Fig. 6-1. A field of cumulus humilis over City College of New York 15 Sep 2008. SDG.

Fig. 6-2. Explosive towering cumulus congestus, with flat base and small pileus cap over Cheyenne, WY 07 Jul 2019. Jan Curtis.

Wonders of the Atmosphere
Chapter 6: Penetrative Clouds

Started 17 Aug 2024

6.1 Cumulus: The Nature of Penetrative Clouds

Cumulus clouds, Joni Mitchell's 'ice cream castles in the air', are the puffy cloud blobs of hot, buoyant rising air. Cumulus is the cloud drawn by almost every child. When small, great numbers of humble *cumulus humilis* may be scattered across the sky as the classic the fair weather clouds, as mid-morning on 15 Sep 2008 over City College (Fig. 6-1) about six hours after a cold front had passed.

As the day heats up, a successful cloud may snuff out its neighbors and win the battle of Survival of the Fittest, rising to gargantuan size as *cumulus congestus* (Fig. 6-2). There it achieves its classical form with puffy, cauliflower towers everyone notices and a flat base most people fail to notice. Cumulus is usually a daytime cloud because that is when the Sun heats the ground and the air just above it. Cumulus clouds may form anywhere, but they congregate over heated places such as hills, dark or paved surfaces, forest fires, and where polar air behind cold fronts pours over warm waters. Cumulus clouds are least likely over relatively cool landscape features such as valleys, lakes, rivers, snow-covered ground, or the Polar Ice Caps.

Stratocumulus, cumulus, and cumulonimbus are penetrative clouds. They consist of hot, buoyant blobs called *thermals* or fountain-like plumes that puncture and rise through the quiescent ambient (surrounding) atmosphere. On occasion, they may penetrate other clouds. The towering *cumulus velum* over Fairfield Lake, NC (Fig. 6-3) punctured a pre-existing smooth cloud veil of cirrus or altocumulus.

Most plumes and thermals are initially invisible unless filled with smoke (Fig. 4-15) and remain so until they reach the condensation level, where droplets form, and which marks the cloud's often flat base. The cloud then extends as high as the plumes or thermals rise.

Fig. 6-3. A towering cumulus (with a tiny pileus cap) penetrates a veil of altocumulus to form a cumulus velum, 30 Aug 2022, Sapphire, NC. SDG.

6.2 Changes of T and T_d in Rising and Sinking Air: Soundings and Stability

Plumes and thermals rise buoyantly so long as they are warmer and less dense than the surrounding quiescent atmosphere. Once they penetrate warmer surroundings, such as when they encounter temperature inversions (where ambient temperature ***in***creases with height) they lose their buoyancy. From that point they decelerate, reaching some maximum height, like a fountain, and then sink back to the equilibrium level where they have the same density as the surrounding atmosphere.

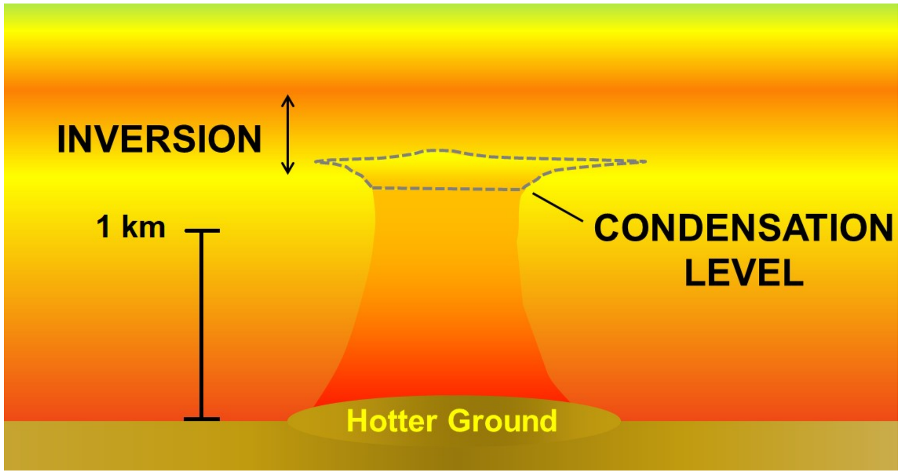

Fig. 6-4. Pancakes of stratocumulus (in dotted outline) are all that can form when an inversion occurs just above the condensation level. SDG.

If thermals enter warmer surroundings just above the condensation level, as in Fig. 6-4, the resulting clouds will be vertically stunted stratocumulus, and may resemble pancakes. If, however, the rising thermal or plume remains warmer than the surrounding, *ambient* atmosphere all the way up to the base of the stratosphere, as in Fig. 6-5, the resulting cloud will be a towering cumulonimbus, often with a fountain-like, overshooting dome that spreads into an extended anvil.

There is one complication. As a thermal or plume rises its temperature changes naturally at rates set by physical processes (recall §4.3). Thus, to determine whether a rising thermal is warmer than the ambient atmosphere at any height, and therefore how high a cloud will rise requires comparing the *situation* of the time, i. e., the sounding, to largely determined physical *processes*.

Soundings of situations where penetrative clouds develop only provide *direct* information about the vertical profiles of temperature, dewpoint and wind in the ambient atmosphere, and not inside the penetrative clouds themselves. That extra information must be inferred by including extra lines in the sounding that represent the physical processes of rising or sinking air.

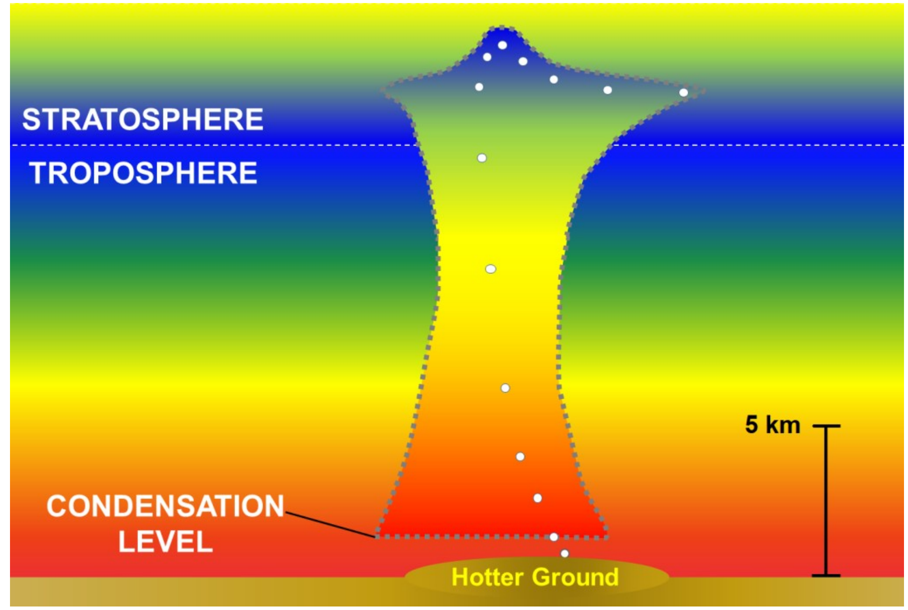

Fig. 6-5. Cumulonimbus with overshooting tops can penetrate the stratosphere when the atmosphere is unstable (ambient *T* decreases more rapidly than cloud *T*) through the troposphere. SDG.

When air rises it is depressurized and expands. This causes both T and T_d to decrease by performing the work of expansion without any loss of heat – *adiabatically*. Adiabatic cooling occurs when air escapes from a pressurized tire or tank or when a person blows air out under pressure. The temperature drop can be understood on the level of molecules. When a molecule confined in the chamber of a pump strikes a piston and pushes it out (which expands the chamber and reduces pressure inside it), the molecule will rebound more slowly than it struck. Temperature decreases as molecules slow because temperature is a measure of the kinetic energy of the molecules.

So long as rising air remains unsaturated (i. e., $T > T_d$), it cools at the constant, *dry adiabatic cooling or lapse rates* (recall Chapter 4),

T decreases ≈ 9.8°C/km
T_d decreases ≈ 1.8°C/km

Once T cools to T_d the air becomes saturated. If the saturated air continues rising and cooling, vapor begins to condense. T and T_d then cool together at the *Saturated (or Moist) Adiabatic Lapse Rate*, which is smaller than the dry adiabatic lapse rate because condensation releases latent heat into the air.

Every gram of vapor that condenses in 1 kg of air warms the air by 2.5°C.

