Fig. 13-1. Saucers over Cheyenne, WY, 09 Feb 2017. Jan Curtis

Fig. 13-2. Pile of plates lenticular clouds over Cheyenne, WY, 19 Jan 2019. Jan Curtis.

Fig. 13-3. Mayan Volcano with cloudy 'hat', 05:53 23 April 2019. Patryk Reba

Wonders of the Atmosphere
Chapter 13: Mountain Wave and Banner Clouds

Started 13Apr 2025

13.1 Flying Saucers are Mountain Wave Clouds

Fig. 13-4. Grand Canyon Altocumulus Lenticularis, 31 Mar 2010. SDG

Of all the patterned airflows that marshal clouds into waves, ranks, and rows, flying saucer altocumulus lenticularis (lentil or lens-shaped) mountain wave clouds (Fig. 13-1) stand out. Mountain wave clouds often form may form directly over a peak or ridge, downwind as series of lee waves (Fig. 13-2), and occasionally they may tilt upwind with height from from the peak. They can be models of smoothness and symmetry, as the cap cloud that forms over Mayan Volcano, as on 23 Apr 2019 (Fig. 13-3), so that from the photo alone it is near impossible from the photo to tell the wind direction. They are unique in that they hover in place, like a silent helicopter (Fig. 13-4), and often have an almost unchanging smooth form. Their smoothness (and uniform gradient of droplet sizes) also often turns their fringes iridescent when seen near the Sun (Chapter 14).

Though artists have portrayed mountain wave clouds for centuries, and though they are seen so often in favored places that they have earned longstanding nicknames (e. g., the Tablecloth over Capetown, South Africa, and the Taieri Pet SE of the long ridge of the Rock and Pillar Range in southeastern New Zealand) worldwide attention was riveted on them for the first time after a likely sighting on 24 June 1947. Experienced pilot, Kenneth Arnold labelled what he saw as 9 shiny Unidentified Flying Objects (UFO's) with saucer shapes apparently racing past Mount Rainier. Within two days newspaper reports suggested flying saucer space ships and the UFO craze was on. We cannot be sure if Kenneth Arnold did, in fact, see mountain wave clouds as astronomer Donald Menzel argued, but there is no doubt that saucer-shaped mountain wave clouds often form above and around Mount Rainier, and many other peaks.

Lenticular clouds form when stable air with humid layers is forced to ascend steep mountain peaks or ridges by fast winds aloft. The smooth appearance of the clouds shows that the flow is laminar, not turbulent, and is the proof that the air is stably stratified and has been forced to rise over the peak or ridge and then often continues oscillating on the lee side.

Mountain wave clouds appear at the height humid layers in the airstream arch above their condensation levels, for example, downwind of Mount Washington in New Hampshire (Fig. 13-5) as illustrated in Fig. 13-6. As the air rises above the condensation level, droplets or ice particles form. Once formed, the droplets and ice particles move with the wind and continue to grow while the air continues to rise (Fig. 13-7). Eventually, after passing the mountain peak or ridge, the air sinks and warms adiabatically, causing the droplets and ice particles to shrink and eventually evaporate.

Fig. 13-5. Concave, saucer-shaped lenticular clouds over Mt. Washington, NH. ©Al Saucier.

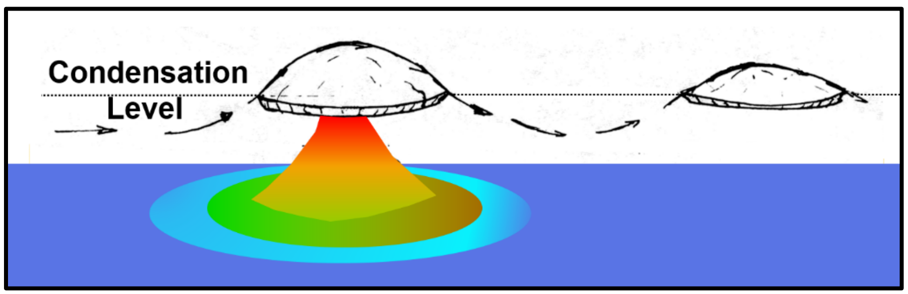

Fig. 13-6. Wave motions for saucer-shaped lenticular clouds over and downwind of isolated peaks. SDG.

Despite the strong winds, mountain wave clouds hover in place because they are fixed in place by the wavy flow pattern, which itself is fixed by the mountains.

What causes the wavy motion that produces trains of wave clouds on the lee side. They often occur when wind speed increases with height and static stability decreases with height. Like a swing that has been pushed too high, after the wind has carried the stable air over a peak or ridge, the air's excess density forces it to descend the lee (downwind) slope. The downward momentum carries the air below its original equilibrium level, where it is buoyant. This causes the air to rebound. Wave clouds fill each wave crest that rises above the condensation level and leave clearings in the troughs.

