaching a tornado resembles zipping of a double helix of DNA. SDG.

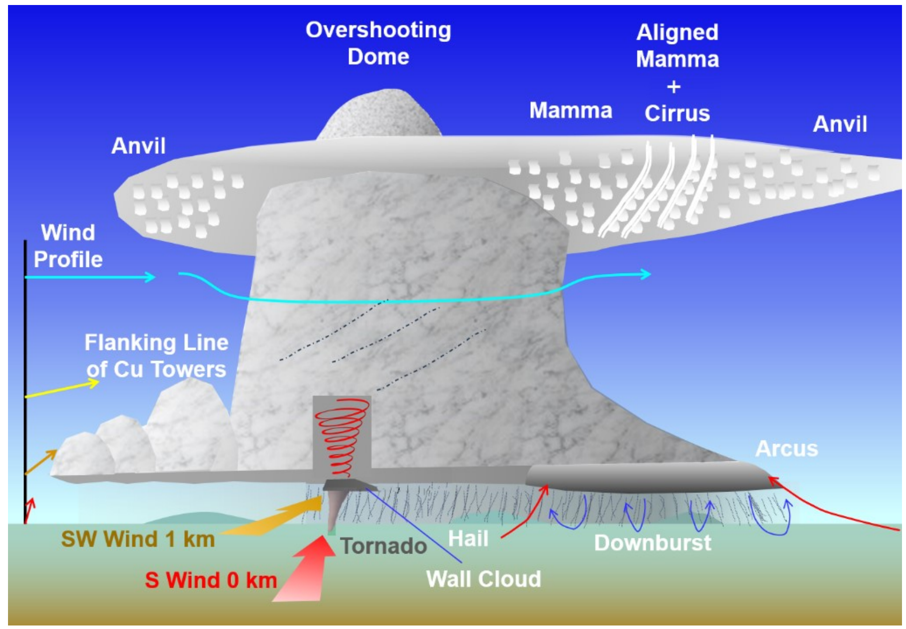

Fig. 7-8. Structure and environment of supercell thunderstorms. SDG.

Though squall line thunderstorms form in atmospheres with significant wind shear, the wind direction does not change much with height. Supercell thunderstorms the greatest and most severe of all thunderstorms can cover an enormous area, as did the storm of 23 Jun 2023 over the Pawnee National Grassland, CO (Fig. 7-6). They form when wind speed both increases and turns consistently with height. This helicity, which resembles a double strand of DNA in the process of zipping (Fig. 7-7) adds to the storm's potential severity and is what provides the initial rotation for tornadoes.

The main structural features and larger scale environment of supercells are illustrated in Fig. 7-8. The larger scale environment of the supercell consists of a 3-layer sandwich,

1. Warm, humid air from the S in the lowest km or so,
2. A hot dry layer from the SW at about 1-3 km,
3. A cold dry jet from the W in the mid and upper troposphere.

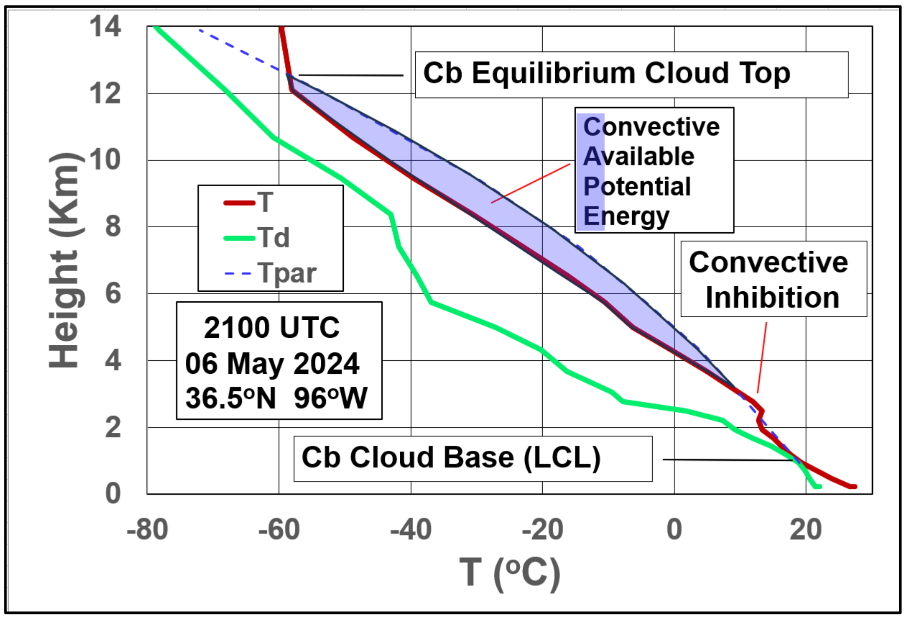

Fig. 7-9. Sounding just before tornado outbreak of 06 May 2024. SDG.

In American supercells, the bottom layer is the storm's moisture source. It consists of a wide river of warm, humid air 1 – 2 km thick streaming up from the Gulf of Mexico. The humid layer is capped by an inversion topped by a layer of hot dry air blowing from the SW. This inhibits convection until potential instability increases to frightening levels and later enhances it by evaporative cooling. For a supercell to form the inversion must have such magnitude that it can only be penetrated after major heating has built a huge potential instability. If the capping inversion is flimsy convection will break out prematurely everywhere but will only produce storms of modest intensity. If, on the other hand, the capping inversion is too large it will completely suppress convection.

