
**Fig. 4-1. Growing Cumulus Congestus Cheyenne, WY 01 Jun 2025 2000 UTC. Cumulus clouds are blobs of buoyant, rising air, which when large have bright cauliflower tops and dark, shaded flat bases at the level condensation begins. Jan Curtis.**

**Fig. 4-2. Cirrus uncinus over Vail, AZ at sunset 15 Nov 2022. Cirrus are trails of falling ice crystals twisted by the wind. Jan Curtis.**


**Fig. 4-3. Stratus opacus, Gstaad, Switzerland, 20 Aug 2007. SDG. Stratus clouds are layers of rising or cooling air that cover most or all the sky and turn it gray.**

# Wonders of the Atmosphere
# Chapter 4: Clouds and Fog: Composition and Forms

Started 25 July 2024

## 4.1 The Composition of Clouds

Clouds exhibit wondrous varieties of forms, colors, lighting, shade, and occasional awesome appearance. In Fig. 4-1 blobs or buoyant rising air produce a flat-based, cauliflower topped cumulus congestus. In Fig. 2, cirrus clouds, trails of falling ice crystals twisted by the wind, reflect the colors of sunset. In Fig. 4-3, stratus opacus, a layer cloud of rising or cooling air, covers the sky and turns it gray.

With all this show of wondrous variety it remains that clouds (and fog) are simply assemblages of tiny water droplets and/or ice particles that block our vision in a region of the atmosphere.

**Fig. 4-4. Droplets are spheres, even when they hang on a spider web. SDG.**

Cloud droplets are spheres (my dears), not tears. Drops are only tear-shaped when they adhere to a surface such as your skin. Otherwise, droplets in mid-air and even droplets that condense on insects or on spider webs (Fig. 4-4) are almost perfect spheres.

Cloud droplets, drizzle drops, and raindrops form a trio based on size. Cloud droplets range up to 100 µm in diameter but are typically between 10 and 20 µm in diameter. Drizzle drops range between 100 and 500 µm. Raindrops, range between 500 µm and about 5000 µm or 5 mm. Thus, raindrops are typically about 50 to 100 times wider than cloud droplets, much as most insects' compound eyes are typically about 50 to 100 times wider than the tiny pixel lenses that make up their eyes.

How much do cloud droplets weigh? Of course, that depends on their size. A single gram of water in a cloud would consist of 240 million cloud droplets 20 µm in diameter, or, because volume is proportional to the cube (third power) of the diameter, that gram would consist of 1.92 billion droplets 10 µm in diameter.

How much do clouds weigh? The typical liquid water density in clouds ranges from 0.1 to 1 $g/m^3$ or from 100 to 1000 kg of liquid water per cubic kilometer, which is a typical volume of a small cumulus cloud (which would consist of 240 million droplets).

Why don't clouds fall? The fall speed or terminal velocity of a droplet 20 µm in diameter is about 1 cm/s or 0.02 mph. Thus it would take 50 hours for a droplet 20 µm in diameter to fall a mile below cloud base, and long before that the droplet would have evaporated and most clouds would be long gone.

Large cloud droplets 100 µm in diameter fall about 25 cm/s, which is fast enough to fall from the cloud and possibly reach the ground, It is also fast enough to fall on smaller droplets and join or coalesce with them, much like large droplets sliding down a foggy bathroom mirror coalesce with smaller, stationary drops in their path. Coalescence is one of the processes by which cloud droplets grow to raindrop size.

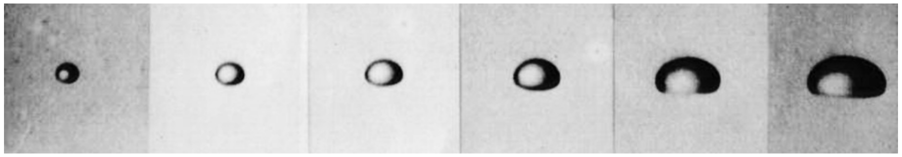

**Fig. 4-5. Raindrop shape vs size from 1.35 to 4 mm. ©Pruppacher and Beard.**

Small drops are spheres because they are held tightly by surface tension and because a sphere has the smallest surface area per volume of any shape. Surface tension is a small-scale force that is less effective for larger raindrops, which also fall faster. Drops larger than ≈ 280 µm in diameter begin to flatten on bottom (Fig. 4-5). Drops larger than about 3 mm in diameter are so flattened they resemble hamburger buns and they also distort, wobble, and break, much like large soap bubbles break, especially if two collide.

Ice particles in clouds come in a wondrous variety of shapes. Some are cloud droplets that have frozen. Droplets that collide with ice crystals often stick and freeze in a process called riming. Some are crystals, which are hexagonal in the form of flakes, plates, pencils, needles, bullets, etc. (Fig. 4-6). They may be quite narrow but can exceed 1 mm in length. A typical fall speed for crystals in clouds is about 0.5 m/s or 1 mph. That is much faster than typical cloud droplets fall and is why crystals fall out of clouds, leaving long trails.

**Fig. 4-6. A sample of ice crystal forms. https://www.snowcrystals.com/ ©Ken Libbrecht.**

The fact that you can walk through a fog and jets can fly through clouds proves that clouds are not solid objects even though they may appear solid from a distance. In a typical cloud, droplets or crystals occupy less than 1 millionth of the volume. And, because most cloud droplets are so tiny that they are passively swept along with any gentle air currents it is possible to walk through a cloud or fog (a cloud touching the ground) without getting wet.

## 4.2 Light and Colors of Clouds

Many clouds seem solid when viewed from afar because they reflect light as well as or better than most solid objects. The fraction of light that is reflected is called the *albedo*. Thick clouds have an albedo up to 90%, much like snow. The albedo is about 15% for forests, 5 - 15% for most rocks, 45% for dry quartz sand, but only about 5% for bodies of water unless the Sun is near the horizon

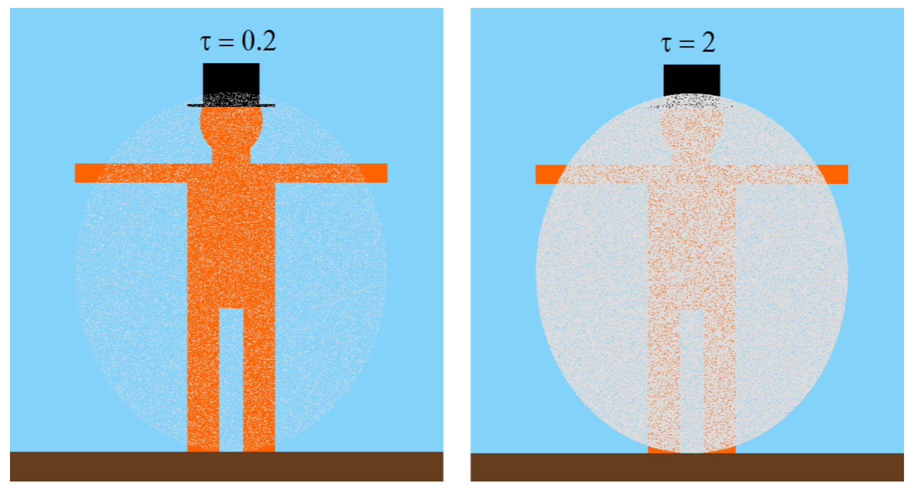


**Fig. 4-7. Visibility of and through a cloud with optical thickness, 0.2 and 2.0. SDG.**

Clouds have high albedos because their water is separated in myriad droplets or crystals much like a smashed ice cube is bright white in sunlight. Sunlight entering a cloud quickly strikes droplets or crystals and is repeatedly scattered. A cloud with 1 g/m$^3$ of liquid water will