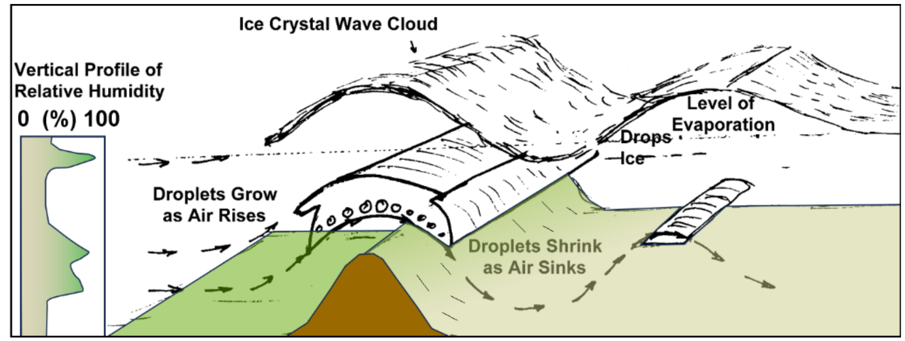

Fig. 13-7. Wave motions for cigar-shaped lenticular clouds over ridges. SDG.

Fig. 13-8. Train of long, wavy cigar-shaped lee wave clouds downwind from the long ridge of Schunemunk Mt, NY. SDG.

The shape of the wave cloud reflects the shape of the mountain and the humidity structure of the atmosphere. Trains of UFO shaped saucers form over isolated peaks (Fig. 13-5), while trains of long cigar-shaped clouds form over long mountain ridges, as over modest, 500 m high Schunemunk Mt., NY (Fig. 13-8). The oft cigar-shaped Taieri Pet, seen from above in the LandSat image of Fig. 13-9 forms downwind of the modest, but straight, escarpment of the long straight-ridged Rock and Pillar Range in southern New Zealand.

Fig. 13-9. The Taieri Pet, 07 Sep 2024, Middlemarch, New Zealand. Earth Observatory image by Lauren Dauphin, using Landsat data from the U.S. Geological Survey.

The shapes of the tops and bases of lenticular clouds depend on the vertical profile of humidity in the ambient air. When a thin layer of high humidity is embedded in an otherwise dry atmosphere, the cloud arches upward in center like an eyebrow and the base is concave, with a hollow look, as in Fig. 13-5. When humidity decreases gradually below the level where it is maximum, cloud base is convex and the cloud is lentil-shaped, as in Fig. 13-10.

Surprisingly often, the atmospheric column has a complex profile of alternating layers of humid and dry air (Fig. 13-7). The humid layers would remain invisible if they were not forced to rise. But when they are forced to rise, cloud veneers can stack up like piles of plates, as in Fig. 13-2 and Fig. 13-11, which reveals at least 12 humid layers. The Renaissance artist, Piero della Francesca, who lived amidst the Appenine Mountains, was the first to paint a pile of plates over the sky in San Sepolcro, Italy in his ***Baptism of Christ*** (1450).

Fig. 13-10. Lenticular Ac with convex base over Cheyenne, WY, 18 Jan 2020. Jan Curtis.

Fig. 13-11. Pile of Plates over Cheyenne, WY, 02 Nov 2019 with at least 12 alternating humid and dry layers. Jan Curtis.

Fig. 13-12.Thin lenticular Cirrocumulus with pronounced transverse waves over Cheyenne, WY, 21 Dec 2021. Jan Curtis.

Fig. 13-13. Altocumulus lenticularis undulatus over Cheyenne, WY, 27 Oct 2018. The waves are only visible at the fringes of the optically thick cloud but dominate the thin cloud at top. Jan Curtis.

The winds that race through mostly smooth, standing lenticular clouds, carrying the cloud droplets, ice particles with them, are revealed by irregular features resulting from variations of humidity, convection cells, thermals, or ripples due to transverse waves produced by wind shear, as in Fig. 13-12 and Fig. 13-13.

Fig. 13-14. Rippling becomes dominant as the mountain wave cloud over Cheyenne, WY, 24 Dec 2014 thins and dissipates. Jan Curtis.

It is likely that shear waves often ‘ride’ atop even smooth lenticular clouds but remain invisible or inconspicuous so long as the amplitude of the standing mountain wave and the cloud thickness are much larger. In the top frame of Fig. 13-14, transverse waves are visible only at the cloud fringes of the lenticular cloud over Cheyenne, WY on 21 Dec 2021 when it is optically thick, but increasingly dominate the main cloud as it thins and dissipates in the bottom frame. The dynamism is dramatized in the video,

https://www.flickr.com/photos/cloud_spirit/25791302405/in/album-72157682860359541

Still-life comes to life with time lapse videos. They show mountain wave clouds as if taking a stand, fighting to stay in place against the wind while the fine scale features and other cloud genera or species succumb to the wind and whiz across the sky and through the lenticular. In such situations, the videos, of which there are many at,

https://www.flickr.com/photos/cloud_spirit/albums/72157682860359541/with/44240106612

bring out the striking contrast between the upright lenticular clouds and all other fleeting cloud species and genera.