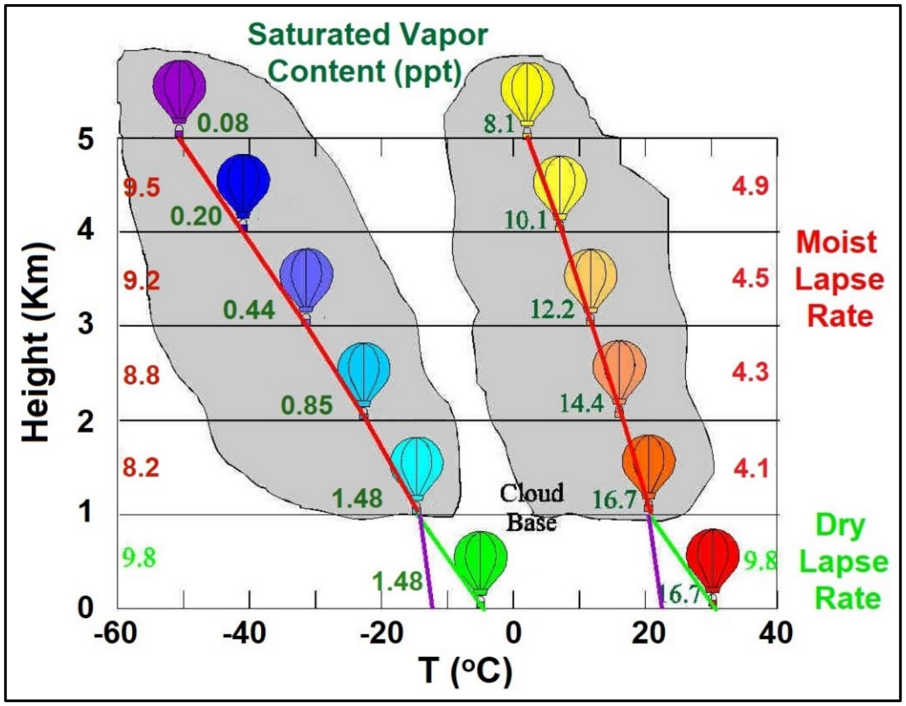

Fig. 6-6. Dry and Moist Adiabatic lapse rates and vapor content for warm and cold rising thermals. SDG.

The added latent heat of condensation offsets some of the cooling due to expansion. Unlike the dry adiabatic lapse rate, which is a constant, the saturated adiabatic lapse rate varies with temperature. The warmer saturated air is, the larger its vapor content and capacity and larger the rate of condensation.

Fig. 6-6 shows the moist adiabatic lapse rate for two rising air parcels, starting at sea level. One parcel starts at T = 30°C and the other starts at T = -4°C. Each parcel becomes saturated at 1 km. The fraction of vapor content of the warm air parcel up to 1 km (T = 20°C) is 16.7 g/kg (parts per thousand). By 2 km condensation amounting to 2.3 g/kg means that the vapor content decreased to 14.4 g/kg. Each gram of vapor that condenses adds 2.5°C of latent heat, so the 2.3 g adds 2.3 × 2.5 = 5.7°C. This offsets the adiabatic temperature decrease of the rising parcel, so its temperature decreases by only 9.8° – 5.7° ≈ 4.1°C.

The cold parcel's initial vapor content is only 1.48 g/kg. By 2 km condensation has decreased its vapor content by 0.63 g/kg. This adds only 0.63 × 2.5 = 1.6°C to the air parcel, so its temperature decreases by 9.8 – 1.6 = 8.2°C, a rate much closer to the dry adiabatic lapse rate.

As each parcel continues rising, less vapor remains to condense, so it cools more rapidly, at a rate that approaches the dry adiabatic rate.

The procedure to determine how high penetrative clouds extend is to lift a thermal along its process lines as it expands and cools adiabatically and compare its temperature to that of the ambient temperature. If the forcibly lifted thermal is cooler and denser than the surroundings, it will sink back and oscillate around its original level when released. This situation is statically stable and it will not produce penetrative clouds. If, however, the lifted thermal is warmer than the new surroundings, it will be less dense and buoyant (like a hot air balloon) and accelerate upward. This situation is statically unstable.

Now we use soundings to reveal why the field of humble cumulus humilis of Fig. 6-1 with sounding in Fig. 6-7 differs so greatly from the towering cumulus congestus of Fig. 6-2 with sounding in Fig. 6-8. In both cases the ambient T (**solid red line**) and T_d (**solid green line**) indicate the ambient atmosphere is unsaturated and clear.

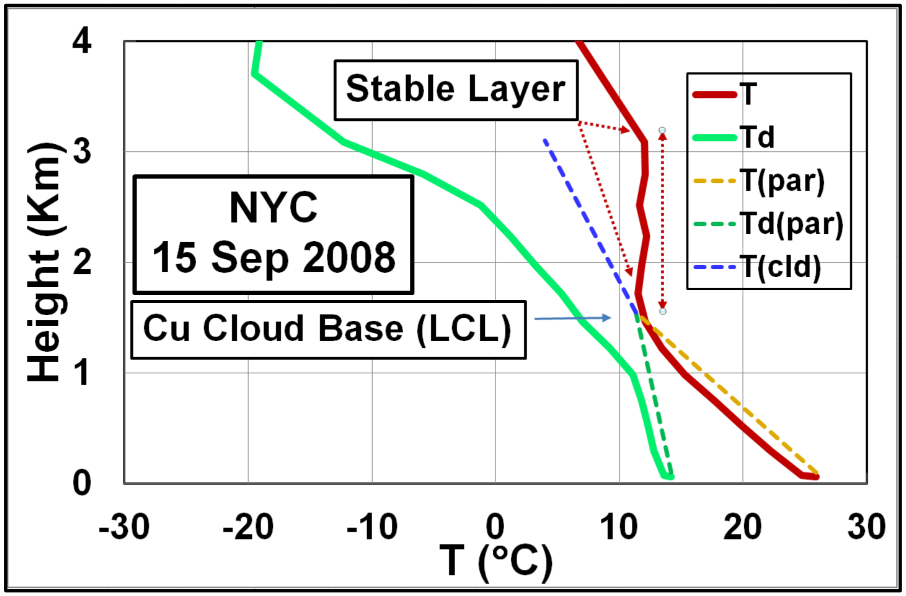

Fig. 6-7. Sounding for cumulus humilis at 1500 UTC 15 Sep 2008 of Fig. 6-1 including the dashed process lines for dry adiabatic lapse rate for T (orange dashed line) and T_d (green dashed line) and moist adiabatic lapse rate for T and T_d (blue dashed line) above cloud base. SDG.

Process lines below cloud base

T decreases at the dry adiabatic rate (**dashed orange lines**).
T_d decreases at the rate (**dashed green lines**).

Cloud base occurs at the lifting condensation level where parcel $T = T_d$.

Single process line above cloud base

T and T_d cool at the moist adiabatic rate (**dashed blue lines**).

In both cases strong solar heating at the ground renders the rising thermals warmer than the ambient atmosphere below the lifting condensation level. Hence the heated thermals are buoyant and rise and the surface boundary layer is unstable.

The difference between the two soundings occurs above cloud base.

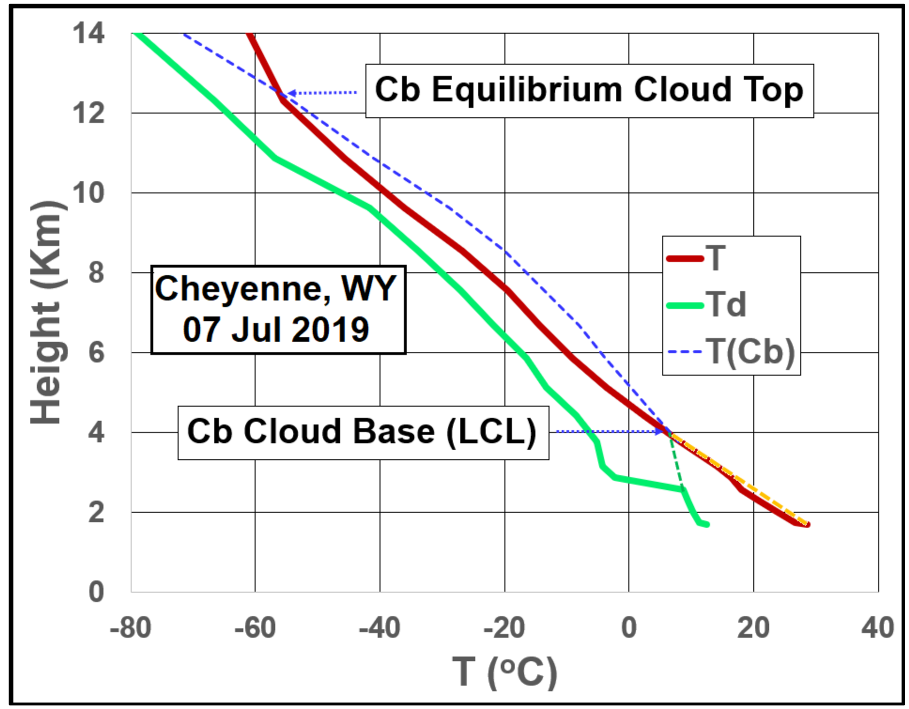

Fig. 6-8. Sounding for towering cumulus at 2100 UTC 07 Jul 2019 of Fig. 6-2 with same process lines as Fig. 6-7. SDG.