**Fig. 4-8. Thin fog reduces visibility of objects gradually with distance in Saddle River, NJ. SDG.**

**Fig 4-9. Growing cumulus congestus looks solid and white where sunlit. SDG.**

have 240 million droplets/m$^3$ of diameter 20 μm and will scatter 15% of a sunbeam in a single meter. Such a cloud will have an optical thickness, $\tau = 1$ if it is 6 m wide, $\tau = 10$ if it is 60 m wide, and so on. (Recall the treatment of optical thickness in §2.4.) Most light that enters a cloud with $\tau = 1$ will pass through it, but most light that enters a cloud with $\tau = 10$ will be scattered so many times that it will not penetrate the cloud but instead will reemerge in an incoherent fashion from the same side it entered and be reflected.

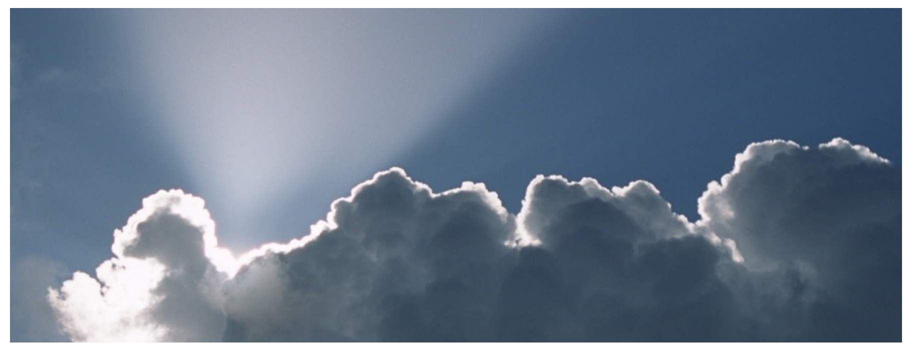

**Fig 4-10. Towering cumulus cloud with silver lining, dark core, and a crepuscular ray. SDG.**

The apparent solidity of a cloud depends on its optical thickness (Fig. 4-7). When optical thickness, $\tau \leq 0.2$ the cloud blocks so little light it is barely visible while a person behind the cloud appears clearly. At $\tau = 2$, the cloud is easy to see but it almost masks the person. For $\tau \geq 3.5$, the person is invisible because the human eye cannot detect differences of light and color less than 2%.

**Fig. 4-11. Underside of a thunderstorm lit by the setting Sun over Cheyenne, WY, 20 May 2020. Colors grade from near white above to near red on the arcus cloud near the surface at left. Scuddy clouds at lower right are dark because they are shaded. Jan Curtis.**

The concentration of droplets or crystals at cloud edge also impacts the impression of solidity. Evaporating or slowly forming clouds and much fog (Fig. 4-8) appear amorphous and indistinct because they have fewer and smaller drops at the edges so you can see a good distance into them, though with fading clarity.

Ice crystal clouds and rain or snow fall streaks also tend to appear fuzzy rather than solid because they contain fewer (though larger) particles than water droplet clouds. For a given water content, optical thickness varies inversely with droplet (or crystal) diameter.

Rapidly growing clouds, such as cumulus congestus and cumulonimbus appear solid because they have a high concentration of vision-blocking droplets right to the outer edges of their turrets. When such clouds punch up into clean, dry air, the visual contrast redoubles their impression of solidity (Fig. 4-9). They can have optical thicknesses that range up to 1000 or more, which is why it gets so dark when they come overhead.

Clouds near the Sun increase to a blinding bright maximum as optical thickness increases to $\tau \approx 2.5$ because 1: the fraction of scattered light increases to over 90%, 2: most of the light scattered light by cloud droplets and ice particles is only deflect by small angles (much like dirty windshields facing the Sun)) and, 3: the light is only scattered at most a few times so that it penetrates the cloud. This is the case with optically thin altocumulus, cirrocumulus and cirrus. It also explains the silver linings of thick cumulus clouds (Fig. 4-10).

As $\tau$ continues to increase above $\approx 2.5$ multiple scattering becomes more important and blocks more light from penetrating the cloud.

For $\tau > 20$ less than 10% of the scattered light penetrates so that the *cores* of thick cumulus clouds ($\tau >> 100$) that block the Sun are very dark.

The *colors* of sunlit clouds close to an observer closely match the colors of the light that strikes them because droplets and crystals are large enough to scatter all wavelengths of light with nearly equal efficiency. When the Sun is high in the sky thick sunlit clouds and optically thin cloud layers that transmit much sunlight appear white because the Sun is white. Shaded clouds and the bases of optically thick clouds appear dark gray simply because little light reaches them.

When the Sun is near the horizon, nearby sunlit clouds that are high in the sky, where the air is thin, may still be white while clouds close to the ground appear golden or red because the sunlight that has

**Fig. 4-12. A yellow thunderstorm lit by the setting Sun over Cheyenne, WY 22 Jul 2017. The color grades from pale yellow at cloud top through yellow to orange-red at cloud base. The cloud at extreme lower right is purple due to admixture of blue skylight with red sunlight. Jan Curtis.**

**Fig. 4-13. Distant view of the top of a thunderstorm in New Mexico at twilight. The sky was black. SDG.**

reached them after it passed through a great optical thickness of atmosphere is golden or red. At that time, any cloud that extends from near the ground to great heights will experience a gradation of color from red at base to yellow to white at the top (Figs. 4-11, 4-12)

The colors of distant clouds are altered by scattering in the intervening atmosphere. Distant sunlit clouds are tinted pink even when the Sun is high in the sky (recall Fig. 2-12), and yellow orange or red when the Sun is near the horizon. Fig.4-13 is a distant view of the top of a sunlit towering thunderstorm at twilight (so that the sky is already black) that is not only reddened by its long optical path to the thunderstorm but also by its long path back to the observer.

The shaded sides of clouds often turn purple when the Sun is near or below the horizon (Fig. 4-14). Because purple is not one of the spectral colors, but rather a combination of blue and red light, any time purple appears in the sky (recall twilight skies of Fig. 2-2 and Fig. 2-9) or on clouds (lower right of Fig. 4-12) the explanation must consist in how red and blue light combine. For example, a cloud that is optically thin will transmit to the shaded side some of the sunlight that hits it, which is red. An optically thick cloud transmits very little light, so its shaded side is illuminated by skylight, which is largely blue. In that setting, the purple cloud is the one with an intermediate optical thickness, which transmits an amount of red sunlight almost equal to the blue skylight it reflects.

**Twilight colors of Ac and Cc clouds are the focus of §12.2.**

## 4.3 Formation of Clouds and Precipitation

**In this section we present Cloud Physics. If you find the going tough and long, focus on the indented blue text, which summarizes essential highlights without the details.**

Clouds form much the same way that dew and frost form. When the ground and the grass cool at night, some of the water vapor in the air condenses to water drops, just as a fog of droplets condenses on the cool surface of the mirror when you take a hot shower in a cold bathroom or on the outside of a glass of ice-cold drink on warm, humid days. Frost forms as ice crystals in the same way, except at temperatures below freezing.