Fig. 13-15. Horizontal striations spin cyclonically around the periphery of the cylindrical wave cloud over Cheyenne, WY, 16 Oct 2020 . Jan Curtis.

For example, the video, starting at daybreak on 11 Dec 2024,

https://www.flickr.com/photos/cloud_spirit/54199111035/in/album-72157682860359541/lightbox/

begins with ripples traversing the length of elongated wave clouds. A few hours later, convection cells cross from one stationary wave cloud to a second but evaporate in the trough between them.

In the time-lapse video of 15 Nov 2021 over Cheyenne, WY,

https://www.flickr.com/photos/cloud_spirit/51681764842/in/album-72157682860359541

that compressed 30 minutes of real time into 10 seconds, horizontal striations and other irregular features could be seen rotating around the periphery of a cylindrical wave cloud, almost as if it were a tornado. A suggestion of the cyclonic rotation is seen by comparing the positions of the striations in the two frames from the video in Fig. 13-15.

The thin, horizontal gray striations, so prominent in Fig. 13-15 are seen quite often at the heights the lenticular clouds are widest. The relative darkness of the striations compared to the thicker main cloud occurs because most of the light entering a thin cloud veneer is scattered vertically. Only little light makes it through their width.

The time lapse video of the pile of plates over Cheyenne, WY on 19 Jan 2019 (Fig. 13-2) shows endless bands of cirrus racing across the sky while the mountain wave clouds stay more or less in the same place, pulsing, swelling, shrinking, appearing or disappearing according to the changes in ***RH*** over a range of heights and over a period of almost 3 hours. The end of the video shows a satellite video of the scene.

https://www.flickr.com/photos/cloud_spirit/46807241071/in/album-72157682860359541

Underlighting of lenticular clouds reveals structures normally masked or invisible during the day. Fig. 13-16 illustrates the simple situation when two humid veneers, embedded in an otherwise dry atmosphere are forced over an isolated, conical peak at twilight. In

Fig. 13-17, the cloud base has red rings that encase shaded concavities. Slightly right of center is an inner red ring revealing a second humid veneer below the main cloud.

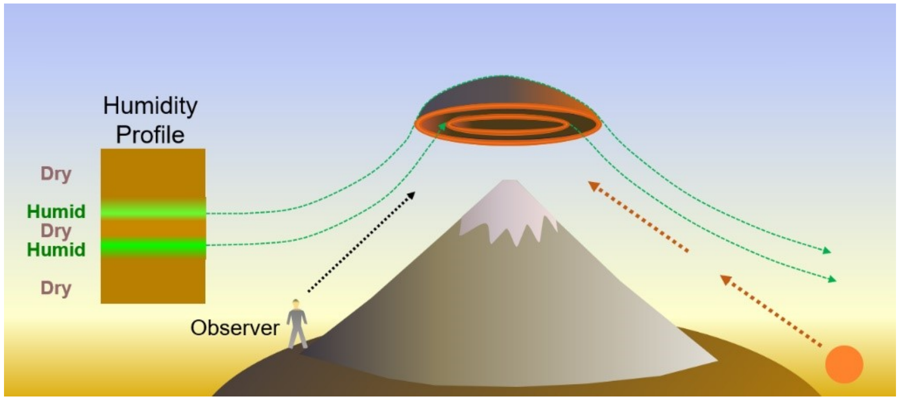

Fig. 13-16. Diagram of an underlit lenticular cloud over an isolated peak at twilight with two humid veneers in an otherwise dry atmosphere. SDG.

Nature sometimes provides even greater complexity.

Fig. 13-18 shows the lurid level of phantasmagoria that the undersides of lenticular clouds can attain at twilight if the humidity profile is complex and abrupt enough. This image, the Mother Ship of lenticular complexity (classified as asperitas because of its contorted base) was photographed by Witta Priester in the valley of Hanmer, NZ. The valley is enclosed by mountains on all sides with

Fig. 13-18. Under the Mother Ship of lenticular clouds at twilight at Hanmer Springs, NZ, 06 Mar, 2005. ©Witta Priester.

two narrow canyon opening for the Waiau Uwha River. The tortuous flow and cloud patterns follow from the complex topography of the Southern Alps, with ridges and valleys pointing in multiple directions, though with highest peaks to the NW. At the time, on 06

Fig. 13-17. Lenticular Ac underlit at twilight with concavities in the base revealing a second (donut-shaped) humid veneer over Cheyenne, WY. Jan Curtis.

Mar 2005, fast NW winds crossed the Southern Alps. Three hours before sunset the atmosphere was saturated through the entire troposphere. Around sunset time humidity began decreasing. That increased the probability of the distinct alternating dry and humid laminae needed to produce the fantastic underlit wave clouds.

