Fig. 15-25. Georgia O'Keefe. *Sky Above Clouds IV*. 1965. Chicago Art Institute.

Artists, photographers, and the computer face fewer limitations than nature imposes and can modify or alter according to their whims. They can easily exceed the modest maximum values of the color purity of real rainbows, ice crystal halos, and sky color. The computers can be programmed to produce ranks and rows of altocumulus or cirrocumulus consisting of perfect linear sinusoidal or even circular wave trains; it can remove unaesthetic obstructions or irregularities, and eliminate haze, as in Fig. 15-26. It can include small irregularities that make it more difficult to distinguish image from reality, for example the wrinkles in the AI generated arcus cloud of Fig. 15-27. On the other hand, it can be programmed to be garish, for example, to make rainbows opaque, it can easily create monstrosities, or impossibilities that might seem at first glance to be natural to the uninformed, such as up-side-down cumulus. The cirrus and cumulus in the band on the left side of Fig 15-26 would match nature better up-side down. But there is no denying the beauty and impressive photorealism of the images already created using AI, as in

Fig. 15-26. AI generated scene with a sky of cirrus and cumulus that would be closer to nature up-side down. ©Ryan Allen.

the twilight towering cumulus of Fig. 15-28, and the rate at which the AI-generated images are improving.

Fig. 15-27. AI generated scene with arcus below a thunderstorm. In reality, the cloud brightens inside the arcus and may turn green. ©Ryan Allen.

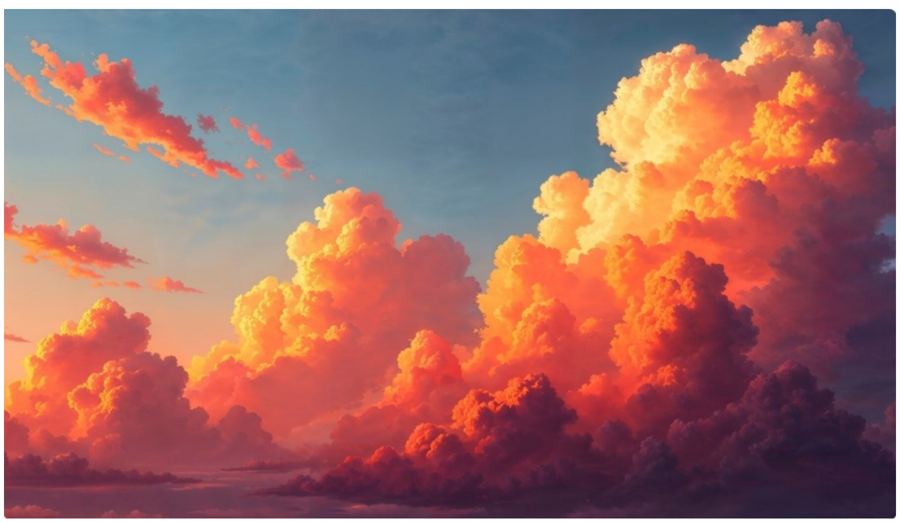

Fig. 15-28. AI generated scene of cumulus congestus at sunset. ©Freepik.

15.3 Complex Convective Skies

In much of ***Wonders of the Atmosphere*** we too cheated by selecting scenes with a single cloud species or optical phenomenon. In this final section we celebrate the atmosphere's complexity, and display scenes where two or more cloud species or optical phenomena occur simultaneously.

Focusing on a single cloud species or optical phenomenon was done in the name of simplicity. When the situation was appropriate we did treat aspects of the complexity. One example is hole punch clouds (e. g., Fig. 4-17 and Fig. 10-14), where jets pass through altocumulus clouds consisting of supercooled droplets and freeze some of the droplets to produce cirrus cloud cores. Halos in the hole constituted proof that the fall streaks consist of ice crystals, as in Fig. 11-15. Another example is the pile of plates lenticular wave clouds, which show that the atmosphere often consists of alternating layers of dry and humid air, for example in Fig. 13-2, Fig. 13-11, and other figures in Chapter 13. Pileus (§13.2) is similar to lenticular clouds though it is classified as an attendant cloud because it is produced by another cloud instead of by a mountain.