For the cumulus humilis almost immediately above the condensation level the ambient atmosphere is marked by a stable layer of almost constant temperature from 1.5 km to 3 km. and the rising parcel is cooler than the sounding. The thermals arrive at the condensation level with some velocity and quickly decelerate so that the clouds can only rise a short distance further.

By contrast, for the towering cumulus congestus, the rising thermal remains warmer than the ambient atmosphere all the way to 12.3 km, above which it is cooler than the surroundings and decelerates.

Now we can begin to understand…

6.3 The Realm of Penetrative Clouds

Fig. 6-9. Pancake stratocumulus above cold waters. SDG.

The realm of penetrative clouds extends from wafer-thin stratocumulus clouds that top out just above the condensation level to towering cumulonimbus that puncture the stratosphere. Whenever the surface is cold, no penetrative clouds rise from it. This is the case on clear, calm nights, when the ground radiates heat to space and cools the air just above. If cooling is sufficient, fog and low stratus may form, but they will be utterly lacking in buoyancy and hug the ground. For the same reason, penetrative clouds are almost completely absent over the refrigerated ice caps.

The cold, upwelled ocean waters on the east side of the Subtropical Highs, and off the west coasts of the continents are only slightly less repressive to penetrative convection. They chill and humidify the air in the lowest kilometer enough to produce extensive sheets of fog, stratus, and stratocumulus that are bounded by a capping inversion that separates them from much warmer and drier air above.

Fig. 6-10. Pancake stratocumulus over San Mateo, CA, 17 July 2011. SDG.

Fig. 6-11. Aerial view of elongated cells of stratocumulus clouds capped by an inversion at 800 m 100 km west of the Oregon coast, 1830 17 Aug 2017. SDG.

This can be seen both from the air (Fig. 6-7) and from the surface. The repressed environment of the sky over San Mateo, CA on 17 Jul

2011 served up a flattened layer of stunted, pancake stratocumulus (Fig. 6-8). The clouds were driven inland from the cool Pacific Ocean by a westerly wind around the subtropical North Pacific High. Wind shear can elongate the cells and orient them in parallel ribbons, as in Fig. 6-9 over the cold Pacific waters west of Oregon on 17 Aug 2017. The clouds in this case were capped by an inversion 800 m above the sea surface.

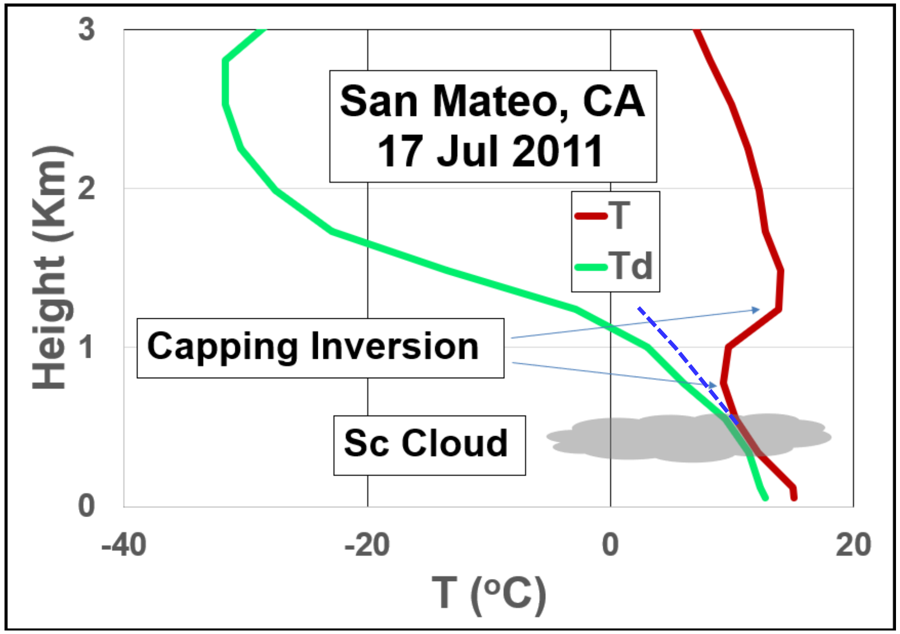

Fig. 6-12. Sounding for the stratocumulus of Fig. 6-6 capped by an inversion. SDG.

All soundings for these stratocumulus clouds look alike. The sounding corresponding to the San Mateo case (Fig. 6-12) reveals the two distinct air masses. Maritime air that had been cooled and humidified by contact with the cold sea surface occupied the lowest 800 m of the atmosphere. The clouds were confined to the thin layer of saturated air between 250 and 500 m in this layer. Above 1200 m, warm air, with very low ***RH***, marked by the large difference between $\boldsymbol{T}$ and $\boldsymbol{T}_d$, filled the atmosphere. The extreme dryness of this air indicates that it had sunk from the upper troposphere as it coursed around the North Pacific High. The temperature inversion between 800 and 1200 m marked the zone where the two air masses mixed and was the lid on the flattened, pancake clouds below.

The dashed blue line of moist adiabatic ascent in the sounding of Fig. 6-12 shows why the clouds were so flattened and stunted vertically. Immediately upon being lifted the parcel would be colder and hence denser than the ambient temperature (solid red line). Thus, even if cloud air were thrust upward, for example, forced by the west wind to cross over the Coast Range, it would quickly sink back to its equilibrium level.

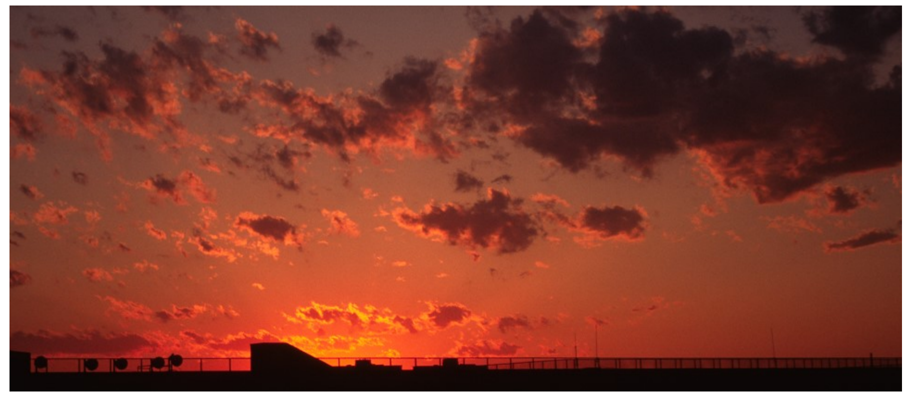

Fig. 6-13. Shriveled stratocumulus at sunset over CCNY. SDG.

Fig. 6-14. Stratocumulus clouds over Tromsø, Norway at midnight, 02 Jul 2008. SDG.

Fig. 6-15. Stratocumulus clouds over Reykjavik, Iceland, 1600 03 Oct 2024. Their darkness is characteristic of sunlit thin cloud veneers opposite the Sun. SDG.

Stratocumulus clouds are also the most likely form of penetrative cloud produced by feeble daytime or fading late afternoon heating. They often appear as the disintegrating remnants of afternoon cumulus that have stopped rising, mix with drier, ambient air, and evaporate as the low or setting Sun no longer heats the ground. The stratocumulus of Fig. 6-13, which enhanced the twilight colors, is a typical example, and disappeared less than an hour after the photo, leaving the sky cloudless.

Stratocumulus clouds are common afternoon clouds in the mid and high latitudes during autumn and winter, when the Sun remains low in the sky and the days are short. The weak heating makes them a signature cloud of the polar regions even at the height of summer, as in Fig. 6-14 at midnight on 02 Jun 2008 over Tromsø, Norway (latitude, 69.71° N) in the Land of the Midnight Sun.

Stratocumulus clouds sometimes form from the disintegration of a layer of stratus. This was the case at Reykjavik, Iceland on the afternoon of 03 Oct 2024 (Fig. 6-15). Daytime heating, weak as it was, was enough to warm the air at cloud level, and begin to evaporate the thin stratus cloud deck, acting in cooperation with the advance of drier, polar air in the wake of a departing low pressure area.

Fig. 6-16. Sunlit field of optically thin cumulus at Boynton Beach, FL 13 Feb 2014. SDG.

Stratocumulus clouds viewed from the ground are often gray even if sunlit. Optically thin cloud veneers seen far from the Sun reflect or scatter little sunlight to the viewer but block enough skylight to appear darker than the sky. They appear especially dark when compared with nearby optically thick clouds, whose sunlit sides reflect sunlight with much greater efficiency. Optically thick stratocumulus do appear bright when viewed from above, as in Fig. 6-8, or when sunlit and optically thick, as in Fig. 6-12, but are seldom as bright as the sunlit sides of cumulus and cumulonimbus, which almost always have much greater optical thickness and which reflect up to 90% of the incident sunlight

Fig. 6-17. An anvil-topped cumulus street over the Bronx. SDG.