In the ideal scenario the capping inversion is only punctured in a few isolated places. Then thermals and plumes of the warm, moist air can rise into the top layer of cold dry air. The rising fountains of the warm moist air will be so much warmer and lighter than the cold dry air aloft they will race upward at speeds of perhaps 50 m/s. For supercells (and all thunderstorms), the wind shear will be large enough to tilt the updrafts so that precipitation falls off to the side but not so large that it shreds the updrafts.

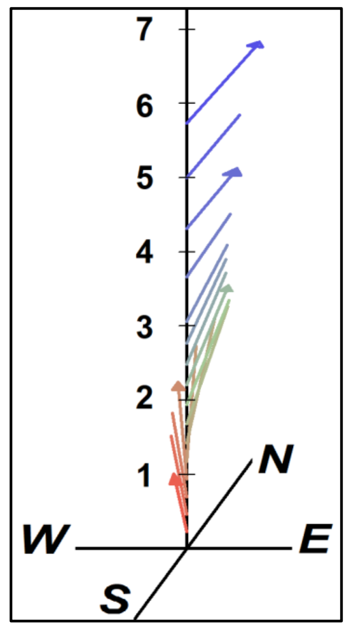

Fig. 7-10. Hodograph just before the tornado outbreak of 06 May 2024. SDG.

The sounding (Fig. 7-9) and wind profile *hodograph* (Fig. 7-10) at 2100 UTC of 06 May 2024, three hours before an outbreak of supercell thunderstorms that spawned 33 tornadoes including an EF4 tornado that struck Barnsdale and Bartlesville, OK fit the above description to a tee. The inversion extending from 2 to 2.7 km represented the region of convective inhibition, which weakened in the hours following the sounding. The lavender shaded area, where the parcel temperature exceeded the ambient temperature represents the ***C****onvective* ***A****vailable* ***P****otential* ***E****nergy* (CAPE) for the storm, a value (> 3600 J/kg) great enough to produce an updraft speed of 60 m/s. The hodograph for the same time showed the wind from the SSE at the surface and from the SW aloft and therefore possessed significant helicity.

Fig. 7-11. Thunderstorm over Africa with pancake-shaped anvil top and overshooting dome seen from the International Space Station ESA/NASA.

These general conditions persisted over the next four days over a large region extending eastward from Oklahoma, Iowa, and Texas to Pennsylvania and Georgia. The result was that severe and tornadic supercell thunderstorms continued breaking, out ultimately producing 179 tornadoes.

The concurrence of the large scale features conducive to severe weather, shown by the soundings and hodographs and therefore, the general region severe weather will break out can often be predicted days in advance. For examples, the first notices of potential severe weather for the 06 May 2024 outbreak were given on 29 April and as the days went by the warnings beccame progressively more certain and more dire. The situation was so classic in its signature that the National Weather Service gave a rare tornado-driven high risk outlook on the morning of 6 May.

Forecasting the precise location of each supercell is much more difficult than forecasting the general region of severe weather. Indeed, it is much like forecasting which kernel of pop corn will pop first. That can only be forecast as the convection begins to develop.

7.3 Accessory Features of Thunderstorms

Thunderstorms, and particularly severe storms have several accesory features that add to their majesty and beauty. They include 1: the

Fig. 7-12. Thunderstorm with anvil-shaped anvil, east of Cheyenne, WY 2008 MDT 22 Jul 2017. Jan Curtis.

anvil, with undersides graced by 2: mamma and cirrus, 3: the arcus (arc or shelf cloud) attached to the advancing cloud base, or leading it as a roll cloud, 4: rain/hail shafts that may appear green or blue, and, 5: tornadoes. Lightning (Chapter 8) and rainbows (Chapter 9) are two attendant phenomena.

The anvil, or crown of the thunderstorm forms at the equilibrium level, where the rising plume has the same temperature as the ambient atmosphere. For towering thunderstorms this occurs at the base of the stratosphere. Active thunderstorms often have overshooting domes because the updraft reaches the equilibrium level with a large speed and overshoots. Ultimately, it is forced back and spreads out into the anvil, which, can extend far out from the thunderstorm's core much like an umbrella's cap extends far out from its narrow shaft. When seen from above, the relatively flat anvil top ofen resembles a pancake with a overshooting dome of cauliflower cumulus poking through it (Fig. 7-11), and circular waves sometimes propagating out from it much like waves moving out from where a stone is thrown in water. When seen from the side the asymmetric anvil shape is often pronounced (Fig. 7-12) especially when it is blown downwind if immersed in the jet stream and warn that a thunderstorm is approaching. Anvils often appear smooth because hydrometeors at the edges evaporate as the air sinks as it moves inward and because it consists of a smaller concentration of ice particles.

Mamma are smooth, breastlike pouches of sinking cloud air that hang down from anvils as in Fig. 7-1 and Fig. 7-13, and illustrated in

Fig. 7-13. (Top) Sunlit mamma with rainbow and anticrepuscular rays, 12 June 2016 . (Bottom) Shaded mamma, 09 May 2018. Both at Cheyenne, WY. Jan Curtis.