Fig. 13-19. Screaming blood-red lenticular cloud, Cheyenne, WY, 11 Dec 2024, 13 minutes after sunset. Jan Curtis.

At twilight, underlit mountain wave clouds can turn as blood red as Edvard Munch suggested when describing the inspiration for his iconic painting, ***The Scream*** (see Fig. 15.xx). On 11 Dec 2024, the underlit mountain wave clouds over Cheyenne, WY turned 'screaming' blood-red a mere 13 minutes after sunset (Fig. 13.19).

Mountain wave clouds develop tails (Fig. 13-20) when the droplets that condense at the upwind side freeze inside the cloud. This is likely if the air in the crest of the wave cloud cools enough, typically, $\boldsymbol{T} \leq -30°C$. Once ice forms, it grows rapidly at the expense of the supercooled droplets (recall §4.3). The ice-filled tails then extend downwind and below the condensation level of supercooled water because ice does not begin to sublimate until the relative humidity with respect to supercooled water, $\boldsymbol{RH}_{\mathrm{LIQ}} <\approx 70\%$. On occasion, the tails persist through the troughs, revealing the entire wave pattern.

Fig. 13-20. Lenticular Ac with ice particle tails over Colorado Front Range. ©Robert Gedzelman.

The worst case is to get caught in the *rotor*, a giant, often invisible vortex on the downwind side of the mountain that can plunge unfortunate glider pilots into the ground like a huge breaking ocean wave can wipe out surfers. Why would anyone take such a risk? The answer: Fig. 13-21 though it was shot from a motorized plane. See the video,

https://www.youtube.com/watch?v=0j2LHdP1Gg0

The entire pattern of mountain wave clouds may be so large it can only be seen from space. Imposing trains of lee wave clouds often extend 200 to 500 km or more downwind from the Blue Ridge Mountains when strong northwest winds prevail during outbreaks of cold air, as on Stan's 80th Birthday, 23 Nov 2024 (Fig. 13-22). Some subtlety is involved in the formation of the lee wave clouds because a foehn wall formed on the upwind side of the Blue Ridge and skies remained clear downwind over Virginia on 16 Nov, 2024 despite similar vertical profiles of temperature, humidity, and wind on the two dates. Most likely, wind speed at ridge top (≈ 1 km) was too small to excite lee waves on 16 Nov (8 knots vs 20 knots on 23 Nov).

Fig. 13-21. The Taieri Pet in all its glory from the Air over the Otago region, NZ, 1630 NZST 29 Aug 2020. ©Geoff Beckett.