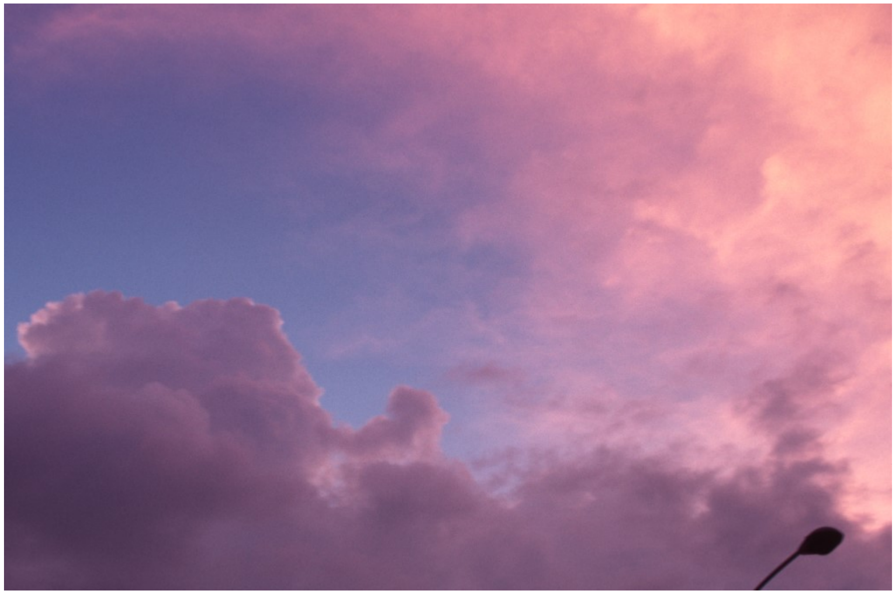

**Fig. 4-14. A partly cloudy sunset or twilight sky with pink and purple shaded clouds and blue sky. SDG.**

When the Sun comes up in the morning and heats the ground, dew evaporates and frost sublimes back to vapor. Likewise, no droplets ever condense on the hot outside of a cup of boiling water even when steam wafts up from the boiling water. Clothes dryers work on the same principle by heating the air and effectively creating wind in the dryer by tumbling the clothes to enhance evaporation. Clouds and fog form and dissipate in the same way.

***Clouds form when air cools enough for water vapor to condense to cloud droplets or ice crystals. They dissipate when air warms enough so droplets and crystals evaporate.***

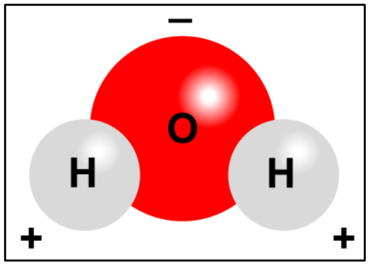


**Fig. 4-15. An $H_2O$ molecule and its electric charges. SDG.**

It pays to think of these changes in terms of molecules. First, $H_2O$ molecules are attracted to each other by hydrogen bonds, which result from the asymmetric shape of the $H_2O$ molecule and its electric charges (Fig. 4-15). The two hydrogens are positively charged on one side while the oxygen is negatively charged on the opposite side. Since opposite electric charges attract, the hydrogen atoms of one $H_2O$ molecule attract the oxygen atom of a nearby water molecule. By contrast, because molecules of $N_2$, $O_2$, and $CO_2$ form straight lines and do not have such asymmetrical charges, their attractive forces are much smaller and as a result they do not condense to liquids until the temperature is much, much lower.

Think of moving molecules to explain how $H_2O$ molecules overcome the hydrogen bonds that hold them together. In water vapor, a gas, molecules move freely in all directions, and with a wide range of speeds. The higher the temperature, the more energy molecules have and the faster they move on average. The mean speed of molecules is comparable to the speed of sound, which is ≈ 331 m/s in air at 0°C.

When temperature is very low $H_2O$ molecules have so little energy and move so slowly that they are locked together in solid ice, though they can vibrate in place. As ice is heated, the molecules vibrate more and more rapidly until finally they have enough energy to slide around their neighbors to melt into liquid water, but they don't have enough energy to break free of the mass. As the temperature continues to rise, the molecules continue to speed up until they have enough energy to completely break free from all other molecules and evaporate or boil into water vapor (a gas) and fly around space.

How then can water vapor and liquid water, and sometimes ice, exist at the same time and place? At any temperature molecules have a wide range of energies and speeds. Thus, there are always a few molecules with enough energy to escape water or ice and float in the air as water vapor, but the lower the temperature the fewer molecules have that critical energy.

Fig. 4-16 illustrates many of the important concepts about water vapor and condensation. The terms it involves include *Saturation*, *Vapor Capacity*, given by the solid line and expressed in units, grams of vapor per kilogram of air at sea level pressure, *Relative Humidity*, ***RH***, and *Dew Point Temperature*, $T_d$.

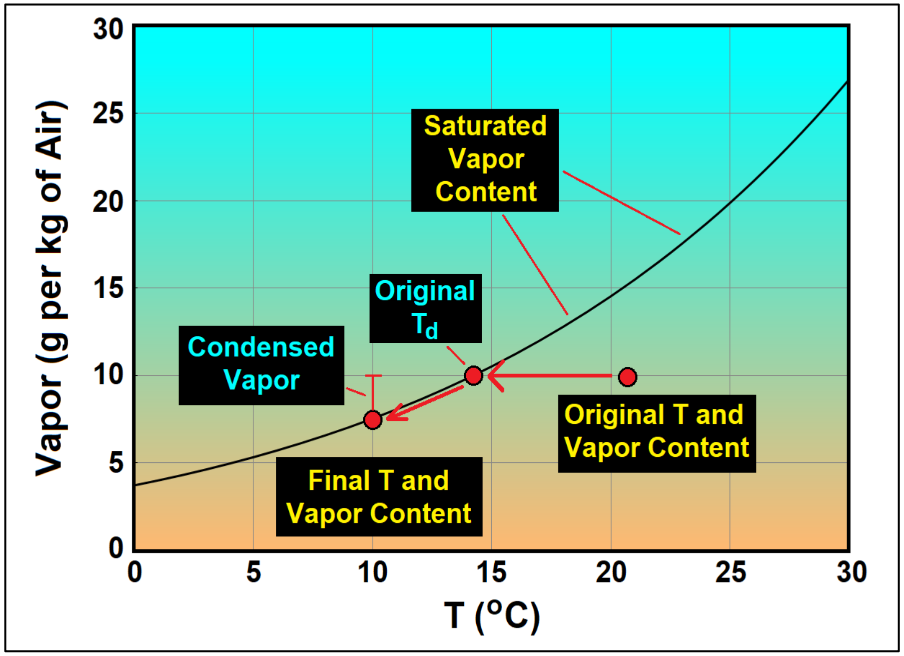


**Fig. 4-16. Saturated Vapor Content vs Temperature. Changes to air cooled from *T* = 21°C and vapor content = 10 g/kg (air) to *T* = 10°C, described in text. SDG.**

- *Saturation* occurs when vapor content equals vapor capacity. When air is saturated with vapor $H_2O$ molecules enter water or ice at the same rate they exit.
- *Relative Humidity*, ***RH*** is vapor content divided by vapor capacity. It is expressed as a percent. When ***RH*** = 100% vapor content equals vapor capacity. When ***RH*** = 50% vapor content is half of capacity.
- *Dew Point Temperature*, $T_d$, is the temperature at which air becomes saturated when it is cooled without evaporation or change of pressure. It is called the dew point because this is the temperature at which dew will begin to condense.