Fig. 7-14. They are more likely to form where the anvil is thick and laden with water and ice, and the air under the anvil is dry. That produces a positive feedback loop of evaporation, cooling, and sinking. For the same reasons, mamma sometimes form below dense cirrus spissatus (see Fig 10-25), altocumulus or stratocumulus. Mamma appear smooth because the hydrometeors at their edges have largely evaporated. Time lapse videos show their bases disappear as they sink, as in *Descending Mammatus*,

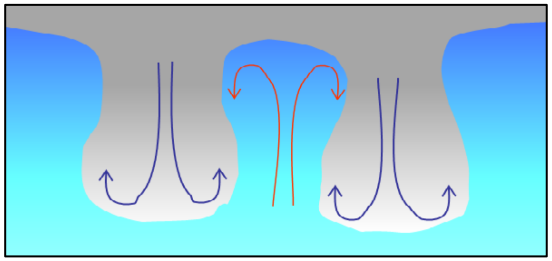

Fig. 7-14. Air motions in mamma. SDG.

https://www.flickr.com/photos/cloud_spirit/41732019035/in/album-72157671673645956

Sunlit mamma appear bright white when the Sun is well above the horizon, as in the top image of Fig. 7-13, where the scene is enriched by a double rainbow crossed by anticrepuscular rays. Around sunrise and sunset, sunlit mamma reflect the light of the low Sun and appear yellow, orange, or deep red, as in Fig. 7-6.

Shaded mamma can appear almost pitch black, as in the almost cosmic scene in the bottom photo of Fig. 7-13. The parent cloud in that case was the optically thin remnant of what had been at most a weak thunderstorm. But mamma are often so optically thin, especially at their bottoms, that when viewed horizontally they are translucent, as in Fig. 10-26. Thus, even though mamma are often associated with severe thunderstorms, they are, in and of themselves, harmless. Mamma are sometimes aligned like pearls on a string when cirrus streamers form at the outer edge of the anvil and then curl under the anvil following the inward motion of the anvil's underside. This can be seen on the left side of the anvil of the supercell in Fig. 7-6.

Since mamma hang from the anvil they can be seen from great distances. That makes them both an early warning sign that a thunderstorm is approaching and an indicator that it is departing.

As thunderstorms draw closer, features attached to or rolling ahead of the base, come into view. These include arcus (arc, shelf, or roll clouds), rain and hail shafts, rainbows, and tornadoes.

Arcus clouds form over or in front of the leading head of cold, rain or hail-soaked downbursts that have struck the ground, splayed out ahead of the storm and curled up in ring vortices illustrated in Fig 7-5 and Fig. 7-8. Arcus clouds are harmless in and of themselves despite their awesome and even ominous appearance. However, since they form at the leading edge of the advancing thunderstorm's severe weather, the onset of the storm's fury occurs as they pass overhead, as can be seen and heard in the video of the thunderstorm that passed over Cheyenne, WY late on the afternoon of 06 Jul 2025.

https://www.flickr.com/photos/cloud_spirit/54638208522/in/album-72157667543992515

Because downbursts splay out ahead of the rain and hail, they are normally invisible unless they stir up dust. And so, without any warning they have caused many aircraft fatalities before they were identified, understood, and now mostly avoided.

The arcus often resembles a smooth, gray convex plow on top, as in the top image of Fig. 7-15 and Fig. 7-16. By contrast, the underside of the arcus often appears ragged and highly convoluted, especially so in the bottom image of Fig. 7-15. The top of the arcus is smooth when the head of the advancing vortex ring at the leading edge of the downburst undercuts warm, moist air approaching the thunderstorn and forces it to rise above its condensation level before it is buoyant, because the forced flow is laminar. The underside of the arcus is ragged because it is in direct contact with highly turbulent flow of the vortex head and downburst.

Fig. 7-15. Approaching arcus with marked blue tint and rain below, Cheyenne, WY 06 Jul 2025. Ragged underside is due to turbulent flow Jan Curtis.

Fig. 7-16. An arcus with smooth top and ragged bottom beneath the thunderstorm over Cheyenne, WYT 02 Aug 2023. The rain shaft is the dark gray area within the arcus. Jan Curtis.

As an arcus draws overhead, the sky often becomes incredibly dark and remains so until it has passed by and rain or hail begins in earnest, whereupon the sky often brightens noticeably. This can be seen in the thunderstorm of 26 Aug 2021 (Fig. 7-17) and is apparent in the video of the 06 Jul 2025 thunderstorm.

It can be so dark under the arcus that street lights turn on even in the middle of the day. The darkness is due to the huge total cross section area or optical thickness of the myriad tiny droplets in the arcus plus the droplets and ice particles in the main cloud above it. The rain/hail shaft is much brighter because even in a deluge the total cross section area of large raindrops and hailstones is minute compared to an equal mass of tiny droplets.

That may sound impossible, but the following typical example explains why it is true. A 1 mm wide raindrop is 100 times wider than a 10 µm wide cloud droplet and has 1 million times the mass. But since, for a given total mass of droplets, surface area and optical thickness is inversely proportional to radius, 1 million of those tiny cloud droplets have 100 times the total area and hence 100 times the optical thickness and light scattering power of that one large raindrop.