Fig. 6-18. Thunderstorm over Kimball, NB with an overshooting dome above the anvil at the equilibrium level, 08 Jul 2018. Jan Curtis.

Clouds that block or appear near the Sun are dark if optically thick but can gleam blindingly bright if they are optically thin, as with the field of cumulus in Fig. 6-16. In such clouds lighting prevails over form.

Form dominates the curious anvil-topped line of cumulus mediocris in Fig. 6-17. The modest height of the clouds shows that the unstable layer is shallow but the anvil indicates that 1: the degree of instability within the layer is quite large so that the air rises rapidly until it slows and spreads abruptly upon reaching a sharp capping inversion. The small cumulus turrets that rise slightly above the otherwise level top represent miniaturized versions of the overshooting dome tops seen in growing cumulonimbus clouds, as in Fig. 6-18.

Fig. 6-19. Trade wind cumulus over the Bahamas on the way into Hurricane Hortense 11 Sep 1996. SDG.

Overshooting domes occur in growing, active thunderstorms, because the rising thermals or plumes often have large upward

Fig. 6-20. A field of cumulus humilis with white sunlit sides and gray shaded bases over Cheyenne, WY 23 Apr 2019. Jan Curtis.

velocities when they reach the equilibrium level, marked by the anvil. Their momentum carries them as much as a kilometer or two before they sink back down, much like the jet in a fountain.

The height of the overshooting dome above the equilibrium level depends on three main factors, 1: the range of height through which the parcel is warmer than the surroundings, 2: the parcel's mean temperature excess over that range and, 3: the ambient temperature profile above the equilibrium level. The first two factors combine as a measure of the potential energy that is available to be converted to kinetic energy of the updraft. This quantity, called the Convective Available Potential Energy (CAPE) helps to estimate the maximum updraft speed at the equilibrium level. The ambient temperature profile above the equilibrium level determines how rapidly the rising parcel decelerates. The most rapid deceleration occurs with a marked inversion immediately above the equilibrium level.

In the Trade Wind belt unusually narrow cumulus burst upward for some distance, buoyed by the large release of latent heat of condensation in the otherwise stable air. A pretty case occurred over one of the Bahama Islands on the way into Hurricane Hortense on 11 Sept 1996, whose outer winds tilt the clouds (Fig. 6-15).

Not only does intense, prolonged heating lift thermals and plumes it turns the entire atmosphere unstable. Now we look at some of the more noble cumulus, noting that even the most towering and formidable thunderstorm starts from a successful cumulus humilis that was born only a few hours earlier (Fig 6-1 and Fig. 6-20).

Fig. 6-21. Cumulus humilis 06 Oct 2023, Fairfield Lake, NC. SDG

Fig. 6-22. Cumulus mediocris 03 May 2024, Boynton Beach, FL SDG.

Fig. 6-23. Cumulus Congestus enhanced by orography Vail, AZ 18 Aug 2018. Jan Curtis.

Fig. 6-24. Stand-alone growing cumulus congestus with cauliflower protuberances and flat, dark shaded base Ranchettes, WY. 05 Sept 2016,. Jan Curtis.

Fig. 6-25. Cumulonimbus, the thundercloud with flat base, fuzzy cirriform anvil and growing cauliflower towers, 22 June 2023, Ranchettes, WY. Jan Curtis.

Consider a day that is cloudless at dawn. After a few hours the surface air has been warmed enough to produce thermals that rise above the condensation level and produce small, humble *cumulus humilis* that may resemble powder puffs (Fig. 6-21). Each small cloud mixes with the environment and dies within minutes but the vapor that has been pumped aloft increases the ambient RH so that subsequent cumulus can rise higher and last longer before evaporating.

After a few more hours of intense, mid-day solar heating the cumulus clouds have grown wider and higher, and cover a larger fraction of the sky. They have now become *cumulus mediocris* (Fig. 6-22) and, unless large vertical wind shear tilts and distorts the clouds, they almost always have marked flat, dark bases.

If the atmosphere is unstable through a deep layer of the troposphere, a few of the 'fittest' cumulus clouds will win the 'struggle' for survival and continue widening and rising to towering cumulus congestus with growing cauliflower shaped tops, in Fig. 6-23 and Fig. 6-24.

Ultimately, at typical heights between about 8 and 18 km, they will encounter a stable layer, perhaps the stratosphere, where they spread out into great anvil caps and metamorphose into the thundercloud, cumulonimbus (Fig. 6-25). As the air rose, large quantities of water and ice condensed and accumulated in the cloud. That water weighs the cloud down, and produces downdrafts filled with rain or even hail that hurtle toward the ground and soak it.

The cloud photographs chosen above involve deception in that they are highly selective, textbook images. Enormous time and patience are needed to capture such model cumulus standing separately or solo in pristine, deep blue skies of unlimited visibility. Stand-alone, towering cumulus are uncommon over isolated peaks, such as Mt. Fuji in Japan; over flat ground they are exceptional.

Fig. 6-24 represents an extreme example. For half an hour, the nearest cloud in the line of cumulus presented its face unobstructed, and with no other clouds on either side as well.

The vast majority of cumulus skies contain a chaotic jumble of clouds at all stages of development that makes it difficult to see the complete outline of any cloud, as the the field of cumulus over Mtez, Austria (Fig. 6-26). Shreds of juvenile clouds appear side by side with mature growing beauties and aged dissipating clouds. All these clouds are spread around the sky almost like buckshot, which befits their unstable, turbulent nature indicated by their cauliflower corrugations. (All doubts about the turbulent nature of towering cumulus are dispelled the moment a jet flies through one and undergoes violent shaking.) Furthermore, fields of cumulus clouds often arise in hazy air of high humidity, which further limits visibility and mars the clouds' potential beauty.

Fig. 6-26. Overlapping cumulus, Melk, Austria, 07 May 2018. SDG.

6.4 Mountains, Mushrooms and Motions

Mountains act as elevated heat sources on sunny days. Even though temperature decreases with height, the air on the sunlit mountain slopes is warmer than the air in the free atmosphere at the same height. The heated air slides up the slopes fom the valley as a valley breeze (recall Fig. 5-6). If the background wind is slow enough and the air rises high enough, the first place a cumulus cloud will form is above the peak, as with the new, baby cumulus humilis over Mount Coe in Baxter State Park, ME on 28 Aug 2005 (Fig. 6-27).

Such *orographic* clouds can grow to towering heights and result in thunderstorms over the mountains (Fig. 6-28) while the lowlands remain clear. This is not the time to celebrate a successful climb at the peak. Thus the saying, "mountains make their own weather."

Fig. 6-27. Orographic cumulus over Mount Coe ME, 28 Jul 2005. SDG.

Fig. 6-28. Orographic cumulus Vail Az Rincon Mt. 15 Oct 2018. Jan Curtis.

Fig. 6-29. Flat-based orographic cumulus over the Alpine peaks east of Zermatt, Switzerland 12 Jun 2004 SDG.

Fig. 6-30. Orographic cumulus Vail AZ 20 Aug 2022. Jan Curtis.

When cloud base is below the peak, young, growing orographic cumulus clouds can be seen rising up the slopes , as around Zermatt, Switzerland (Fig. 6-29) and Rincon Mountain, near Vail, AZ, where a complex humidity structure in the valley and on the slopes produced cloud bases at various heights (Fig. 6-30).

Fig. 6-31. Orographic cumulus cloud street 160 km long over Cheyenne, WY 23 Dec 2020. Jan Curtis.

Fig. 6-32. Stratocumulus lenticularis over Cheyenne, WY 29 Mar 2021. Jan Curtis.

Fig. 6-33. Cumulus line over the Palisades. SDG.

Uplift by winds that cross ridges of even modest height can generate cumulus when the atmosphere is unstable. On 23 Dec 2020 near Cheyenne, WY (Fig. 6-31) a NW wind crossing a low ridge at a 90° angle coupled with an unstable sounding up to about 3 km provided sufficient lifting to produce a line of cumulus 160 km long that persisted for 2 hours. On 29 Mar 2021 a W wind crossed the same ridge when the atmosphere was stable and produced laminar stratocumulus lenticularis in the same place (Fig. 6-32). Lenticular, mountain wave clouds are the subject of Chapter 13.

Cloud lines form when the wind crosses the modest Palisades of New Jersey, a cliff 90 m high at Fort Lee. If the atmosphere is stable, as it tends to be with an E wind. the cloud line is smooth and laminar at both top and bottom, but when the atmosphere is unstable, as in Fig. 6-33, buoyant cumulus turrets bubble up turbulently from the flat-based cloud line.