In Fig. 4-16, air initially at ***T*** = 21°C with vapor content, 10 g/kg (air) is cooled to ***T*** = 10°C. At ***T*** = 21°C vapor capacity = 15 g/kg (air). Therefore, ***RH*** = (10/15)×100 ≈ 67%. The air becomes saturated once it is cooled to ***T*** ≈ 14°C; therefore $T_d$ ≈ 14°C. Further cooling forces vapor to condense. At ***T*** = 10°C the vapor content has been reduced from 10 g/kg (air) to the vapor capacity ≈ 7.5 g/kg (air) so that 10 – 7.5 = 2.5 g/kg (air) condensed.

The solid curve in Fig. 4-16 also shows that

***Water vapor capacity doubles for roughly every 9°C increase of temperature.***

**Fig. 4-17. Hole punch clouds of cirrus fall streaks in supercooled altocumulus on 12 Dec 2014 in Boynton Beach, FL. Compare satellite image in Fig. 5-7. SDG.**

Conversely vapor capacity halves for roughly every 9°C decrease of temperature, so RH doubles for roughly every 9°C decrease of temperature. This is why relative humidity usually rises to a daily high around dawn, the coldest time of day, and sinks to a daily low in mid-afternoon, the hottest time of day.

Thin layers of patterned cloud elements or cells (altocumulus) sometimes have circular or long, straight clearings with streamers of cirrus cloud that fall from and curve toward their centers (Fig 4-17) These hole-punch or fall streak clouds, which were never reported before aviation and are most often seen near major airports, illustrate a curious but important phenomenon. They are produced when a plane flies through altocumulus clouds at temperatures typically between about -15°C and -25°C that consist of *supercooled* liquid water below 0°C. The temperature in the cloud in Fig. 4-17 was ***T*** = -23°C.

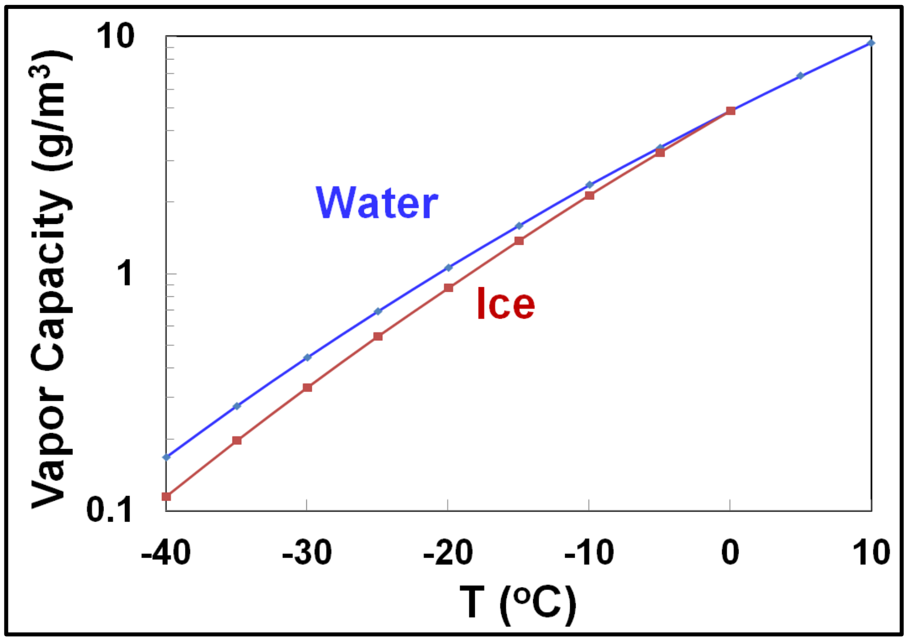


**Fig. 4-18. Vapor capacities of supercooled water and ice vs. *T*. SDG.**

Clouds made of supercooled droplets are surprisingly common. Planes cool and disturb the air enough at the wing tips to freeze the droplets into ice particles, which then grow and fall, and are driven toward the center by the flow of wing-tip vortices in the plane's wake. The cloud hole is near circular if the plane rose or descended through the cloud steeply and it forms a long line if the plane flew through the cloud almost horizontally.

How is supercooled water possible? Crystals melt automatically above 0°C, but droplets must overcome an energy barrier to freeze when temperature drops below 0°C, much as you must tug very hard to start a gas-powered lawn mower. In fact, it is possible to cool a tiny cloud droplet of pure water down as low as -38°C before it must freeze! When water freezes to ice it expands to form hexagonal crystals. Moving $H_2O$ molecules apart and in line requires more energy than tiny droplets have to overcome their mutual attraction.

On average, molecules have less energy in ice than in supercooled water at the same temperature, and therefore require more energy to escape from ice than from supercooled liquid, so fewer do escape. Hence vapor capacity is lower when ice is present (Fig. 4-18). A simple rule is that,

> ***Vapor capacity with respect to ice decreases about 9% for every 10° C below 0° C below vapor capacity with respect to supercooled water.***

For example, air at ***T*** = -20°C that is saturated with respect to ice ($\boldsymbol{RH}_{\mathrm{ICE}}$ = 100%) has $\boldsymbol{RH}_{\mathrm{LIQ}}$ = 82% with respect to supercooled water. This difference has great significance for producing precipitation because *if any ice crystals are present in air* below 0°C *supercooled droplets will begin to evaporate*. In general,

> ***When T < 0°C ice crystals grow at the expense of supercooled droplets., which may ultimately evaporate completely.***

Ice or no ice, if air is cooled enough vapor capacity will decrease below the vapor content. The excess vapor above capacity must then condense to droplets or crystalize or deposit to ice.

**Fig. 4-19. Pyrocumulus forms when hot (smoky) air from burning vegetation rises and cools enough to initiate condensation and form a cloud. Everglades, FL. SDG.**

And that leads to the secret of clouds and rain.

> ***All clouds and precipitation are produced by lowering air temperature until vapor capacity falls below vapor content.***

Three processes operate in the atmosphere to lower temperature.

1. Contact with a cold surface
2. Loss of heat by radiation
3. Depressurization of air as it rises.

The first two of these cooling processes are relatively slow, seldom more than 2° C per hour, and are confined to thin layers of the atmosphere, for example just above the ground. They can produce fog and create or enhance thin cloud layers but they never produce thick, towering clouds, or precipitation.