Fig. 7-17. Bright rain streaks behind a black arcus Cheyenne, WY 26 Aug 2021. Jan Curtis.

Fig. 7-18. Chaotic thunderstorm sky Cheyenne, WY 16 Jul 2025. Jan Curtis.

The turbulent flow under the approaching thunderstorm at Cheyenne, WY on 16 Jul 2025 produced patterns so chaotic and lighting contrasts so extreme (Fig. 7-18) that would make El Greco proud (see his ***View of Toledo***, Fig. 15-15). The video of that storm

https://www.flickr.com/photos/cloud_spirit/54661210650/in/album-72157667543992515

brings all its chaos to life. The video starts with a distinct helical flow amidst the swirling. A cumulus line at left moves away from the camera while the overcast above moves toward the camera from the left. Soon thereafter a rippled low-lying cloud sheet moves in from the right while an arc cloud just above the distant horizon approaches. The sky darkens as the roll cloud nears, then brightens as it races overhead with bubbling motions, heavy precipitation, and a distinct blue tone.

Fig. 7-19. A roll cloud ahead of a hailstorm in Cheyanne, WY on July 04, 2023. Note distinct blue-green tone behind the roll cloud. Jan Curtis.

Sometimes, the vortex outflow moves well out ahead of the parent thunderstorm, just as a smoke ring self-propagates across a room with no wind. The arcus can then detach from the parent storm, riding like a surfer on the updraft at the head of the outflow vortex as a *roll* cloud.

The roll cloud in Fig. 7-19, was produced by a strong thunderstorm that crossed Cheyenne, WY at 70 kph. As the roll cloud passed overhead the wind gusted to 80 kph and 0.6 cm of rain mixed with

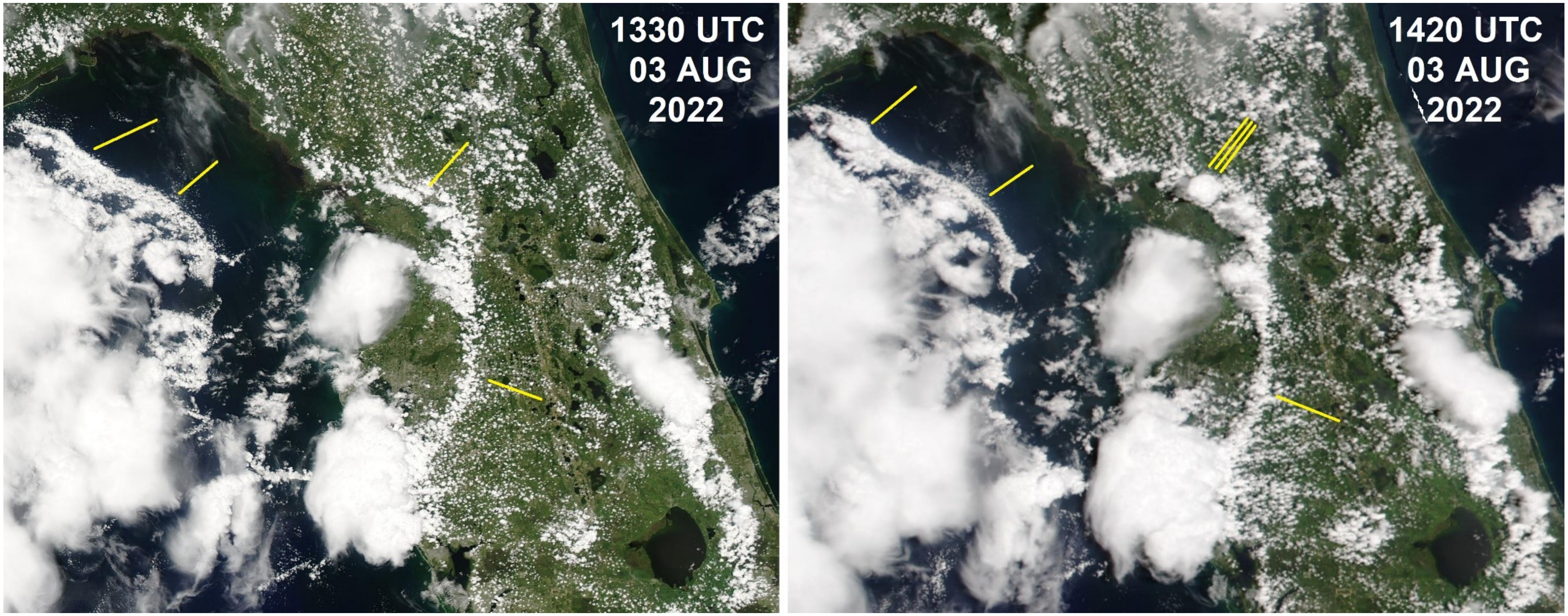

Fig. 7-20. NASA MODIS AQUA (left) and NOAA VIIRS 20 (right) views including roll clouds east of thunderstorms (indicated by yellow lines) on 03 Aug 2022. The updraft of the roll cloud helped a cumulus cloud begin to develop into a cumulonimbus at the triple yellow line.

pea-size hail fell in less than 10 minutes.