Animated satellite loops show that clouds flow out of tropical and extratropical cyclones and thunderstorms and evaporate. The clouds disappear but the expelled water vapor does not and this outflow is a major source of interspersed humid layers in the mid and upper troposphere.

In tropical cyclones, clouds of the main inner part of the storm circulate counterclockwise in the North Hemisphere, often around an open eye. At the same time, cloud bands at the storm's top outer edge are thrust outward and clockwise, sometimes with parallel streamers of cirrus acting as spokes, as with Hurricane Isabel (Fig. 15-29). As these cloud bands and spokes move out from the storm they mix with the drier environment, sink, warm adiabatically, and evaporate.

The same is true of mature extratropical cyclones. Clouds of the main storm spiral inward and counterclockwise while at the leading outer edge of the warm, moist conveyer belt, broad cloud bands are expelled and turn clockwise (antricyclonically) and primarily eastward as they join the jet stream. These upper cloud bands also tend to sink and evaporate after departing the storm.

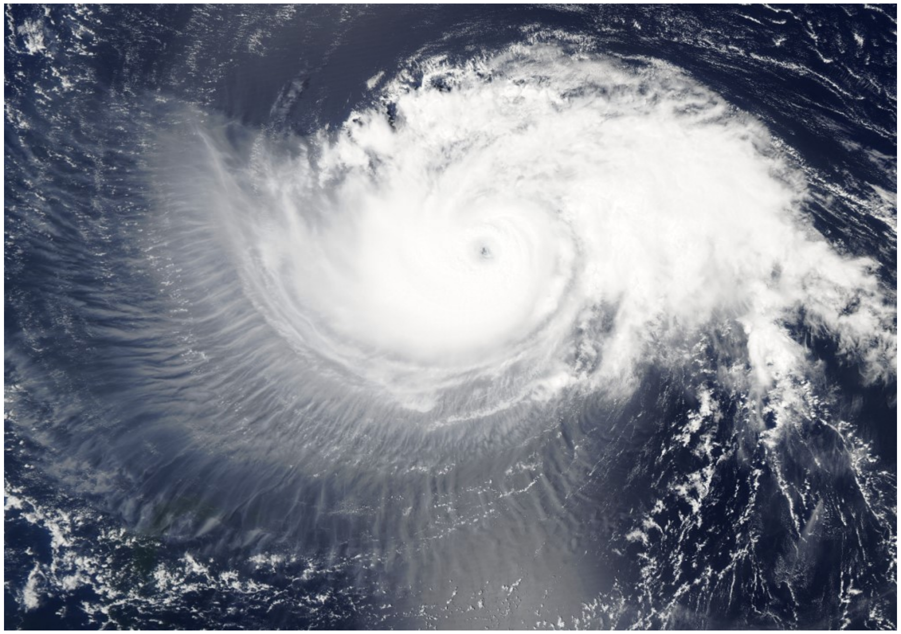

Fig. 15-29. Hurricane Isabel 10 Sep 2003 with Cirrus outflow. NASA AQUA.

Anvils are the exhaust plumes of thunderstorms. Day after day, and on into the night during summer thunderstorms burst up like popcorn. The anvils spread and ultimately evaporate. Since thunderstorms are much smaller than the cyclonic storms, this can often be viewed from the ground. Often, the outer edge of the spreading anvil simply thins and evaporates but at times it frays into individual streamers of cirrus, as in Fig. 7-1 or fractures into altocumulus or cirrocumulus, as in Fig. 15-30. Many thunderstorms die from the bottom up, with the anvil the last remnant to fragment and disappear, as in Fig. 15-31. Sometimes, cloud bands are thrust out of the anvil like pulsed waves, as in Fig. 15-32.