Rising air in storms cools much faster and through a great thickness of the atmosphere. Depressurization cools rising air adiabatically (without any loss of heat) at 9.8°C/km if it is unsaturated and between about 4 and 9.8°C/km depending on the vapor content once it is saturated (see §6.2). Since air typically rises 0.5 km/h in winter storms and at least 20 km/h in thunderstorms, cooling rates due to rising air in storms range from at least 2°C/h to more than 100°C/h (although air in thunderstorms seldom rises for more than 10 or 15 minutes, by which time it nears cloud top). Therefore…

> ***Most clouds (other than fog) and all precipitation are produced by rising air,***

This process is illustrated in Fig. 4-19. After sugar is extracted the cane is routinely burned. This makes the smoky air hot enough to rise. If it rises and cools enough it will reach the condensation level where droplets begin to condense from vapor. The resulting cloud is called pyrocumulus, a cloud form that has become increasingly common due to the panflagration of huge forest and brush fires in the Western United States and many other seasonally dry places around the world.

But droplets and crystals do not form automatically once RH rises above 100%. Just as supercooled water must overcome a barrier to crystallize as ice, cloud droplets must overcome the energy barrier imposed by surface tension to cluster and condense from vapor. If an $H_2O$ molecule joins a tiny cluster with few $H_2O$ molecules, it will produce a noticeable expansion. Surface tension opposes this because it 'tries' to minimize surface area. This effect is much greater for tiny droplets than for large droplets with zillions of molecules, when adding a molecule does not produce a noticeable expansion. For example the expansion of surface area caused by adding a molecule to a small droplet is 100 times *greater* than the expansion of surface area caused by adding a molecule to a droplet 1,000 times larger.

The barrier surface tension imposes on droplet formation would, if acting alone, require RH to exceed 300 or 400%! But in the atmosphere, surface tension has an opponent.

Aerosols, the atmosphere's impurities, are what overcome the energy barriers to droplet and crystal nucleation, Water droplets readily condense on water-loving (hydroscopic) gases and particles, such as salt. For example, table salt (NaCl) becomes wet (deliquesces) once RH exceeds 75%. Hygroscopic aerosols reduce the energy barrier on cloud droplet growth imposed by surface tension from a few hundred percent to a few hundredths of a percent above 100% RH.

Ice crystals nucleate more easily on aerosol particles with templates that help the $H_2O$ molecules align properly, such as clay particles. Even with these aerosols nucleation is not easily activated in the atmosphere until the temperature falls below about -15°C, which is why thin altocumulus clouds at or above that temperature consist entirely of supercooled droplets if no jet disturbs them.

Once the cluster grows beyond its barrier growth proceeds by the steady statistical process of diffusion, in which there is a net drift of vapor molecules toward the droplet or crystal.

Diffusion is the fundamental and ubiquitous process by which quantities drift from regions of higher concentration to regions of lower concentration. Diffusion is the great leveler. If diffusion reigned supreme the universe would become uniform and inert.

Diffusion in the air is due to the random motion of molecules. It is a discrete process but because there are so many molecules it appears continuous. Statistics ensures that more molecules will move from where concentration to where it is lowest. An example is that any smelly gas emitted in one part of a room gradually spreads around the entire room by diffusion without the slightest wind.

Condensation and evaporation are the diffusion processes connected to growth and evaporation of tiny droplets and crystals. They grow by diffusion of when the vapor density (or vapor pressure) of the surrounding air is greater than right at their surfaces. Since the vapor concentration or density just outside a droplet or crystal is close to the saturated value, in order for droplets or crystals to grow, the ambient air must be slightly supersaturated. Cloud droplets shrink by diffusion and will eventually evaporate completely when the surrounding air is subsaturated, i. e., when the relative humidity is less than 100%.

Diffusion is the dominant growth process for tiny droplets and crystals. But the larger droplets and crystals grow, the slower they expand by diffusion. In fact, the expansion rate due to diffusion varies inversely with the droplet's or crystal's radius. In winter storms over land, where air contains so many nucleating aerosols and so many droplets it would take about two days for a droplet to grow to the size of a drizzle drop, 400 μm in diameter, by diffusion alone. This is too slow to produce precipitation in a timely manner, and another process is needed to grow the droplets to raindrop size.

At sea, air is much cleaner on average and contains fewer aerosols and therefore fewer droplets than over land. Each droplet gets a larger share of the available water and will grow faster and larger by diffusion and can reach drizzle drop size much sooner than over land.

Ice is almost inevitably what helps particles reach raindrop or snowflake size. In the first place, ice crystals are a far rarer breed than droplets. Since ice clouds contain far fewer crystals than water droplet clouds (even at sea), each crystal gets a larger share of the available water and will grow faster and larger by diffusion.

The elephant in the room regarding ice in a cloud of supercooled droplets is the lower saturation vapor density above ice. Not only will ice crystals grow much faster than supercooled droplets, they will, as in hole punch clouds, grow at the expense of the supercooled droplets (Fig. 4-20). The importance of this process for producing precipitation was first theorized in 1911 by Alfred Wegener, the founder of the theory of Continental Drift, and later documented in the atmosphere by Tor Bergeron and Walter Findeisen.

The faster diffusional growth rate of ice particles allows them to grow large enough to fall fast enough to either reach the ground growing solely by diffusion (sometimes as beautiful crystal flakes), or after gathering other crystals and droplets in their path by the process of accretion or coalescence (Fig. 4-21).

*Accretion* is the term used when snowflakes collect ice crystals or when hailstones collect drops. *Riming* is the term for ice crystals that collect droplets and look covered by parasites. *Coalescence* is the term for drops that collect and merge with other drops or droplets.

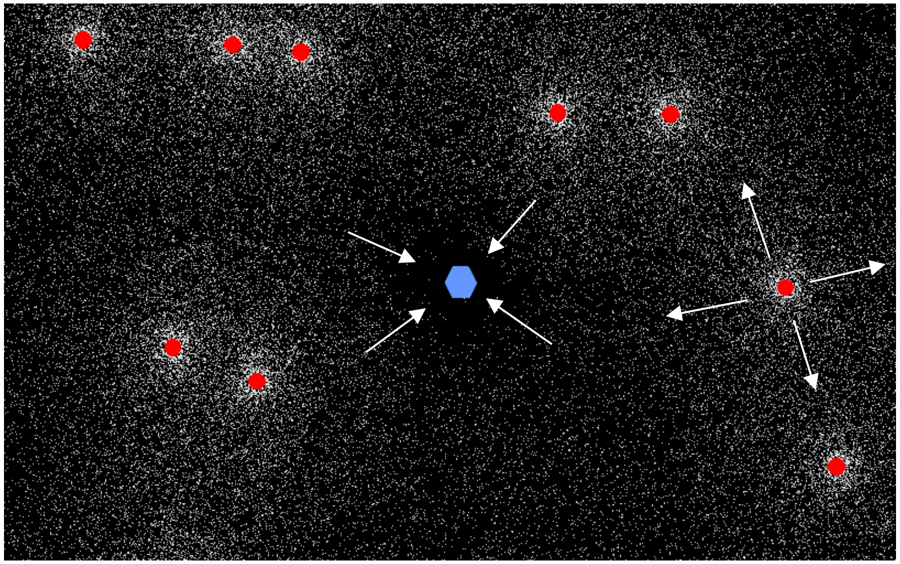

**Fig. 4-20. Wegener-Bergeron-Findeisen process. In this supercooled cloud, droplets (red circles) shrink and crystals (blue hexagon) grow as vapor molecules (white dots) diffuse (arrows) from where they are most (the surface of droplets) to least concentrated (the surface of ice crystals). SDG.**

Growth by diffusion adds one molecule at a time. Growth by accretion adds zillions of molecules from another particle all at once. The finite growth in an instant by accretion is particularly important in jump-starting the process when the collecting particles are only slightly larger than the rest of the crowd.