Roll clouds may appear ominous as they advance across the sky but are harmless by themselves. However, they may provide critical extra uplift needed to grow any cumulus mediocris they collide with into a new thunderstorm. This occurred in the satellite images of 03 Aug 2022 over central Florida (Fig. 7-20). Several of the cumulus clouds began to develop into cumulonimbus once crossed by the roll cloud.

Similarly, if the air in the forced updraft of an arcus has a significant upward speed when it reaches the level where it becomes buoyant, it will strengthen the resulting thunderstorm updraft.

7.4 Green Thunderstorms

The rain and hail shaft behind the roll cloud of Fig. 7-19 has an unmistakable green-blue color, as does the rain shaft behind the arcus of the 06 July 25 thunderstorm in Fig. 7-15. Other cases at Cheyenne, WY include the thunderstorm of 20 Jul 2016 (Fig. 7-21) where the the green rainshaft appears luminous in contrast with the almost pitch black underside of the turbulent arcus, and the almost blue rain-hail shaft of the thunderstorm of 08 Jun 2024 (Fig. 7-22). An extraordinary, almost bizarre case of a green thunderstorm is shown in Fig. 7-23, The hail shaft is a deep green while the bright gaps between the black blobs of the arcus that penetrate into the cloud above are turquoise.

Fig. 7-21. An arcus with dark ragged bottom and green rain/hail shaft beneath the thunderstorm at Cheyenne, WY on 20 Jul 2016. Jan Curtis.

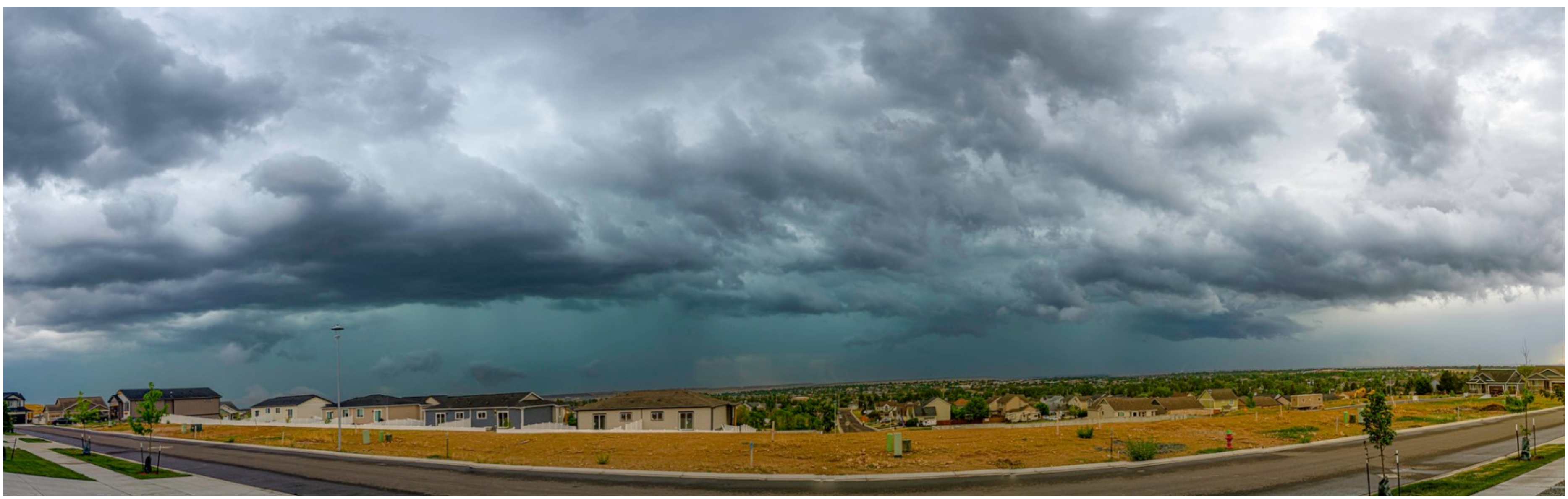

Fig. 7-22. A blue rain/hail shaft beneath the thunderstorm at Cheyenne, WY on 08 Jun 2024. Jan Curtis.

Fig. 7-23. A green and blue shaft. ©Grundlesquatch.

These are the so-called green thunderstorms, though the photos show that the color varies and often contains blue. Green thunderstorms are rare enough and so distinctive that they come as a surprise. What could be their cause? Perhaps it should not be surprising. We are not surprised to see the distinctive turquoise color of shallow water. And the colored part of green thunderstorms is always the bright rain or hail shafts behind dark arcus clouds.

Fig. 7-24. Water color vs depth Paradise Island Nassau 31 Dec 2008. SDG.

Green and blue thunderstorms occur because both water and ice preferentially absorb red and orange light, allowing green and blue light to scatter and pass through. But water's color, which grades with depth from turquoise to cobalt blue as in the Bahamas (Fig. 7-24) does not begin to emerge until the depth exceeds 10 cm (Fig. 7-25).

Fig. 7-25. Blue color deepens with water depth in pool. Each step is about 15 cm. SDG.