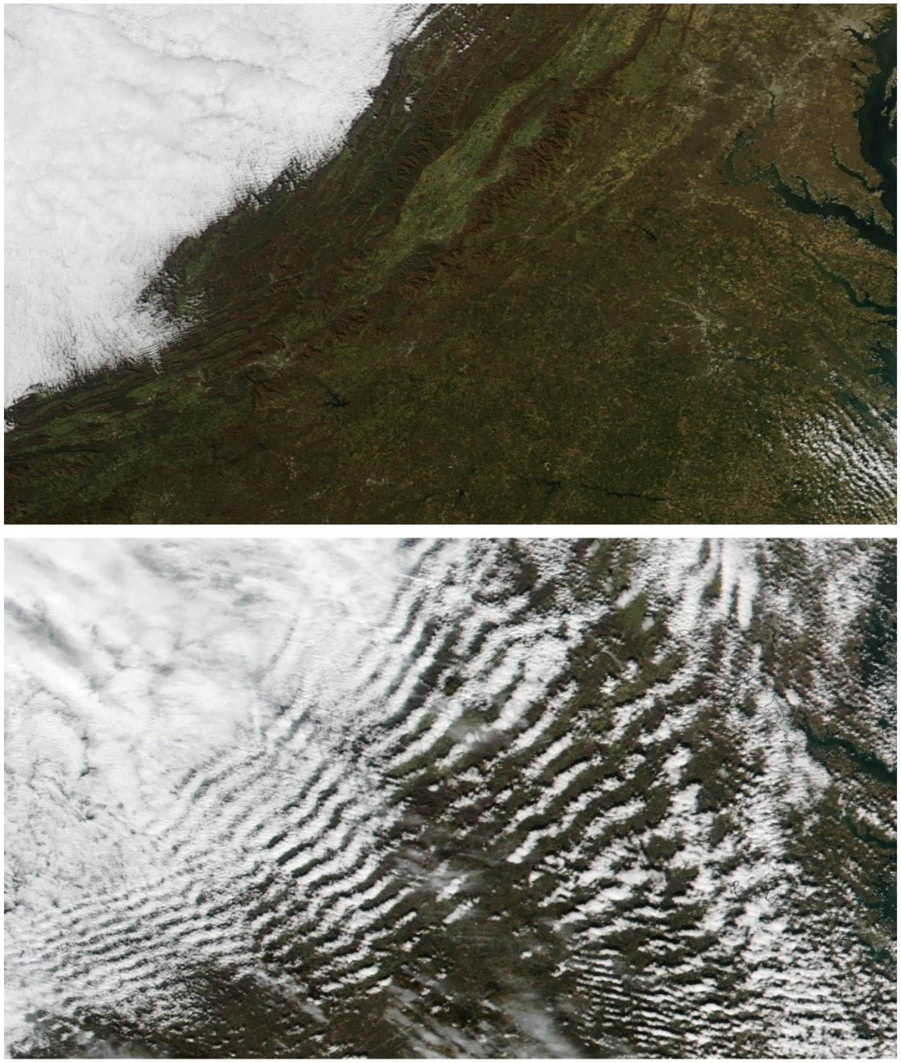

Fig. 13-22. **Clear skies east of the crest of the Blue Ridge Mountains of Virginia and West Virginia on 16 Nov 2024 (top, NASA AQUA image) vs. Lee Wave Clouds on 23 Nov 2024 (bottom, SUOMI VIIRS/NPP image).**

The Foehn Wall Cloud is a common sight on the lee side of long mountain ranges, such as the Andes over Argentina, the Sierra Nevada over Nevada, the Rockies over Colorado, the northern slopes of the Alps, and the Southern Alps of New Zealand to mention a few. Fig. 13-23 shows a Foehn Wall Cloud over the Presidential Range of the White Mountains in New Hampshire. No lee wave clouds formed in this case.

Fig. 13-23. Foehn Wall Cloud over the Presidential Range of the White Mountains, NH. No lee waves formed. SDG.

One reason why Foehn Wall clouds may form without lee wave clouds is illustrated by the contrast between the two panels of Fig. 13-24. In the top panel, when a thin, elevated humid layer surmounts the crest, droplets or crystals remain so small they move with the wind. On the lee side, the air rebounds after sinking, and clouds re-form at the same height they formed atop the crest. In the bottom panel a thick humid layer with a low condensation level ascends the upslope side. Droplets or ice crystals grow large enough to fall, collide, coalesce, and produce precipitation. This dries the air so that when it sinks after surmounting the crest, the remaining droplets and crystals evaporate and disappear at a greater height than they formed. Looked at from the lee side, where the descending air is hot, dry, and cloudless, the mountain will be capped by a foehn wall. Lee waves will still be produced in the oscillating air, but they will be cloudless because the new condensation level is higher than the wave crests.

Mountain wave clouds are not merely things of beauty. Glider pilots maintain an ongoing love affair with them because of the reliable uplift the standing waves provide. By using mountain wave clouds to locate updrafts, gliders have soared to heights of 15 km over the Rocky Mountains and over 8 km at Mount Washington in New Hampshire, in other words roughly 4 times higher than the peaks! But the pilots must avoid downdrafts or gain enough altitude before crossing them as quickly as possible.

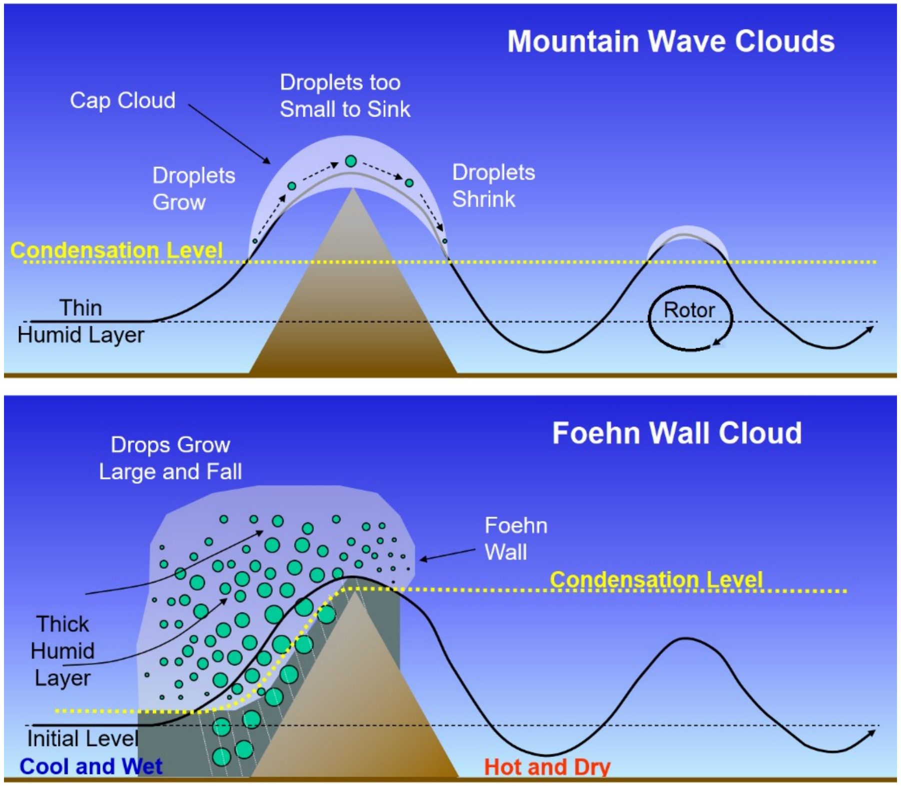

Fig. 13-24. Lee Wave Clouds (top) vs Foehn Wall Cloud (bottom), where precipitation dries the air so that lee wave crests remain below the elevated condensation level. A rotor may also occur with a Foehn Wall Cloud. SDG