Fig. 15-30. Spreading anvils from distant thunderstorms fraying into altocumulus and cirrocumulus over Cheyenne, WY, 06 Jun 2019. Jan Curtis.

Fig. 15-31. Anvil remnants fraying into altocumulus with a cumulonimbus behind 22 Jun 2023 over Cheyenne, WY. Jan Curtis.

Skies become more complex when multiple thunderstorms form in an area. Updrafts at the leading edge of the outflow boundary below mature thunderstorms often kindle new thunderstorm nearby. The new thunderstorm is likely to rise into the anvil of the old storm, as in Fig. 15-33. When several nearby thunderstorms pop up, their spreading anvils may overlap, and get woven into a cover of high clouds that new thunderstorms rise into, as in Fig. 15-33 where two new thunderstorms are rising into the edge of an altocumulus sheet that formed from the merger of several anvils.

Fig. 15-32. A banded anvil, Cheyenne, WY, 14 Aug 2021. Jan Curtis.

5.4 Multi-level Clouds: The Time Lapse View

The water vapor expelled from the tops of storms can move invisibly for hundreds or even thousands of kilometers before condensing once again into visible clouds. Two cooling processes make clouds reappear in the mid and upper troposphere – adiabatic cooling in rising air and radiative cooling.

Radiation can either heat or cool humid layers in the mid and upper troposphere. Water vapor emits and absorbs radiation with much higher efficiency than dry air. At night when the ground is cold, humid layers emit infrared radiation more rapidly than they absorb it from the ground and can cool faster than 1°C/hr. As a result, much cirrus and many patterned cloud sheets form overnight, and are seen most frequently early in the morning. Conversely, when the Sun is high in the sky and the ground is hot, humid layers aloft absorb radiation more rapidly from the ground (and to a lesser extent directly from the Sun) than they emit it. This heating occurs without any uplift, as opposed to air at ground level, which rises buoyantly (and cools adiabatically) when heated. As a result, upper level clouds tend to evaporate during the heat of the day though they may reform late toward evening as the ground cools.

Fig. 15-33. A thunderstorm rising into cirrus at anvil edge of an older thunderstorm. Cheyenne, WY, 04 Aug 2023. Jan Curtis.

On average, infrared radiation cools the mid and upper troposphere at ≈ 1°C per 24 hours, and thin, humid layers can cool much more rapidly. Because $\boldsymbol{T}$ of rising air cools adiabatically 8° more per km than $\boldsymbol{T}_d$, for every 8°C of radiative cooling in a humid layer, the condensation level drops 1 km.

Fig. 15-34. Two thunderstorms poking up into a sheet of cirrocumulus from older thunderstorms. Cheyenne, WY, 12 Aug 2017. Jan Curtis.

Clouds will reform once the humid air rises to the new condensation level. Contrails can spread out and morph into clouds without requiring air to rise because they bring air to saturation by injecting water vapor.

On the morning of 23 Oct 2023, atmosphere humidity was high enough between 7 and 12 km over much of the SE United States so that the sky was laced with cirrus and a web of contrails. The contrails that formed over Fairfield Lake, NC (Fig. 15-35) spread into altocumulus bands consisting of supercooled droplets near the bottom of this layer where $\boldsymbol{T} > -20°C$ and cirrus streamers consisting of falling ice crystals higher in the humid layer where $\boldsymbol{T} < -40°C$.

At intervals of several days, middle and high clouds grace the rainless summer skies on the eastern side of the subtropical highs. The clouds occur when disturbances in the mid and upper troposphere with wide bands of ascending, humid air pass through the highs. The resulting cirrus or patterned cloud sheets stand out visually because the air below the clouds down to the surface boundary layer is dry and almost always pure (except during forest fires). Along the coast, fog or fractostratus produced over the cold waters adds to the picture.