The difficulty for explaining the color of green thunerstorms is that even the most prolific thunderstorm never contains much more than a depth of 10 cm of liquid water or ice. The solution is that the water in a cloud is subdivided into drops and hailstones. Scattering by the largest hydrometeors lengthens the effective optical path by at least a factor of 10 over a water body. That is more than enough to turn the beams turquoise or blue and still allow enough light through to be bright. If the 10 cm depth of hydrometeors were as small as cloud droplets they would block so much light the rain/hail shaft would be darker than the arcus. This difference is illustrated by the contrast between the luminous turquoise color of the bright gaps of the turbulent, black underside of the arcus in Fig. 7-23. The color of green thunderstorms is enhanced by skylight that penetrates the rain/hail shaft.

Distance changes the apparent color of green thunderstorms. Rayleigh and Mie scattering in the intervening atmosphere makes rain/hail shafts further than about 10 km tend appear green rather than blue. Rain/hail shafts close to the observer are the bluest.

Few rain/hail shafts are green or blue but even without color they can still appear very dramatic – almost biblical. If shaded and if they block the light from the clear sky or sunlit clouds behind, they can be almost pitch black. If sunlit they gleam with the same color as the sunlight that strikes them, and stand out from the dark, shaded cloud base. For example, numerous sunlit rain shafts brightened the otherwise dark underside of the thunderstorm of 24 Sep 2018 (Fig. 7-26).

The thunderstorm of 14 Aug 2021 (Fig. 7-27) popped up rapidly after 1900 MDT. It produced 1 inch hail and a double rainbow. The rain/hail shafts were sunlit and bright and slightly reddened both because the Sun was only 18° above the horizon (determined by the rainbow) and by Rayleigh and Mie scattering in the intervening atmosphere. A video showing many features of the storm including Jan getting peltied by hail as he retrieved a camera is available at,

https://www.youtube.com/watch?v=11jkffhxNd8

When shaded rain/hail shafts block bright skylight or blindingly bright reflected cloud light in the background behind a thunderstorm they can give the impression of the 10th Plague of Egypt descending from the heavens, as in the thunderstorm of 31 May 2017 (Fig. 7-28). This is a case when appearances are deceiving. The video,

https://www.flickr.com/photos/cloud_spirit/34980434346/in/album-72157667543992515

shows that while some of the streamers reached the ground as rain gushes others evaporated harmlessly before reaching the ground as *virga*. In this respect though they almost obliterate the background lighting and appear black by contrast they can be compared to opaque but delicate streamers of cirrus.

The not-so-delicate, pitch-black rain shaft of the thunderstorm on 03 Jul 2019 (Fig. 7-29) sported a *rain foot*, a rain shaft whose leading edge tilts outward from the storm. The tilt is caused by wind flowing out from thunderstorm downbursts at speeds up to 50 m/s, sweeping raindrops sideways because they only fall at about 7 m/s.

Hailstones, a product of some severe thunderstorms, can grow much larger than raindrops, and can fall at speeds that exceed 50 m/s. Stones about 2.5 cm in diameter fall at about 12 m/s. It is the really large stones, 8 cm or more in diameter that fall 50 m/s or more and have been lethal. The largest measured hailstone, 20 cm across weighing 760 grams, fell on Vivian, SD on 23 Jul 2010 (Fig. 7-30).

How in the world can the atmosphere produce such monsters? The answer is rapid updrafts, which only occur in severe thunderstorms, can suspend the hailstones for perhaps half an hour at levels high in the atmosphere where it is cold enough for supercooled drops to strike them and freeze to them. When they finally do fall from the cloud through the warmer air below melting must be minimized. This is why hailstorms tend to occur in elevated locations such as Wyoming and Kenya and why hail is so rare in tropical lowlands or places like Florida despite abundant thunderstorms.

Fig. 7-26. Sunlit rain shafts from the thunderstorm at Cheyenne, WY 24 Sep 2018. Jan Curtis.

Fig. 7-27. Sunlit hail and rain shafts from the thunderstorm at Cheyenne, WY 14 Aug 2021. Jan Curtis.

Fig. 7-28. Shaded rain shafts and virga appear almost black in contrast with sunlit background at Cheyenne, WY, 31 May 2017. Jan Curtis.

Fig. 7-29. Rain/hail foot, 03 Jul 2019, Cheyenne, WY. Jan Curtis.

Fig. 7-30. Vivian, SD record hailstone with ruler marked in inches. NOAA.

Fig. 7-31. Tornado (EF5) of 22 Jun 2007 at Elie, Manitoba with debris. ©Justin Hobson

7.5 Tornadoes

It should be no surprise that the same thunderstorms with the awesome updrafts needed to produce large hail also produce the atmosphere's single most terrifying phenomenon, the tornado.

Tornados are the umbilical cords of thunderstorms, attaching them to Mother Earth, but bringing death instead of life.

The United States, because of its particular geography, is the tornado capital of the world, with an average of about 1200 per year. Tornadoes are graded on the EF (Enhanced Fujita) scale, originally devised by Tetsuro Fujita. The scale is based on the maximum 3-second wind gust speed in mph (EF3 > 215 kph, EF4 >265 kph, EF5 > 320 kph) and closely linked to the severity and nature of the damage. EF4 and EF5 tornadoes can do incredible damage, obliterating solid brick homes, levelling forests and stripping bark from trees, and ripping away the soil to the bare rock below.