13.2 Pileus Plus: Mountain Wave Cousins

Pileus, the cap cloud, is essentially a mountain wave cloud produced by a penetrative cloud instead of a mountain. The resemblance can be striking, as on 08 Oct at Granada, Spain (Fig. 13.25).It appeared to

Fig. 13-25. Pileus over cumulus Granada, Spain 08 Oct 2007. SDG.

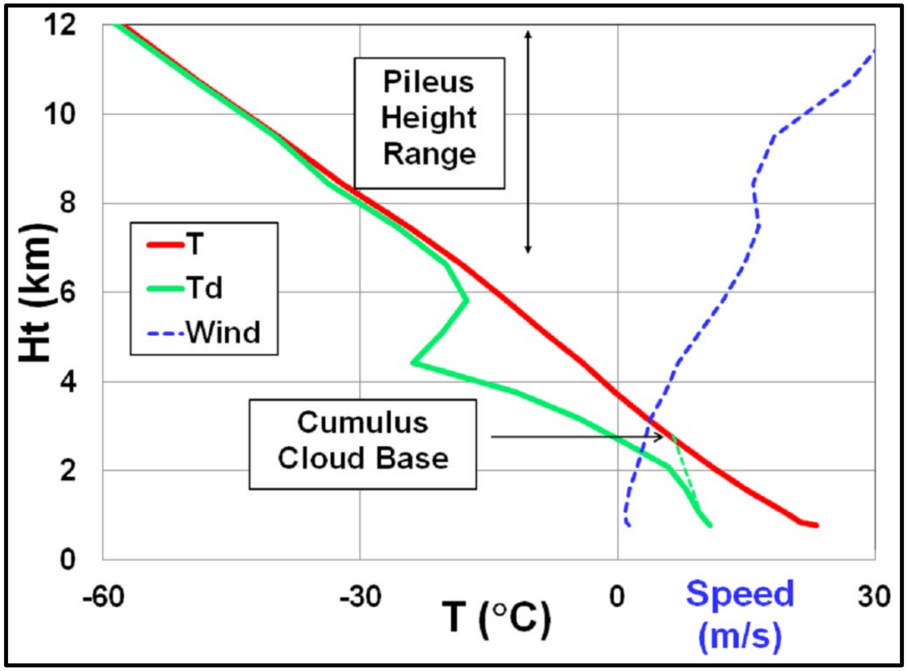

Fig. 13-26. Sounding at Granada, Spain 1500 UTC 08 Oct 2007. SDG.

be a pile of plates mountain wave cloud but the sounding (Fig. 13-26) showed that winds were almost calm below 4 km, well above the nearby peaks but increased atop the cumulus congestus in the almost saturated air above 6 km where the pile of plates pileus formed Thus, even though a rising cumulus or cumulonimbus is not as solid as a mountain it still acts as a solid barrier to the ambient air and a dynamic, rising one at that.

This dynamism has several consequences for pileus.

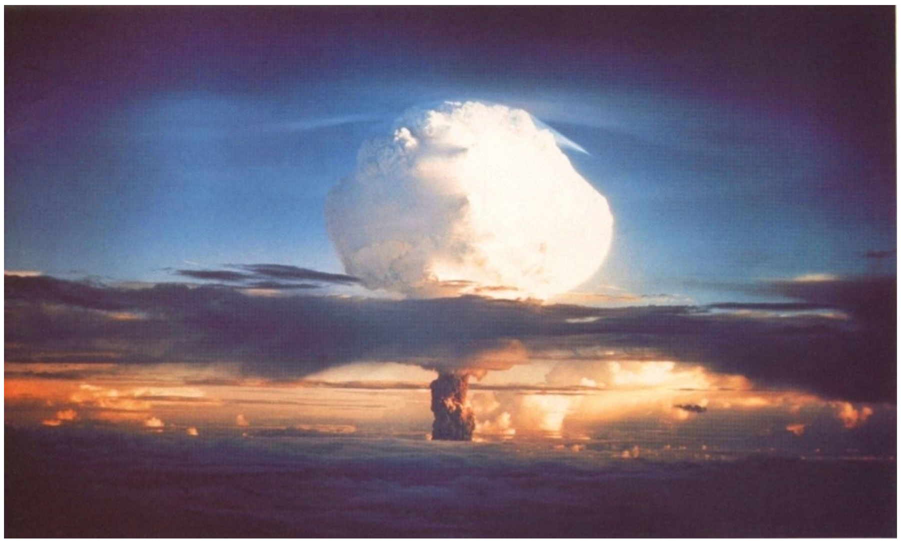

Fig. 13-27. Pileus above Ivy Mike's rising mushroom cloud, 01 Nov 1952. Charles Wyckoff, Public Domain.