Fig. 15-35. Cirrus and altocumulus spread from contrails over Fairfield Lake, NC, 23 Oct 2023. SDG.

Such was the case at San Mateo, CA on 02 Sep 2013 shortly before sunset. Altocumulus at 7 km formed above altostratus at 5 km at the same time fog poured from the cold ocean over the Coast Range and shredded into fractus over the warmer land (Fig. 15-36). The fractus and lower sheet of altocumulus have begun to assume orange and gold sunset colors. Half an hour later (not shown here), the altostratus fragmented into altocumulus and turned blazing orange while the higher altocumulus remained white.

Broken sheets of stratus or stratocumulus often occupy the surface boundary layer at high latitudes and over cold polar waters, and persist at all hours of the day or night. Mid and high level clouds help beautify such skies. On the afternoon of 03 July 2008 altocumulus

Fig. 15-36. Altocumulus above altostratus with fog and fractostratus below at San Mateo, CA, 02 Sep 2013. SDG.

Fig. 15-37. Altocumulus above fractostratus at Tromsø, Norway, 03 Jul 2008. SDG.

stratiformis passed over Tromsø, Norway while a broken deck of stratus occupied the boundary layer (Fig. 15-37).

Inland from cold waters and over land that is not covered by snow, early morning fog and low stratus burn off and are replaced by growing cumulus clouds, which take their turn sharing the sky with evaporating remnants of mid and upper clouds.

In complex, chaotic skies it is not always easy to disentangle different cloud species and heights. In these cases, videos not only add drama and dynamism, they provide a sense of depth that makes it easy to distinguish the different cloud species. This is especially true when the speed and direction of the wind change with height, carrying the clouds with it.

Fig. 15-38. The moment of a cold front passage at Cheyenne, WY on 05 July 2023. Altocumulus and cumulus are easy to distinguish in a video. Jan Curtis.

This was the case for the sky over Cheyenne, WY late on the afternoon of 05 July, 2023 (Fig. 15-38). A glance at the photo might well give the impression that there is only one cloud species. But the video from which the photo was extracted,

https://www.flickr.com/photos/cloud_spirit/53025445108/in/album-72157665379832755/

shows that there are two species moving in two different directions. The bright, optically thin sunlit clouds, which move from left to right and toward the camera (from the SW) are altocumulus. The dark cloud is a broken line of shaded cumulus that moves from right to left (from the N) and marks the leading edge of a cold front.

It would be difficult without the video,

https://vimeo.com/173004483

to unravel the baffling complexity of the chaotic sky over Cheyenne, WY on 30 June 2016 (photo not shown here). The video makes it easy to identify the constantly changing cloud species and genera which appear at three or more heights Not only that, but it reveals that the highest clouds move from the NW, the mid-level clouds from the S, and the low-level clouds from the E.

And it would be almost impossible to recognize two clashing outflow boundaries amid the general cloudiness (photo not shown) without the video,

https://www.flickr.com/photos/cloud_spirit/24606595334/in/album-72157665379832755/

Recall that Jan has produced 1000+ time-lapse videos, many of which show clouds at different levels moving at different speeds and directions. These are available at

https://www.flickr.com/photos/cloud_spirit/albums/72157664743046092/with/25094176990

5.5 Complex Clouds and Optics

Time lapse videos are always informative but photos do just fine when skies are photogenic,. We conclude this book with a sampling of skies with various combinations of clouds and optics.

Fig. 15-39. Cirrus uncinus with cumulus humilis emerging from the surface haze layer over Spring Valley, NY the day after a cold front. SDG.

Fig. 15-40. Cirrocumulus and cumulus Cheyenne, WY, 31 Mar 2020. Jan Curtis.

Fig. 15-41. Cirrocumulus and Altocumulus over Cheyenne, WY, 01 Nov 2018. Jan Curtis.