As droplets and crystals grow, the rate of growth by accretion occurs ever faster because the larger the droplets and crystals are 1: the faster they fall and, 2: the larger the area they sweep out. The growth rate of the particle radius by accretion is roughly proportional to the radius. As a result, for particles larger than about 50 to 100 μm in diameter growth by accretion takes over and gets raindrops, snowflakes and especially hailstones to their final size.

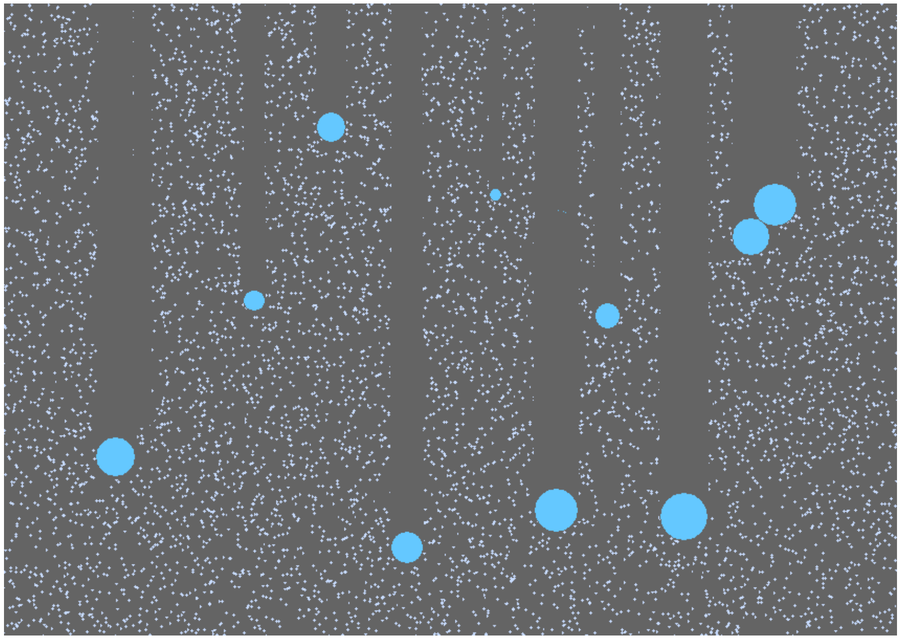

**Fig. 4-21. Coalescence growth. Raindrops collect cloud droplets in their path. At upper right a larger drop is about to overtake and collect a smaller drop. SDG.**

Thus, in the final stages, raindrops and snowflakes grow somewhat like planets. The craters on Mercury, Mars, the Moon, and Earth were produced by the impacts of meteors. Each meteor buried itself in the body it struck and added its mass to the mass of the body although some mass may "splash" away. This process of collision and collection, known as *accretion* in the case of planets, is the process by which the Moon and all the planets grew.

To produce rain by accretion, most clouds must be at least 3 km thick to allow enough collisions to grow droplets and crystals to the size of raindrops and snowflakes that can reach the ground as precipitation.

Once drops and crystals have grown large enough (≥100 µm) they fall fast enough to fall out of the cloud, whereupon they begin to evaporate. As a drop falls below a high cloud base in the desert it is

**Fig. 4-22. Sunlit white virga from thin stratocumulus clouds. Air was cold enough for ice crystals to form in the mostly supercooled liquid cloud over Cheyenne, WY 17 Dec 2021. Jan Curtis.**

**Fig. 4-23. Dark, shaded virga falling from a backlit thunderstorm over Cheyenne, WY 31 May 2017. Jan Curtis.**

surrounded by ever drier air. Then, vapor concentration at the drop's surface of the drop is much higher than in the surrounding air. Vapor molecules then diffuse into the surrounding air. As each vapor molecule drifts away from the drop it is replaced by another from within the drop so that small drops and crystals may evaporate completely before reaching the ground, leaving a trail of fall streaks called virga, hanging in mid-air (Fig. 4-22, Fig. 4-23).

## 4.4 Cloud Forms

For eons it was customary to view clouds as protean mists that blur or hide objects, and as bringers of life that water the Earth or takers of life that drown or immobilize. Few knew that clouds could be viewed as solid objects with distinct forms, other than artists, who by centuries ago provided graphic but mute testimony about the unnamed entities they painted so accurately.

| Cloud Name | Cld | Definition |
|---|---|---|
| Cirrus | Ci | Detached clouds in the form of white, delicate filaments or white or mostly white patches or narrow bands, with a fibrous appearance, and/or a silky sheen. |
| Cumulus | Cu | Detached clouds, generally dense with sharp outlines (perhaps ragged), developing vertically in the form of rising mounds, domes or towers, whose bulging upper part often resembles a cauliflower. Their sunlit parts are mostly brilliant white; their bases are relatively dark and nearly horizontal. |
| Stratus | S | Generally grey layer with a fairly uniform base, which may give drizzle, snow or snow grains. The Sun may be visible through the cloud. Stratus does not produce halo phenomena except, possibly, at very low temperatures. |
| Cumulonimbus | Cb | Heavy, dense cloud with considerable vertical extent, in the form of a mountain or huge towers. At least part of its upper portion is usually smooth, or fibrous or striated, nearly always flattened and often spreads out in the shape of an anvil or vast plume. Under the base, which is often very dark, there are frequently low ragged clouds either merged with it or not, and precipitation sometimes in the form of virga. |
| Nimbostratus | Ns | Grey layer, often dark, that blots out the Sun. Its appearance is made diffuse by more or less continuously falling rain or snow, which in most cases reaches the ground. Low, ragged clouds often occur below the layer, and may merge with it. |
| Stratocumulus | Sc | Grey and/or whitish patch, sheet or layer that almost always has dark parts, composed of tessellations, rounded masses, rolls, etc., which are non-fibrous (except for virga) and which may be merged; most of the regularly arranged small elements have an apparent width of more than 5°. |
| Altocumulus | Ac | White and/or grey patch, sheet or layer, generally with shading, of laminae, rounded masses, rolls, etc., which are sometimes partly fibrous or diffuse and which may be merged; most of the regularly arranged elements usually have an apparent width between 1° and 5° |
| Cirrocumulus | Cc | Thin, white patch, sheet or layer of cloud without shading, composed of very small elements in the form of grains, ripples, etc., merged or separate, and more or less regularly arranged; most of the elements have an apparent width of less than 1°. |
| Altostratus | As | Greyish or bluish cloud sheet or layer of striated (grooves or channels in cloud formations, arranged parallel to the flow of the air), fibrous or uniform appearance, totally or partly covering the sky, and having parts thin enough to reveal the Sun at least vaguely, as through ground glass or frosted glass. Altostratus does not show halo phenomena. |
| Cirrostratus | Cs | Transparent, whitish cloud veil of fibrous or smooth appearance, totally or partly covering the sky, generally producing halo phenomena. |

**Table 4-1. Names, abbreviations, and definitions of the 10 cloud genera modified from the World Meteorological Organization.**

With all the attention that clouds drew it is mind-boggling that they were not named until 1802 when Jean Baptiste de Monet Lamarck in France and Luke Howard in England independently classified them following Linnaeus's ***Systema Naturae*** (1758). Lamarck's scheme, which emphasized cloud forms (e. g., dappled clouds) was essentially ignored, but Howard's original articles "On The Modification of Clouds" (1803a,b), attracted attention and praise, and constitute the core of the currently accepted system of cloud classification.