1: The faster the updraft and the higher it rises, the more likely pileus will occur, and possibly at several levels. This connects pileus to some of the most awesome natural and anthropogenic phenomena in the atmosphere, thunderstorms, and the even more violent major volcanic eruptions and nuclear explosions.

The infamous mushroom cloud of the first hydrogen bomb, Ivy Mike (Fig. 13-27), which obliterated the atoll, Enewetak created a pileus on the way up and then wrapped in a skirt cloud with several veneers produced when air around the rising stem was forced to rise and entrained into the stem (Fig. 13-27) by Bernoulli's Principle, like your finger gets pulled into a water jet shot from a nozzle.

Fig. 13-28. Skirt clouds (velum) wrap the rising stem of Ivy Mike, 01 Nov 1952. Charles Wyckoff, Public Domain.

Perhaps the most ironic of all clouds is the halo-shaped cloud, produced by the pressure troughs of the explosive shock waves of the nuclear blasts. The Dakota device, detonated on 25 Jun 1956 produced the 'pile of halos' of Fig. 13-29. What irony that such an angelic looking cloud form was produced by such a diabolic device!

Clouds of explosive volcanic eruptions vie with nuclear mushroom clouds, so it is no surprise they produce the same attendant clouds.). A pileus (out of sight) and several skirt clouds dressed the rising shaft of Tonga's preliminary eruption cloud (Fig. 13-30) on 14 Dec 2022. Tonga's explosive, major eruption the next day produced a ring cloud seen from space. A closer view from pace opccurred when

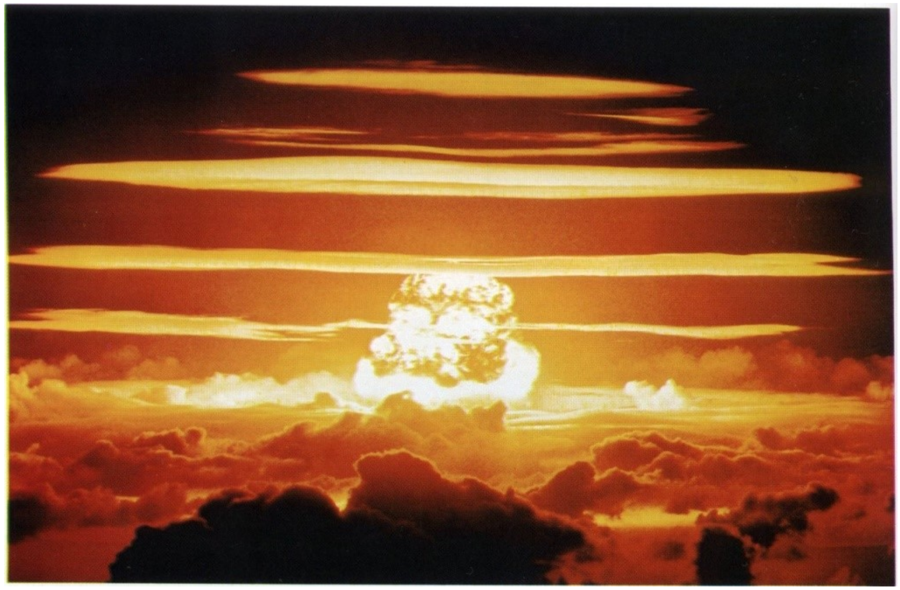

Fig. 13-29. Halo-like ring clouds produced by Dakota's blast, 25 Jun 1956. Public Domain.

Fig. 13-30. Skirt clouds Tonga Eruption, 14 Dec 2022. Tonga Geol Svcs,

a NASA satellite passed directly over Sarychek peak in Siberia just as the burgeoning volcanic cloud produced an arching pileus with a small spreading ring (Fig. 13-31).

Fig. 13-31. Pileus capping the ash cloud of Sarychev Peak 12 June 2009. A pyroclastic flow cascades down from the peak at bottom. NASA/JPL

All these features of nuclear and volcanic clouds are ilustrated and explained in the video,

https://www.youtube.com/watch?v=BMc8Tdr7Hcw

2: Pileus tends to be highly ephemeral, with a lifespan often of mere seconds and a few minutes at most. It forms as the rising cap of penetrative cloud impinges on and lofts the humid layer and evaporates once the cap has passed above the humid layer and the downdraft surrounding the cap causes the humid layer to sink. On occasion it survives and "change clothes" to a skirt cloud. which, as we have seen, forms when air is drawn into a rising plume.