Flying over Spring Valley, NY a day after a summer cold front, left no doubt about the different heights occupied by cumulus and cirrus (Fig. 15-39). The tops of cumulus humilis that formed in the hazy surface boundary layer poked up into the clear, dry air above. At the same time a band of cirrus uncinus with distinct comma-shaped trails traversed the deep blue sky above.

Throughout the year, the dry and clean atmosphere over the western United States (when there are no wildfires) provides an excellent setting to showcase all cloud forms, and helps highlight differences when distinct cloud species share the sky. And, during the cold time of year over much of the USA, when thunderstorms take a break from their summer dominance of the sky, and jet stream winds often zoom overhead, middle and high clouds are much more likely to dominate the sky and reveal themselves in all their glory.

Fig. 15-42. Cirrocumulus stratiformis undulatus and altocumulus stratiformis over Cheyenne, WY, 05 Jan 2019. Jan Curtis.

Fig. 15-43. Altocumulus lacunosis above stratocumulus lenticularis with fractocumulus on left over Cheyenne, WY, 11 Feb 2019. Jan Curtis.

On 31 Mar 2020 it was easy to distinguish both form and height of the cumulus humilis and cirrocumulus over Cheyenne, WY (Fig. 15-40). On 01 Nov 2018, it was more difficult to discern the smaller difference in height between the cirrocumulus that dominated the sky over Cheyenne and the altocumulus on the right on but the difference in form was unmistakable (Fig. 15-41).

Fig. 15-44. Twin anvils tower behind stratocumulus cloud streets at Jaraíz de la Vera, Spain, 15 June 2008. SDG.

This was also the case on 05 Jan 2019 (Fig. 15-42), where the cirrocumulus contained ripples oriented in several directions, much as the ocean contains complex wave trains from various directions.

The cloud complex of 11 Feb 2019 over Cheyenne, WY (Fig. 15-43) formed under high wind conditions. Shear waves crossed by cirrus-type streamers in the partly glaciated altocumulus added to the lacunar appearance of the altocumulus. Closer to the ground the line of stratocumulus (note the smooth tops of the cells at the left of the line) resulted from an intertwining of surface heating and laminar lee wave flow.

Similar intertwining of laminar and convective flow occurred on the morning of 15 June 2008 over Jaraíz de la Vera, Spain, with strong

Fig. 15-45. Altocumulus undulatus shaded by higher altostratus Cheyenne, WY 18 Mar 2018. Jan Curtis.

west winds crossing the ridge line of the Sierra del Grados. Cirrus and cirrocumulus formed in a humid layer between 7500 and 8500 m with $-26 \leq \boldsymbol{T} \leq -33°C$ above a broken sheet of stratocumulus stratiformis in a separate humid layer between 3000 and 4400 m. Over the next two hours the air aloft dried and the upper clouds disappeared while the stratocumulus morphed into asperitas with aligned rows and large-amplitude, smooth, wavy bases. The tops also smoothed, indicating laminar lee wave flow capped by a stable layer except in the few places where thermals had enough buoyancy to burst through the stable layer into tops that resembled anvils (Fig. 15-44).

Overcast, gray skies can be alluring when cloud bases are distorted such as arcus or asperitas, or when multiple cloud layers can be distinguished. When altostratus and/or cirrostratus cover the sky lower clouds appear dark because they are shaded. On 18 Mar 2018 at Cheyenne, WY, strong vertical wind shear produced altocumulus undulatus in a humid layer beneath a cover of altostratus and color was added to the scene as the setting Sun broke through near the horizon (Fig. 15-45). On 07 Mar 2019 unusual spots of fractocumulus resembling gray chicken pox were darkened by a cover of altostratus (Fig. 15-46).

Fig. 15-46. Altostratus with shaded and darkened fractocumulus at Vail, AZ, 07 Mar 2019. Jan Curtis.

Fig. 15-47. Altostratus with cumulus below and shadows of Ci above at Cliffside Park, NJ, SDG.