The highest wind speed ever recorded on or near the surface of the Earth was measured by a mobile doppler radar unit and came in at 517 kph during the Moore, OK tornado of 03 May 1999. (Another lethal EF5 tornado hit Moore on 20 May 2013.)

Tornadoes are rendered visible by condensation because they are intense low pressure areas, and by the debris they lift and swirl in the air. The minimum pressure deficit in the center of extreme tornadoes can exceed 10% of the ambient atmospheric pressure. This effectively lowers cloud base in the tornado by more than 1 km and since cloud base is often less than 1 km above ground, it makes the tornado visible right to the ground.

The classical funnel cloud (Fig. 7-31) or *tuba* is narrowest at the ground and widens the closer it gets to cloud base because as the air spirals upward $\boldsymbol{T}$ approaches $\boldsymbol{T}_d$ and only requires a smaller pressure decrease within the vortex to produce condensation. Thus, the visible vortex cloud is only the inner, visible part of the tornado vortex; the outer, invisible part of the vortex can still blow you away.

The width of tornadoes varies from about 10 m to 4 km and the path length ranges up to 1000 km. In general, the more violent the tornado the wider it is and the longer its path on the ground. The typical EF0 tornado is about 20 m wide, has a path length of 1 km and a maximum wind gust of 120 kph. The typical EF4 tornado is about 500 m wide, has a path length of 40 km and a maximum wind gust over 265 kph! Ironically, the extreme width of many EF4 and EF5 tornadoes plus the enormous airborne debris makes them less photogenic than many much less intense tornadoes.These "wedge" tornadoes resemble short, wide black tubes extending down from cloud base that obliterate any sight of the ground. The 1.6 km wide Binger Tornado of 22 May 1981 (Fig. 7-32) was one terrible example

Fig. 7-32. 1.6 km-wide EF4 Tornado Binger, OK, 22 May 1981. NSSL Photo

Weak tornadoes (even the weakest have wind gusts of 104 kph) can have smooth outlines and will appear light or dark like all clouds, depending on whether they are sunlit or shaded. The short-lived sunlit tornado of 17 Jun 2017 to the NE of Cheyenne, WY (Fig. 7-33) was captured in the video,

https://www.flickr.com/photos/79387036@N07/33711850968/in/dateposted/

Fig. 7-33. Tornado 10 km NE of Cheyenne, WY 17 Jun 2017. Jan Curtis.

One of the most celebrated photographs of a sunlit tornado was taken by storm chaser, Eric Nguyen and was at the correct angle (42° from the antisolar point) to include a rainbow (Fig. 7-34). The white dots and vertical streaks in the photo are hailstones. Why the streaks (which also appear during rainstorms)? During the time of the exposure, typically 1/250th of a second a hailstone that falls at 25 m/s will fall 10 cm and consequently look vertically elongated if near the camera.

Some supercell thunderstorms generate several tornadoes during their lifetimes of several hours. On rare occasion, a supercell will spout two tornadoes at the same time (Fig. 7-35).

Fig. 7-34. Sunlit tornado of 12 Jun 2004 near Mulvane, KS with rainbow and white hail streaks. ©Eric Nguyen

The airflow in tornadoes is so rapid and has such large shear that it may become unstable and generate smaller, short-lived vortices that whirl around the main vortex like whirling dervishes. Multiple vortex tornadoes (Fig. 7-36) are not seen often but are more common than would appear because the narrow, short-lived vortices are easily visible only during clear intervals when the main vortex is not filled with a funnel cloud.

Fig. 7-35. Double tornado (EF4) near Pilger, NE, 16 Jun 2014 Ethan Schisler/NOAA Weather in Focus Photo Contest 2015.

Fig. 7-36. Multiple vortex EF4 tornado of 09 May 2016 near Katie, OK. Justin Cox, KFOR TV, OKC. https://www.youtube.com/watch?v=T5Et2iIzdgI

Tornadoes are more likely to develop multiple vortices when the swirling speed is much greater than updraft speed. The secondary vortices or 'suction' vortices make multiple-vortex tornadoes potentially the deadliest because wind speed is increased in the places where the wind of the small vortices adds to the wind of the main vortex. The deadly Xenia, OH tornado of 03 Apr 1974, at times a wide, 'wedge' tornado and certainly no pretty sight (Fig. 7-37) was perhaps the most notorious multiple vortex tornado. It killed 32 people, destroyed much of Xenia, and, with wind speeds estimated up to 500 kph was among the strongest tornadoes ever recorded.

Fig. 7-37. Xenia OH tornado, 03 Apr 1974, laden with debris. ©Fred Stewart, Xenia Hospital

It is mind boggling that almost all that is known about severe thunderstorms and tornadoes was unknown until quite recently, and long after the nature and properties of atoms were discovered. Storm chasing is a relatively new activity, begun by Roger Jensen in 1953 and David Hoadley in 1956, neither of whom were professional meteorologists. Tetsuro Fujita was among the early researchers, who worked in good part by analyzing damage patterns left by the storms some time after they had ended. Serious professional storm chasers did not begin work until the 1970's. Over the years, and especially inspired by the film, Twister (1996) more and more people took up storm chasing. Now, professional and amateur storm chasers crowd the roads every time severe weather is forecast and provide images, videos, and measurements of these awesome storms, The increase of attention and knowledge also inspired people unwittingly living in the path of these storms to photograph and video them, sometimes putting themselves in extreme danger.