Fig. 13-32. Humble cumulus humilis generates pileus over Louisville, KY, 18 Aug 2009 with ambient winds with slight left to right vertical shear. SDG

3: Unlike mountain wave clouds, pileus can appear without any ambient wind. All that is needed to produce pileus is a layer of air near saturation just above the rising cloud. Then, a cumulus humilis (Fig. 13-32), or even an altocumulus, or a generating cell of cirrus can produce pileus! Of course, violent clouds do this much more often.

We cannot leave the subject of pileus without again stressing the extraordinary paradoxical, contradictory contrast between the chaotically bubbling protuberances and violence of the parent mushroom clouds of nuclear explosions, explosive volcanic eruptions and thunderstorms, and the fleeting delicacy of the pileus they produce. A paradigm example is the translucent, gossamer thin double layered pileus over a rising cumulus congestus on 23 Aug 2022 at Cheyenne, WY (Fig. 13-33: recall Fig 6-32).

Fig. 13-33. Translucent Lenticular Cloud over rising cumulus congestus, Oracle, AZ 23 Aug 2022. Jan Curtis.

Fig. 13-34. Banner Cloud of Huayna Picchu, Peru. SDG.

Fig. 13-35. Banner Cloud of the Matterhorn, 27 Feb 2009. ©rac819 Flickr.

13.3 Banner Clouds

One more impressive cloud feature hangs from the lee sides of steep, towering, pyramidal peaks such as Mount Everest, Huayna Picchu in Peru (Fig. 13-34), the Matterhorn (Fig. 13-35), and the Durrenhorn (Fig. 13-36). That is the banner cloud that like a huge flapping flag, may extend up to a few km downwind from the mountain flag pole.

Fig. 13-36. Banner Cloud of the Durrenhorn. SDG.

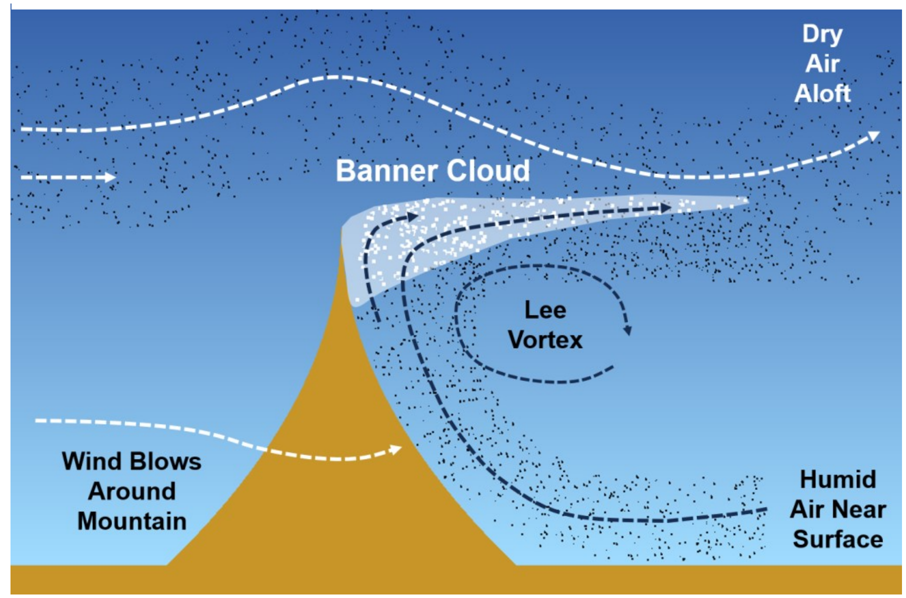

Fig. 13-37. Illustration of the typical situation leading to banner clouds. Fast winds aloft force a lee vortex with air rising up the lee slope. SDG.

As air flows over and around the peak, it creates low pressure on the lee side with a rotor-like vortex that are forces air to rise up the lee face of the peak (Fig. 13-37). Typically, but not necessarily, the humidity is high near the surface and decreases to low values aloft. If the air rises enough and is humid enough the banner cloud forms in the updraft hugging the peak. As the wind sweeps the banner cloud downwind, it mixes with the drier surrounding air aloft, gets diluted, and evaporates in a short distance.

It is perhaps appropriate to conclude this section by pointing out another irony. Most of the mountains that produce banner clouds owe their steep, jagged, pyramidal banner-producing shape to erosion by mountain-tearing glaciers. (Huayna Picchu is a geologically active exception.) And the glaciers owe their existence to different, storm clouds. Thus, with few exceptions, only after clouds have torn away at a mountain, is the mountain able to fly its banner cloud.

13.6 Gallery

Fig. 13-38. Colorado Front Range Lenticular clouds seen from Cheyenne, WY, 10 Jan 2025. Jan Curtis.

Fig. 13-39. Lee waves over Fairfield Lake, NC 22 May 2025.