The significance of Howard's (and Lamarck's) work was assessed cogently by Johann Wolfgang von Goethe, who wrote that Howard,

> was the first to hold fast conceptually the airy and always changing forms of clouds, to limit and fasten down the

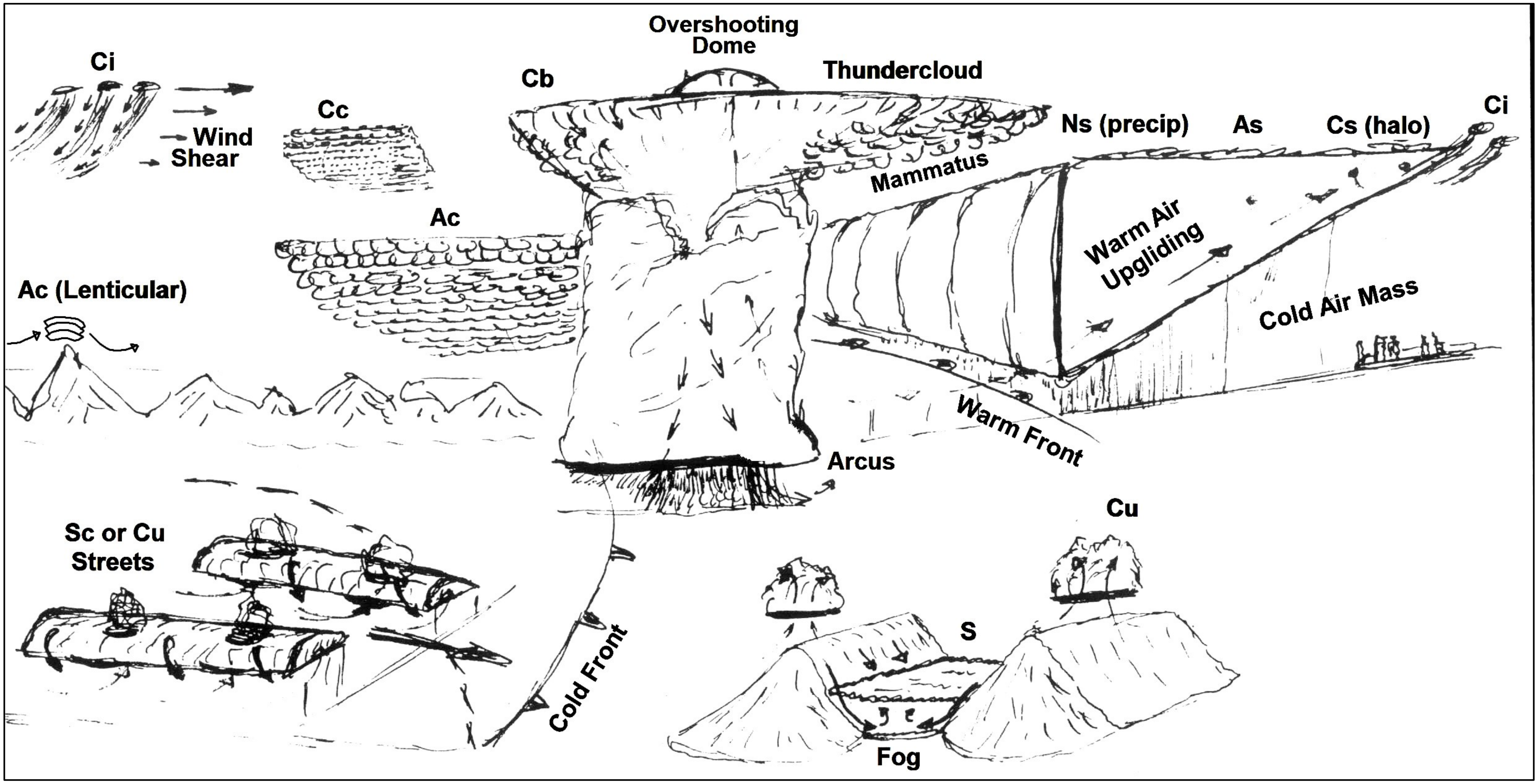


**Fig. 4-24. Cloud chart showing typical forms, heights, airflow, and settings, particularly in relation to the fronts of extratropical cyclones. SDG.**

indefinite, the intangible and unattainable and give them appropriate names.

The system accepted by the World Meteorological Organization has 10 genera (Table 4-1), which use only five words either alone or in combination, *cirrus* → curl, *cumulus* → heap, *stratus* → layer, *alto* → moderately high and *nimbus* → precipitation. plus numerous species and varieties. The genera are classified by the heights of their bases as either low (*Cu*, *S*, *Ns*, *Sc*), with bases below about 2 km above ground level, middle (*Ac*, *As*), with bases between about 2 and 6 km, and high (*Ci*, *Cs*, *Cc*), plus clouds of vertical development (*Cb*)

Cloud charts show the cloud genera in cartoon form (Fig. 4-24) and in photos (Fig. 4-25). The cartoon indicates their relative positions and sizes with the exception that it exaggerates by a factor of about 50 the slope of the warm frontal surface separating the upgliding warm air mass over the dome of cold air, and at the same time, shrinks the horizontal extent of layer clouds, which in reality are larger by the same factor of about 50. It also shows the air motions