Sometimes higher clouds such as cirrus may return the favor by casting shadows and darkening a sheet of altostratus below, as at Cliffside Park, NJ (Fig. 15-46), where the optically thin altostratus, reddened by the setting watery Sun in turn shaded an opaque fractostratus below, turning it almost black.

Fig. 15-48. Red-based cumulus Alcázar de San Juan Spain 16 Jun 2008. SDG.

Clouds sometimes exhibit unusual colors in the middle of the day. Optically thick cumulus clouds have gray bases almost everywhere except regions like the plains of La Mancha, Spain (the country of Don Quixote). There, on days of scattered clouds, optically thick cumulus clouds typically have reddish bases because a significant fraction of their light is reflected from the sunlit red earth below (Fig. 15-47). This is also the case in other dry regions with largely bare red iron oxide rocks or soil, such as Australia's Great and Little Sandy Deserts. Les Cowley mentioned that cumulus bases over extensive fields of yellow-blooming soybeans are tinted yellow.

On rare occasion, overcast skies grade from gray above to blue near the horizon. A blue horizon cloud base appeared to the SW down the Sognafjord from Skjolden, Norway late on the afternoon of 06 July 2008 (Fig. 15-48). A few hours earlier skies had been clear. The most likely source of this unusual blue color was blue skylight reflected off the nearby glaciers from still clear skies ≈ 50 km to the NW.

Fig. 15-49. Blue overcast horizon over Sognefjord, Skjolden, Norway 06 Jul 2008. SDG.

15.6 A Final Search

When the sky sports several different cloud species or genera, it raises the possibility that several different optical phenomena will appear. For example, anticrepuscular rays cross rainbows (at 90°) when cloud fragments are situated so that they shade parts of sunlit rain shafts (recall Fig. 9-54).

It is fitting to conclude with a search that might seem simple but has proven to be quite elusive. It is not too unusual to see a sky with both water droplet and ice crystal clouds such as altocumulus and cirrus or cirrostratus at the same time. That makes it reasonable to expect to see coronas or iridescence and halos at the same time. But that combination turns out to be quite rare.

Fig. 15-50. Neighboring bands of opaque altocumulus and cirrus streamers over Suffern, NY 02 Dec 2011. Alas, sans optical phenomena. SDG.

We have already stated the conditions necessary for brilliant coronas and halos. For both, clouds must be optically thin, i. e., translucent. Multiple scattering, which is almost invariably incoherent, kills any optical phenomenon that must pass through opaque clouds.

For brilliant coronas and iridescence, droplet size along a sunbeam must be almost constant because the scattering angle is highly size dependent. Wave clouds fit this requirement best; droplet sizes in convective clouds range from near zero at cloud base to near maximum at cloud top. This always holds for penetrative convection and generally for gentle cellular convection.

For brilliant halos, crystals must be pristine and large. So-called garbage crystals that consist of rimed particles, etc., produce random scattering. Crystals' effective diameter must also be larger than about 100 μm so that diffraction does not seriously vitiate geometric optics.

Fig. 15-51. Cirrus and cirrocumulus over Vail AZ 05 Dec 2018. Jan Curtis.