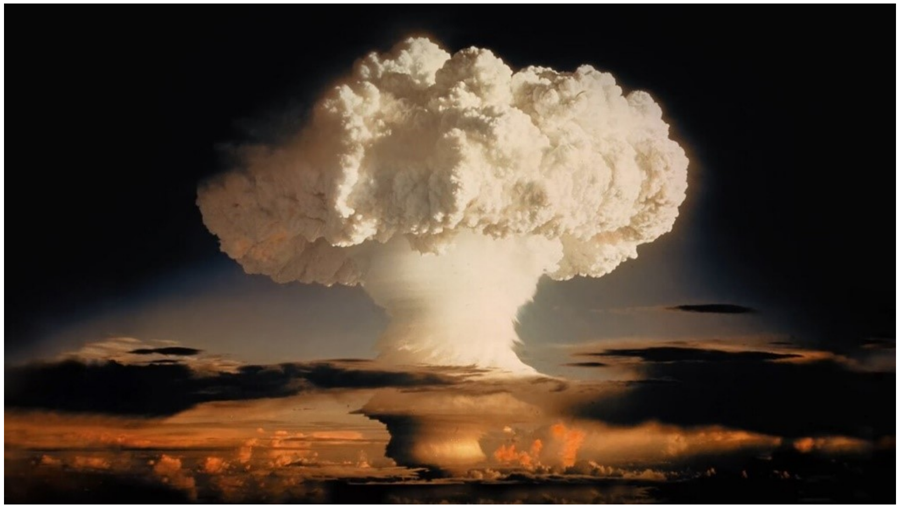

Fig. 6-34. Mushroom cloud of Ivy Mike, 01 Nov 1952.

The turbulent, bubbling motions of cumulus are avaters of the complexity omnipresent in clouds.

Fig. 6-35. Mushroom-shaped cumulus, Boynton Beach, Fl, 05 Feb 2014. SDG.

Even a single cauliflower turret of a single growing cumulus congestus reveals complexity. Simultaneous telephoto and wide-angle views of cauliflower turrets look similar and betray a fractal,

Fig. 6-36. Auspicious cloud scroll, Forbidden Palace, Beijing captures the form and motions of growing cumulus cloud turrets and lobes. SDG.

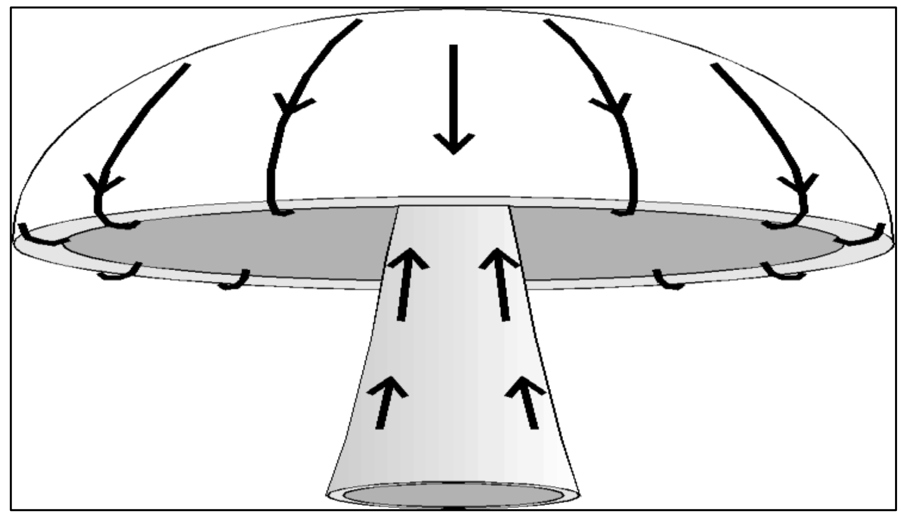

Fig. 6-37. Vortex air flow in a mushroom-capped plume. SDG.

turbulent nature. Large corrugations have smaller corrugations on them, almost in the manner of the infinite series suggested by Jonathan Swift's poem,

> Big fleas have little fleas upon their backs to bite them,
> And little fleas have lesser fleas, and so ad infinitum.

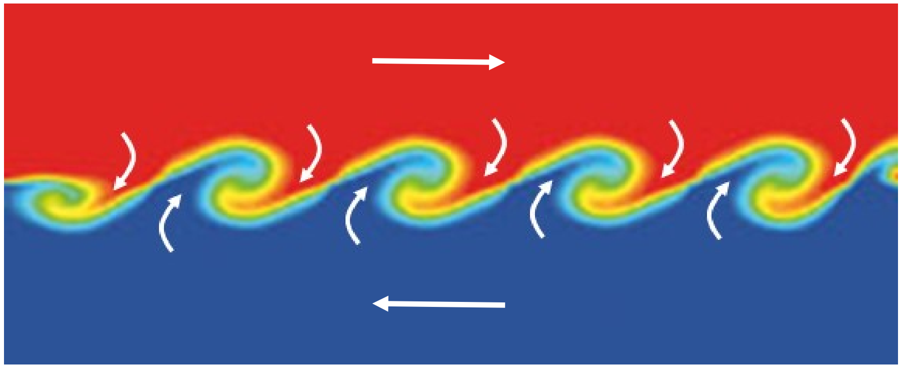

Fig. 6-38. Motions in breaking Kelvin-Helmholtz waves. SDG.

Despite all the complexity, there are simple cloud elements that reveal the truth in the mantra,

Clouds are the signatures of the winds.

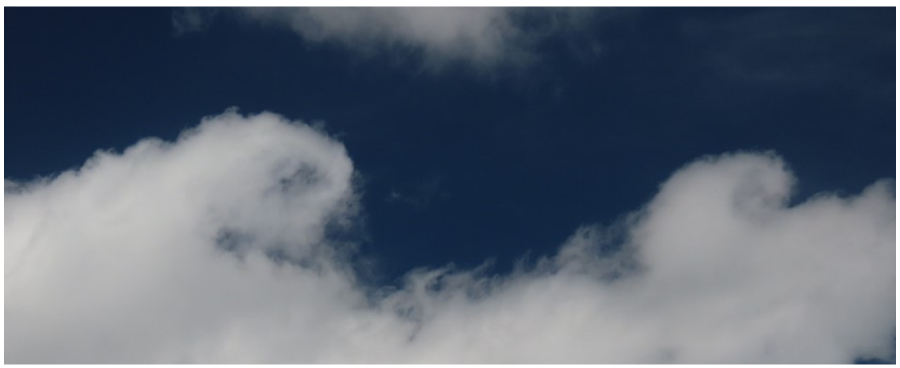

Fig. 6-39. Breaking Kelvin-Helmholtz waves atop Cu *fluctus* in strong wind shear, 10 Aug 2023 Fairfield Lake, NC. SDG.

The iconic simple cloud element is the mushroom cloud of nuclear explosions. Ivy Mike, which rose to over 40 km and evaporated the Pacific island, Elugelab in 1952 is just one example (Fig. 6-34).

Mushroom clouds are far more common and long predate nuclear explosions. They are produced by explosive volcanic eruptions, by more routine explosions (often depicted in movies) and can even be distinguished in mundane cumulus clouds, where on rare occasion a mushroom shape appears alone (Fig. 6-35). The vast majority of cumulus and cumulonimbus are built by many, often overlapping mushroom-shaped thermals of warm, buoyant rising air.

Knowledge of the mushroom cloud is ancient. The Chinese auspicious cloud scroll motif (yunwen) dates from the Shang Dynasty 1500 BCE. It shows that Chinese artists knew the form and motions within cumulus (Fig 5-13, Fig. 6-36). Pliny the Younger, watching the eruption of Vesuvius in CE 79 reported that the cloud resembled a pine tree with a rising trunk and spreading branches.

The basic motion of the mushroom cloud is shown in Fig. 6-37. A plume of hot, buoyant air moves up the mushroom stem and then out, down, and around the cap as it encounters resistance penetrating the quiescent surroundings. This motion is a classical ring vortex, and it is essentially the same as the motion of smoke rings (where the stem is invisible).

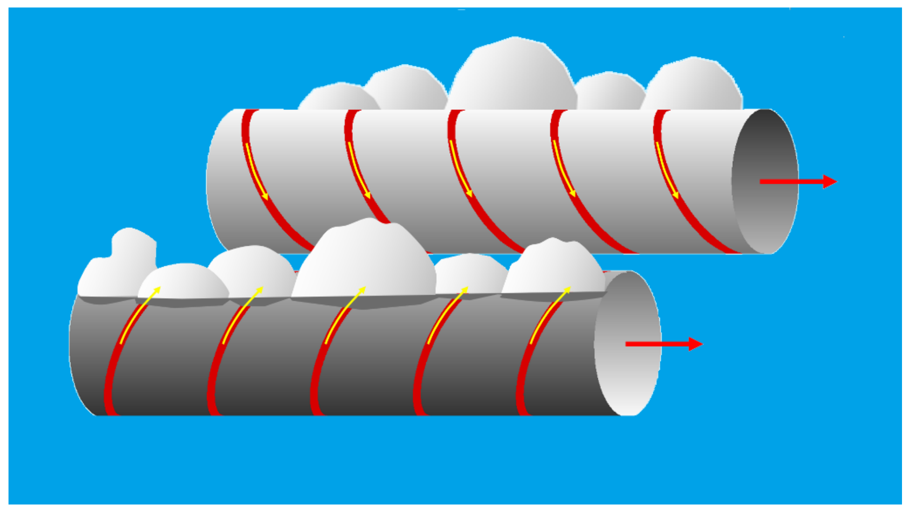

Fig. 6-40. Helical flow produces long parallel cumulus streets alternating with clear lanes, both parallel to the wind. SDG.