It might seem a crazy thing to chase tornadic storms given that tornadoes have killed so many hapless people in their paths, and certainly it is dangerous even when great care is taken. But there is a science to it that turns the odds in the savvy storm chasers' favor.

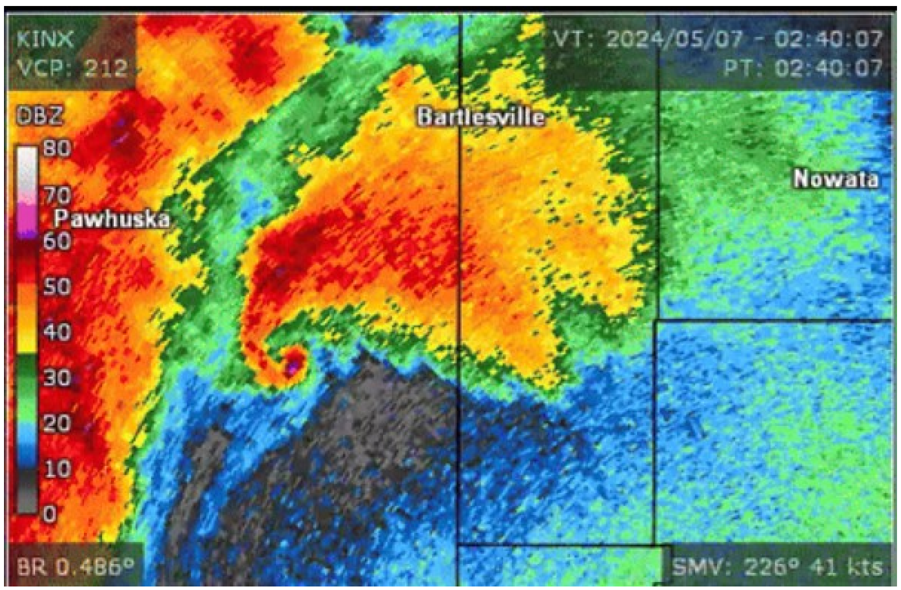

Fig. 7-37. Radar image of Bartlesville, OK tornado of 07 May 2024 showing classic 'hook' echo at SW and debris echo at the tip of the hook. NOAA.

The classic supercell thunderstorm (Fig 7-5) places the tornado at its southwest corner. Storm chasers will therefore try to place themselves under clear skies if possible, south of any promising supercells. They must know the roads well, should have a vehicle designed for storm chasing, and have access to current forecasts and, of course, live radar imagery.

Weather radar provides a way to 'see', quantify, and provide life-saving, short-range forecasts of supercell thunderstorms and the tornadoes they spawn. Doppler radar, which records the line of sight velocity of hydrometeors can often detect rotation within supercells before the tornadoes extend and appear below the cloud and touch down on the ground. The classic radar signal of a tornado is a hook echo, the end of which is sometimes an echo of lifted debris, as in the Bartlesville, OK tornado of 07 May 2024 (Fig. 7-37). The hook occurs because large, radar reflecting raindrops and hailstones take time to grow and are only present in the region of the storm surrounding the core of the main updraft (called the bounded weak echo region), which mainly contains small droplets and ice particles that have not had the time to grow large enough to reflect the microwaves efficiently.

Photos and videos of thunderstorms, spectacular as they are, can never convey a full idea of their awesome nature. Only direct experience can do this. Seeing is believing, but more than seeing – all the senses can be involved. The locomotive roar of the wind that can not only blow you down but toss you around and vault you into the air or ram a piece of straw through solid wood, the whistling and impact of large hailstones crashing into objects on the ground are difficult to believe if not experienced (and survived). Indeed, you need hear just one crash of thunder from the explosive expansion and contraction of air due to a nearby bolt of lightning to get some idea of how awe inspiring but also how terrorizing thunderstorms and their attendant phenomena can be. And after the storm has passed and you view the storm's magnificence as it moves off into the distance, a brilliant rainbow may arc across the sky to impart a feeling of reverence for the wonder of nature that a thunderstorm is.

A few hours later, when only remnants of the anvil remain of the once glorious and terrifying storm, now disintegrated and vanished into the thin air it congealed out of, a sense of wonder persists, that mere air can do all this!

7.6 Cumulonimbus Gallery

Fig. 7-38. Cumulonimbus entraining low-level moist air and dark attendant cloud Cheyenne, WY, 07 Jul 2019. Jan Curtis.

Fig. 7-39. Twilight of the Gods Cheyenne, WY, 20 May 2020. Jan Curtis.

Fig. 7-40. Dying cumulonimbus with aligned mamma at Cheyenne, WY 27 May 2022. Jan Curtis.

Fig. 7-41. Rare cumulonimbus with classical anvil shape and overshooting dome 50 east of San Mateo, CA 01 Oct 2015. SDG.

Fig. 7-42. Cumulonimbus at dawn over New Jersey 07 Oct 2010. SDG.

Fig. 7-43. Cumulonimbus at sunset over Cheyenne, WY 13 Jun 2021. Jan Curtis

Fig. 7-44. Color-graded twilight cumulonimbus. NOAA Weather in Focus Photo Contest 2015 Jeremy Bower.