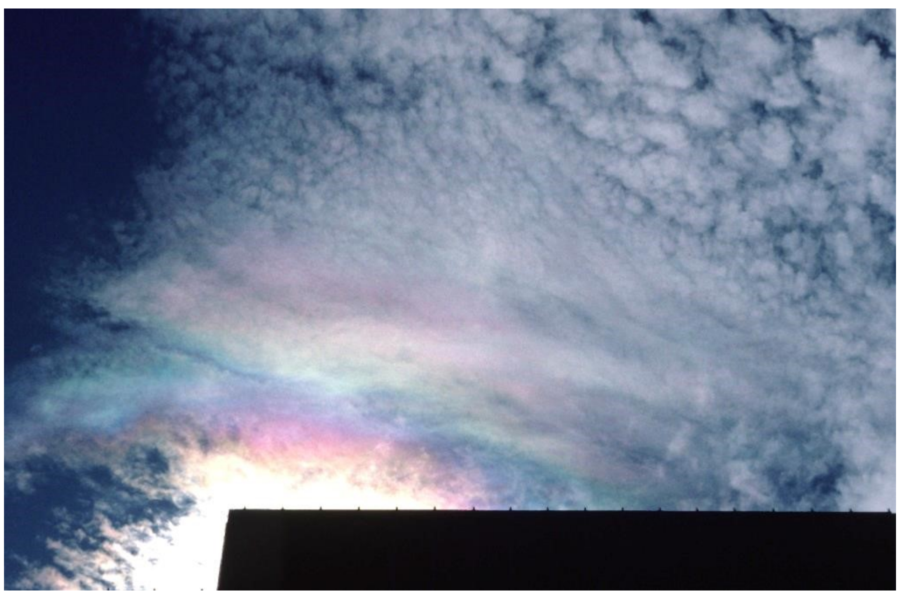

Fig. 15-52. Iridescence only in fibrous part of altocumulus over NYC. SDG.

It is not unusual to see a sky with both cirrus and either altocumulus or cirrocumulus, but each of these produce optical phenomena only a small fraction of the cases for brief times. On 02 Dec 2011 parallel bands of opaque cirrus streamers lined up side-by-side with opaque bands of altocumulus to cover much of the sky over Suffern, NY (Fig. 15-49) but with nary a hint of either optical phenomenon. On 05 Dec 2018, somewhat more delicate cirrocumulus and cirrus shared the sky over AZ (Fig. 15-50), but again with no optical phenomena.

Hole punch clouds seem to offer the best possibility to produce both coronas and halos since they are in effect a combination of altocumulus and cirrus. Of course, the cirrus-filled holes must be in the proper place with respect to the Sun. Thus, the parhelion in Fig. 11-15 did not appear until the hole moved to the same height in the sky as the Sun and 22° to its right. When the hole moved away the parhelion vanished.

Unfortunately for coronas and iridescence, almost all holes form in altocumulus stratiformis opacus, with closely packed convection cells, a lethal combination for coronas. In more than 60 cases of hole punch clouds, many with holes near the Sun, Stan has never seen anything more than the faintest hint of iridescence. That was true for Fig. 11-15. Before, during, and after the time the parhelion flared no hint of a corona or iridescence appeared in the water droplet altocumulus clouds that surrounded the hole. As a result, it is extremely unusual for coronas or iridescence to appear in them.

Most cases of beautiful coronas or iridescence occur in optically thin clouds or cloud edges that have ripples or waves, and/or resemble translucent veils. One afternoon, a sheet of altocumulus stratiformis consisting mainly of closed cells but with one small optically thin veil-like patch passed over the skyscrapers of midtown Manhattan. There was no iridescence but since the veil was drifting slowly toward the Sun, the hope of seeing iridescence was well worth the ten minute wait, all the while every other Manhattanite raced about his or her business never glancing up and therefore, oblivious to the blazing opal in the sky (Fig. 15-52).