A second simple motion pattern is that of Kelvin-Helmholtz waves (Fig. 6-38). The waves form on the interface of two fluid layers moving relative to each and often grow like breaking waves in the

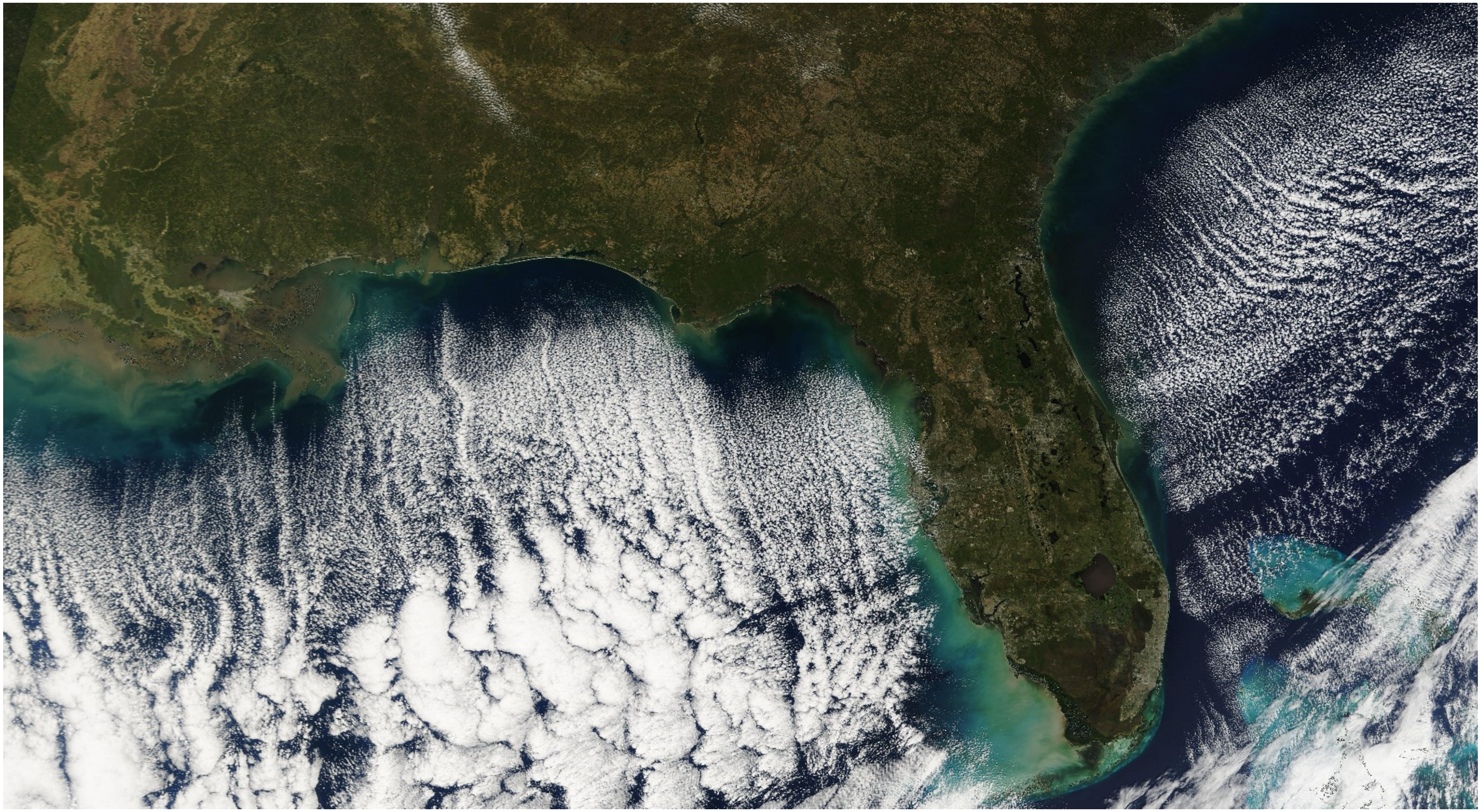

Fig. 6-41. Cumulus cloud streets over the Gulf of Mexico and the Atlantic Ocean behind a cold front while the land is clear on 16 Nov 2008. NOAA GOES.

ocean. Kelvin-Helmholtz waves form at the tops of clouds that occur where there is large vertical wind shear, such as the cumulus *fluctus* cloud of 10 Aug 2023 over Fairfield Lake, NC (Fig. 6-39).

Helical (corkscrew) flow (Fig. 6-40), spiraling forward like each strand of the DNA double helix, produces alternate rows of rising air and sinking air. The result is long streets of cumulus (and other cloud genera alternating with clear lanes closely parallel to the wind.

Cumulus cloud streets are as common as they are dramatic. Their signature form, seen in satellite images, occurs almost every time advancing Polar air behind cold fronts pours over warmer waters. A classic case occurred on 16 Nov 2008 filling the Gulf of Mexico and extending noirthward off the Atlantic coast to New Jersey (Fig. 6-41). As is typical, the sky is clear over land and over a strip of coastal waters typically 50 or more km wide before the cold, dry air acquires enough heat and water vapor to begin to form clouds. Similar features occurred on 11 Dec 2024 (Fig. 6-42), when cloud streets formed behind a cold front over the Gulf of Mexico and the Atlantic, and behind a second cold front over Lakes Superior and Michigan.

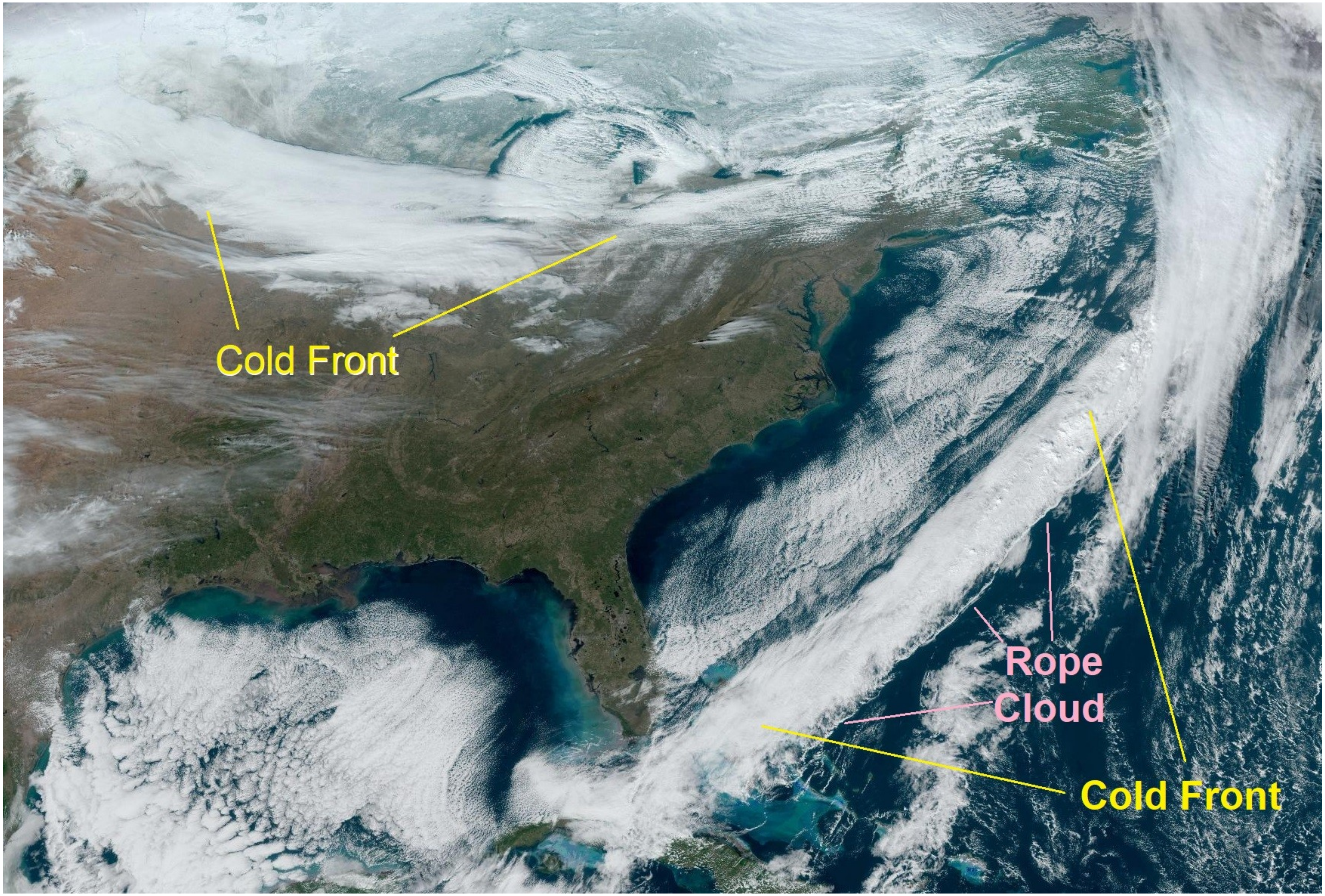

Fig. 6-42. Cumulus cloud streets behind a rope cloud, and over Lakes Superior and Michigan behind a secondary cold front, 1800 12 Dec 2024. GOES 16.