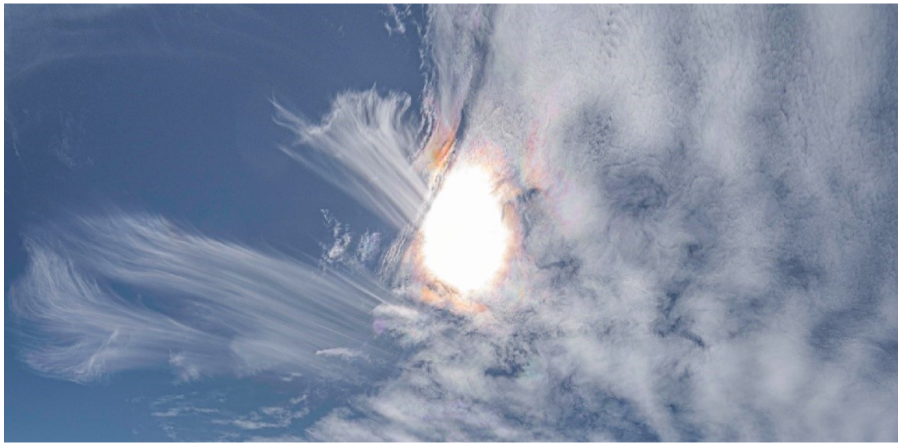

Fig. 15-53. Cirrus and cirrocumulus with corona, Vail AZ, 20 Feb 2020. Jan Curtis.

There are also times when both cirrocumulus and cirrus appear together that a corona lights up in the translucent wavy cirrocumulus but no halos appear in the cirrus, as on 20 Feb 2020 over Vail, AZ (Fig. 15-53). A short time later, after the corona disappeared, faint halos did appear in the cirrus.

Fig. 15-54. Iridescent cirrocumulus and parhelion in cirrus in jet stream over Boynton Beach, FL 08 Jan 2010. SDG.

One promising weather situation for dual optical phenomena in Boynton Beach FL, where Stan spends winters, occurs during the days following cold fronts when long bands of jet stream clouds pass overhead in otherwise crystal clear skies. These clouds are mixtures of cirrus and altocumulus or cirrocumulus. Sometimes, hole punch clouds form in them. At other times, particularly when the clouds are translucent, a corona or iridescence appears. If there are cirrus streamers at the same time, halos may also appear.

For a few brief moments on 08 Jan 2010 iridescence flared in a patch of a cirrocumulus near the Sun the same time a faint parhelion formed in cirrus streamers a little more than 22° to its right (Fig. 15-54). This was a rare find, one that Stan has seen a handful of times, but we need something extraordinary to end a book on the Wonders of the Atmosphere.

Brent Mckean, a nature photographer who specializes in the aurora among other phenomena recognized the extraordinary on a frigid night (most likely) 12 February 2020 near the time of the full Moon (09 Feb).

> "That night was extremely cold and it was roughly 4:30 in the morning, I was on my way to Winnipeg. I usually carry my camera and tripod with me wherever I go, just in case. I had to get out of the car and capture this right away because when you see something rare like that, it could come and go…. A few minutes later, from a field just off the road to work, the halo and arcs had disappeared, the sky had returned to normal -- with the exception of a single faint moon dog."

What Brent saw and photographed in Fig. 15-55 was a brilliant halo complex with a colorful, multi-ringed corona inside it formed around the Moon. The halo complex included the 22° halo, much brighter upper and lower tangent arcs (implying horizontal pencil crystals), as well as the paraselenae (moon dogs) and the parselenic circle (implying horizontal plates) just outside the halo. Matching the angular size of the corona with the Lee Diagram (Fig. 14-25) indicated droplets or near spherical ice particles with radius 10 µm.

A few days after the full Moon, on the early morning of 12 Feb, the temperature, $\boldsymbol{T} \approx$ -26.5°C, was perfect for a mix of ice and supercooled water radiation fog. No distinct cloud or fog was visible, in the blue moonlit sky so its optical thickness had to be very small, and indeed, stars and/or diamond dust ice crystals could be seen.

Fig. 15-55. Halo complex around multi-ringed corona over Manitoba, 12 Feb 2020. ©Brian Mckean.

And just as fast as this thin fog congealed it dissipated. Beauty is too often so fleeting.

With this extraordinary photo we come to the end of the ***Wonders of the Atmosphere***. While we (and many others) continue the endless search it remains for us to point out that.

When the sky's the limit there is no limit.

First rough draft of book completed 09 Aug 2025, second draft 12 Sept 2025.