From satellite, cloud streets resemble lines of puffs. Views from the ground shows the puffs are cumulus turrets, which are often linked but may be separate. Fig. 6-43 shows a cloud street over the waters near Grand Turk on 18 Dec 2013 behind a cold front.

Fig. 6-43. Post cold front cumulus cloud street capped by an inversion at 2.5 km, Grand Turk 19 Dec 2013. SDG.

When the polar air first pours over the warm waters the heated air layer is quite shallow. The result is that cumulus cloud streets typically top out below 2 km until they are far out to sea. This leads to a classical sounding for these cases, marked by an unstable layer that is saturated at top and capped by an inversion of which. Fig. 6-44 taken from the case of 16 Nov 2008, is a representative sounding. It is, in fact, the combination of a thin unstable layer of air flowing over a warm surface confined by a capping inversion that produces the helical flow pattern that leads to cumulus cloud streets.

Cumulus cloud streets also occur over land, as in Fig. 6-45. They have the same basic sounding except that the air must be humid to start with, and they may require assistance from topography (recall Fig. 6-31). If it is cold enough, the cloud may glaciate (giving it a fuzzy appearance) and snow may fall (Fig. 6-46).

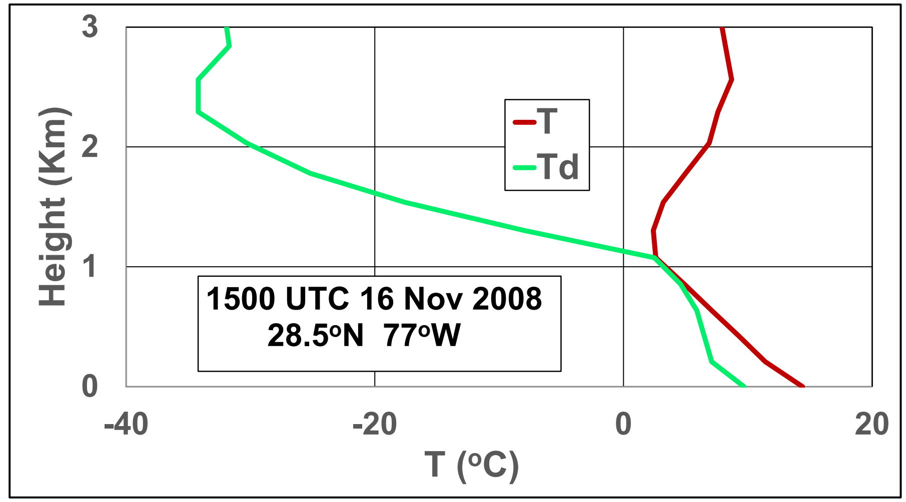

Fig. 6-44. Sounding for cumulus cloud streets at latitude, 28.5°N, longitude 77°W at 1400 UTC 16 Nov 2008. The unstable layer is 1.1 km thick. SDG.

Fig. 6-45. Cumulus cloud streets over CCNY. SDG,

Another distinctive flow and cloud feature associated with cumulus is *pileus* (felt cap). Pileus is a smooth, arched, often veil-like attendant cloud that forms when the top of a rising cumulus approaches a thin moist layers aloft and forces it up to its condensation level (recall Fig. 6-1 and Fig. 6-3). On 29 Oct 2016, at San Mateo, CA, two pileus caps formed over the highest turrets of a modest, cumulus cloud street that was capped by an inversion.

Fig. 6-46. Glaciating, snow-producing cumulus cloud streets over Cliffside Park, NJ. SDG.

Fig. 6-47. *Pileus* atop cumulus turrets San Mateo, CA 29 Oct 2016. SDG.

Pileus, discussed in more detail in §13.2, is similar to mountain wave clouds, though with two main differences. First, the rising mushroom cloud turret serves the role of a very short-lived mountain, Second pileus can form without vertical wind shear, as in Fig. 6-47, because the rising cloud forces the ambient air to rise. No mountain rises quite so fast.

Both mountain wave clouds and pileus are smooth because the forced flow of the stable ambient air is smooth and laminar. Pileus lasts but moments. It evaporates soon after it forms a skirt as the air sinks around the periphery of the mushroom turret sinks back to its original level or even lower.

The skirt cloud, or vellum is less common than pileus but lasts longer because it forms when a growing cumulus punctures a preexisting cloud sheet and does not require lifting (recall Fig. 6-3).

6.5 The Time Lapse View of Clouds

If a picture is worth 1000 words an animation is worth 1000 pictures.

There are countless time lapse videos of clouds, storms, and optical phenomena on the web. Jan has produced more than 1000, all available at the album labelled, *Time Lapse*, at

https://www.flickr.com/photos/cloud_spirit/albums/

Time lapse videos and animated loops of satellite images now eliminate the need for the great patience once possessed only by Chinese artists and few others to visualize the lifespan and motions of clouds and cloud systems. While it is difficult to visualize the growth of the stem and the motions around the mushroom cap of the atom bomb cloud from the series of seven still photos in Fig. 6-48 at one second intervals, the animation loop of the explosion, at

https://www.youtube.com/watch?v=yvGNP6AzyCY

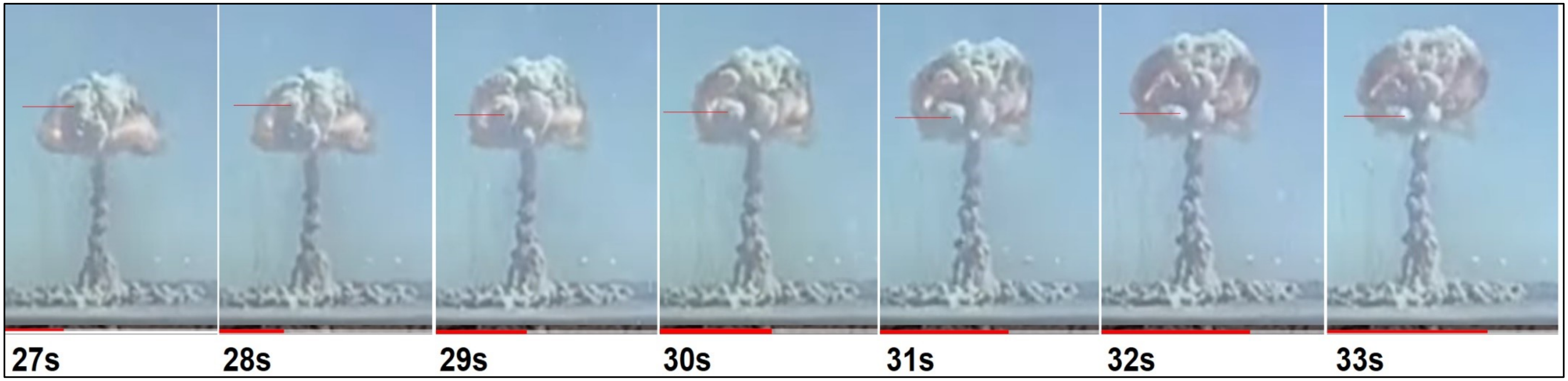

Fig. 6-48. Nevada Atom Bomb Test. from time, 27s to 33s. Red lines show the movement of one lobe.

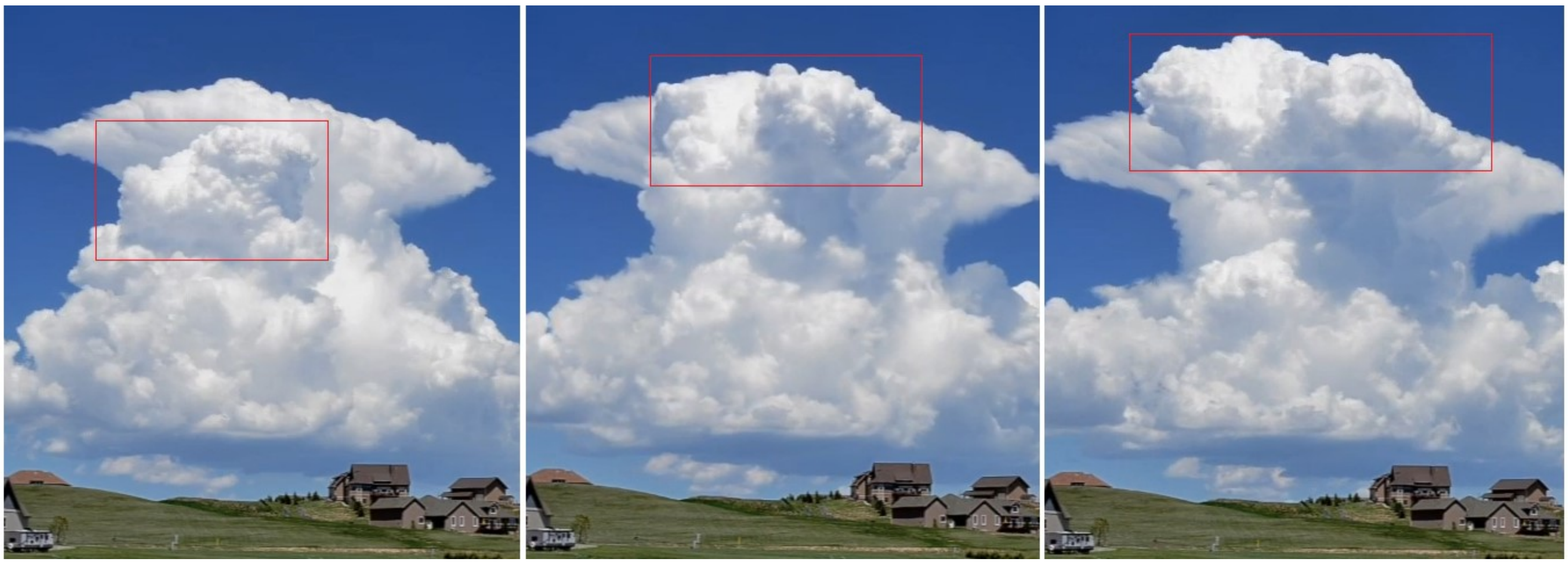

Fig. 6-49. Three frames of a cumulonimbus on 02 June 2017 east of Cheyenne, WY showing a rising and spreading thermal (in the red boxes). Jan Curtis.

makes the motions obvious almost immediately and without effort. Other videos of nuclear mushroom clouds are on the Web under the names, Operation Tumbler-Snapper, Operation Buster-Jangle, and Operation Ivy.

Similarly, only with diligence can you track the much slower motions of two mushroom thermals in the cumulonimbus cloud of 02 June 2017 east of Cheyenne WY from individual frames in Fig. 6-49, while the video, ***Explosive Thunderstorm Development***,

https://www.flickr.com/photos/cloud_spirit/35022437616/in/album-72157667543992515

makes the motions and evolution of thermals in the towering anvil-topped cumulonimbus incus obvious.

The growing mushroom-shaped thermal or plume described and illustrated in the last section is only the first stage in its life cycle. As the rising thermal or plume penetrates the clear, ambient air its upward progress is slowed so that it spreads outward to form a mushroom cap. This violent flow is unstable, which means that even miniscule irregularities grow and self-distort into lobes at all scales, hence the cauliflower appearance. The lobes follow the flow. They appear at the top center of the cap, move out, around, and under the cap. So long as the cap rises its outline contrasts sharply with the background clear sky because of the high concentration of droplets or ice particles right to the outer edge.

Eventually, the supply of warm air is exhausted and/or the thermal rises into warmer surroundings. Then, combined with the weight of condensed water and ice that adds to its density, it begins to sink. The flow direction of the entire cap reverses and it collapses from the center outward, warming as it sinks so that the drops and crystals evaporate. As they evaporate progressively larger lobes vanish until the entire cap disappears. That renders the motion of the cap invisible though it is still turbulent.

One static feature of cumulus stands in marked contrast to the dynamism of the bulk of the cloud in time lapse videos. The flat base, which corresponds to the lifting condensation level, remains in place almost unmoved while the rest of the cloud undergoes a boiling motion. An excellent case that occurred on 05 Aug 2013 was captured in the video,

https://www.flickr.com/photos/cloud_spirit/25162008824/in/album-72157662969788496/lightbox/

Fig. 6-50. Thin deck of altocumulus at dawn appears suddenly when sunlit. Top frame 0711 MDT, bottom, 0719 MDT. From the video, *Perfect Sunrise*. Jan Curtis.

An intriguing way to visualize the motions of cumulus in real time is to pour a thimble of milk into a fish tank full of water. As the milk drifts to the bottom of the tank it forms up-side down thermals with turrets and lobes. When the milk reaches the bottom of the tank it

Fig. 6-51. Sunset stratocumulus clouds are the dying embers of cumulus earlier that afternoon over Catalina Mountain, AZ 16 Mar 2023. Jan Curtis.

spreads out along the bottom, curling up at its outer edge in a vortex ring of a thunderstorm downburst, as exemplified in the spreading dry-ice created fog of Fig. 4-36.

Ground-based time-lapse videos of the penetrative clouds, with their dynamism, contrast with the static nature of videos of most other cloud genera. The cells and ripples of sheets of altocumulus or cirrocumulus and the streamers of cirrus tend to streak across the sky with little change in shape because the circulations inside the cells and ripples and the fall speed of crystals in the streamers are very slow compared to the wind speed. For example, a typical wind speed at the level of cirrus is about 50 m/s but most ice crystals fall less than 1 m/s. Thus, a streamer may move out of sight before it can lengthen much, particularly when old crystals at the streamer's tail evaporate about as fast as new crystals form at the streamer's head.

Time lapse videos or loops of satellite images do cover enough time and space to show how cirrus and altocumulus evolve provided the time interval between frames is not too large. One example is cirrus that form in the lee of mountain ridges and then extend downwind.

Even though little dynamism is apparent in time lapse videos of cirrus and altocumulus, they still provide awesome and surprising views. Optical phenomena, such as halos and coronas, can flash on and off. Changes of illumination during sunrise and sunset can cause cloud veneers to appear or disappear in minutes. The video, ***Perfect Sunrise*** is a perfect example of a sunrise surprise.

https://www.flickr.com/photos/cloud_spirit/43902575520/in/album-72157673924732027/

Fig. 6-50 shows two frames of the video 8 minutes apart. In the top frame at 0711 MDT the sky appeared mostly clear except for a broken layer of golden and rich red altocumulus above the horizon. By 0719 MDT (bottom frame) an extensive banded layer of altocumulus was visibly laced across much of the sky.

Its surprise appearance actually took only two minutes. The layer was invisible before the Sun rose because its optical depth in the vertical direction was so small that skylight from above passed through it almost undiminished. However, once the Sun struck the thin but wide layer broadside much sunlight was scattered and the cloud lit up. The layer then scarcely changed shape as it traversed the sky. Much later with the Sun high in the sky, thin sheets of altocumulus fade from view once again because sunlight passes through them with little scattering. In a sense, these often near invisible thin clouds are much like the recently discovered 'missing' matter in the universe, which was invisible until viewed in the proper light.

6-6. Pyrocumulus and Pyroplumes

Sunset often makes mountains and clouds *seem* as if they were on fire (Fig. 6-1) but sometimes they really are. Since the turn of the millennium average annual wildland fire acreage has more than tripled in the USA to an average of about 30,000 km^2. Lightning (see Chapter 8) sparks many of the fires, but sometimes it is the fires that rouse thunderstorms, or at least cumulus (recall Fig. 4-19).

On the days around 12 Aug 2015, in the worst fire year in the USA since comprehensive records were first kept in 1983, with just over 40,000 km^2 burned, the normally pristine air and deep blue skies around Crater Lake, OR were tarnished by nearby fires. Some of these fires burned so hot in the unstable air they generated towering pyrocumulus clouds, as in Fig. 6-52. On occasion pyrocumulus clouds produce enough rain to quench the fires, but alas, not often.

Too often, of course, wildfires fail to produce clouds, but in strong winds do lead to long plumes, as with the Badger Creek Fire of 11 June 2018 photographed and videoed at Cheyenne, WY, 125 miles east of the fire (Fig. 6-53).

Fig. 6-52. Pyrocumulus north of Crater Lake, OR 12 Aug 2015. SDG.

Fig. 6-53. Pyroplume over Cheyenne, WY, 11 Jun 2018. Jan Curtis.

6-7. Gallery

A bit more eye candy.

Fig. 6-54. 21 Unpolarized (left) and polarized views of a cumulus cloud street facing west from CCNY, Oct 2010. Polarized view shows distant clouds. SDG.

Fig. 6-56. Sea breeze front cumulus Boynton Beach FL 08 Feb 2014. SDG.

Fig. 6-55. 21 Cumulus reflections Fairfield Lake, NC 29 Sep 2023. SDG.

Fig. 6-57. Cumulus sampler. Ramsey, NJ 16 Oct 2010, Fort Lauderdale, FL 18 Dec 2010, Panama Canal 1 Mar 2017, Boynton Beach 18 Dec 2021. SDG