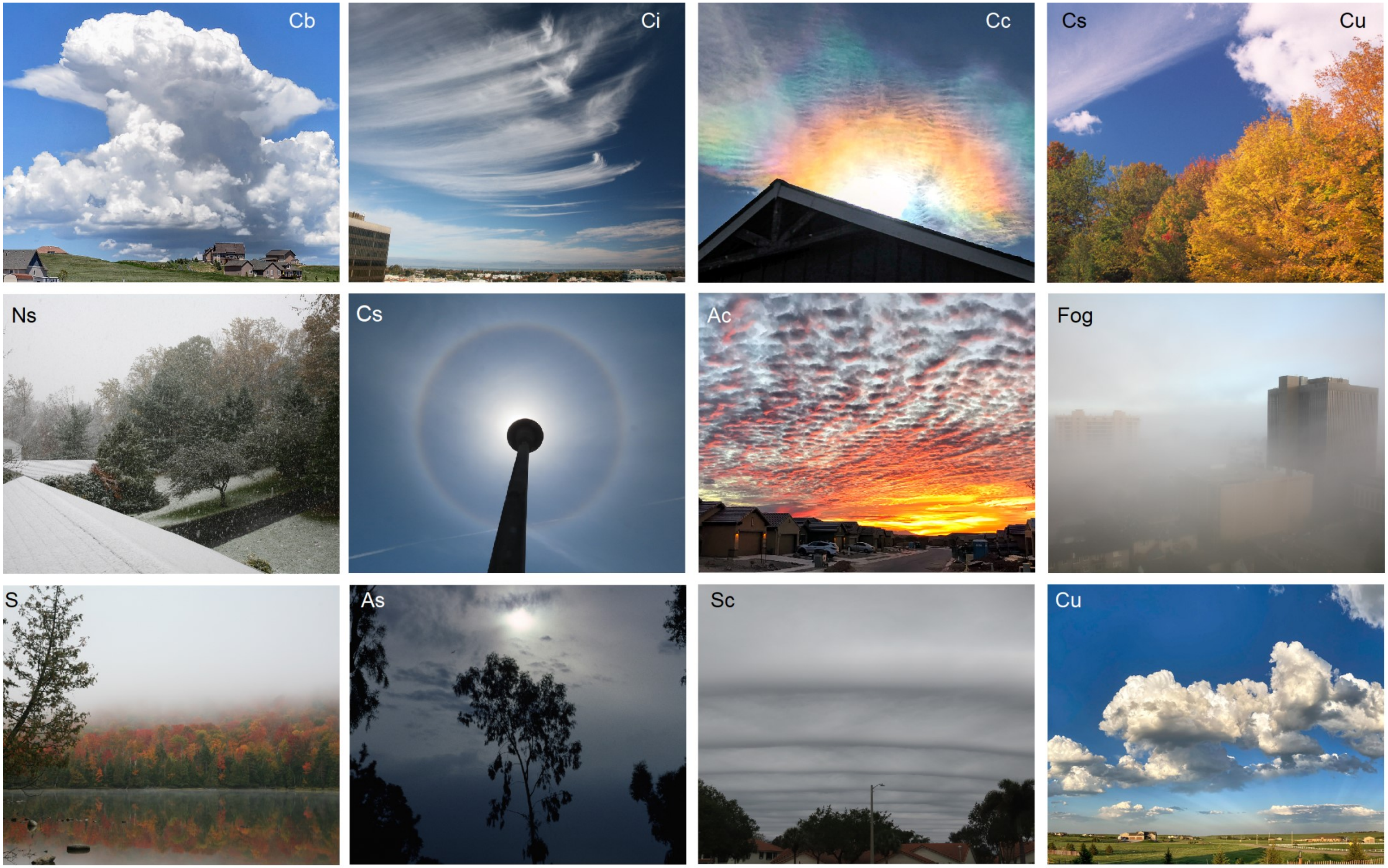


**Fig. 4-25. The cloud genera. Cirrostratus often has a halo. Cirocumulus near the Sun often has a corona or is iridescent. Altostratus often has a 'watery' Sun. Top right photo shows a sky with two distinct genera. Right center photo is ground fog. Jan Curtis and SDG.**

that produce and shape the clouds. For example, at center left it shows the smooth lenticular Ac clouds that form at the crests of wavy airflow when winds cross mountains.

Clouds are shaped by the flow of air. Most cloud particles, and especially cloud droplets, fall so slowly that they are swept along by the wind. Thus,

**Clouds are the signatures of the winds. Their forms are due to the patterns of rising and sinking air.**

Exceptions to the rule occur when particles grow large enough to have substantial fall speeds. Rain shafts extend beneath clouds because raindrops fall between 1 and 10 m/s. Cirrus streamers extend below the generating cell because ice crystals fall speeds around 1 m/s. Thus,

**Cirrus clouds are trails of falling ice crystals twisted by the winds.**

There are only a few basic cloud forms because there are only a few distinct patterns of air motions. Thus,

- When a hot, buoyant puff of air (thermal) rises like a hot air balloon through otherwise quiescent air, the resulting cloud, a cumulus, looks like a puff.
- When a layer of warm air glides over a cold air mass, as on a conveyer belt with a slope of about 1/100$^{th}$, the resulting cloud complex (S, Ns, As, Cs) covers the sky.
- When waves form in the air, the resulting clouds (Sc, Ac, Cc) appear like waves or ripples, with clouds at the crests and clearings at the troughs.

Identifying clouds takes practice but here are some hints.

- Cumulus is a lumpy cloud that often has a flat base and a top that resembles a cauliflower.
- Cumulonimbus, when seen at a distance looks like a huge cumulus, but with a top that resembles an anvil or a gigantic mushroom and with rain falling from its base.
- Cirrus, sometimes called mares' tails often looks like a pony tail.
- Stratus tends to be formless, but turns the sky from blue to gray. If it rains or snows the stratus is a nimbostratus.

Altostratus and cirrostratus are progressively higher and thinner versions of stratus that cover the sky but with distinguishing marks.

- Altostratus are gray, but the Sun is often dimly visible through it, as if seen through smoky glass. Sometimes the base appears wavy, corrugated, or mottled, and it is common to see cloud fragments below and dark silhouettes of higher clouds.
- Cirrostratus is so tenuous that the sky often appears milky blue. Its signature is the ice crystal halo. There are many halos (see Chapter 11), but perhaps the most common is a circular ring with the Sun or Moon in the center and 44° wide (about the diameter of two outstretched hands at arms' length).

Stratocumulus, altocumulus, and cirrocumulus all appear as sheets of flattened cells, bands, or ripples, usually with blue sky between. These three genera can be distinguished by a rule of thumb, that is, use your thumb. When your arm is outstretched,

- Stratocumulus cells or ripples appear wider than your thumb
- Altocumulus cells or ripples appear smaller than your thumb but larger than your pinky nail
- Cirrocumulus cells or ripples appear smaller than your pinky nail.

Cloud height is difficult to estimate visually unless the base intersects a hill or a skyscraper. *Soundings*, vertical profiles of temperature, humidity, and wind of the ambient atmosphere, provide data on cloud height and thickness. Soundings give a picture like one by sticking a straw down through a layer cake, or a core drilled down into the ice caps of Greenland and Antarctica, or through tree trunks to see their rings. It is from soundings that we know which altocumulus clouds are supercooled (e. g., -23°C in Fig 4-13) and how high fog extends.

## 4.5 Fog

Fog is defined as a cloud that touches the Earth's surface and reduces visibility below 1 km. In most cases, fog is produced when air is cooled by the surface below. It therefore extends very little above the surface, from a meter or so up to perhaps a little more than 1 km. As a result, fog is usually be classified as a stratus cloud.

**Fig. 4-26. Radiation fog at San Mateo, CA, 1500 UTC 07 Nov 2014. SDG.**

The definition and properties of fog hide a great variety of forms that fog can assume, causes that produce it, and emotions it can arouse given that fog is often a creature of the night, which adds mystery, fear, and even terror to its obscuration, but also beauty.

The different forms of fog are named for their cause or their location. Radiation fog forms when the surface radiates heat out to space most rapidly, namely when, 1: the air aloft is cloudless and dry, 2: the wind speed just above the surface is slow or calm, 3: the ground is wet and, 4: the difference at sunset between the temperature and the dew point temperature, $T - T_d$ is small just above the surface. Under these conditions, the air just above the surface cools rapidly by close contact to form a classic nocturnal inversion and reaches the dew point so that condensation begins and fog forms. Because the cold, foggy air is denser than the air aloft it hugs the ground, and friction slows it even more, sometime to a dead calm. If the radiation fog is so thin an observer on a small rise can see above it, it is called ground fog.

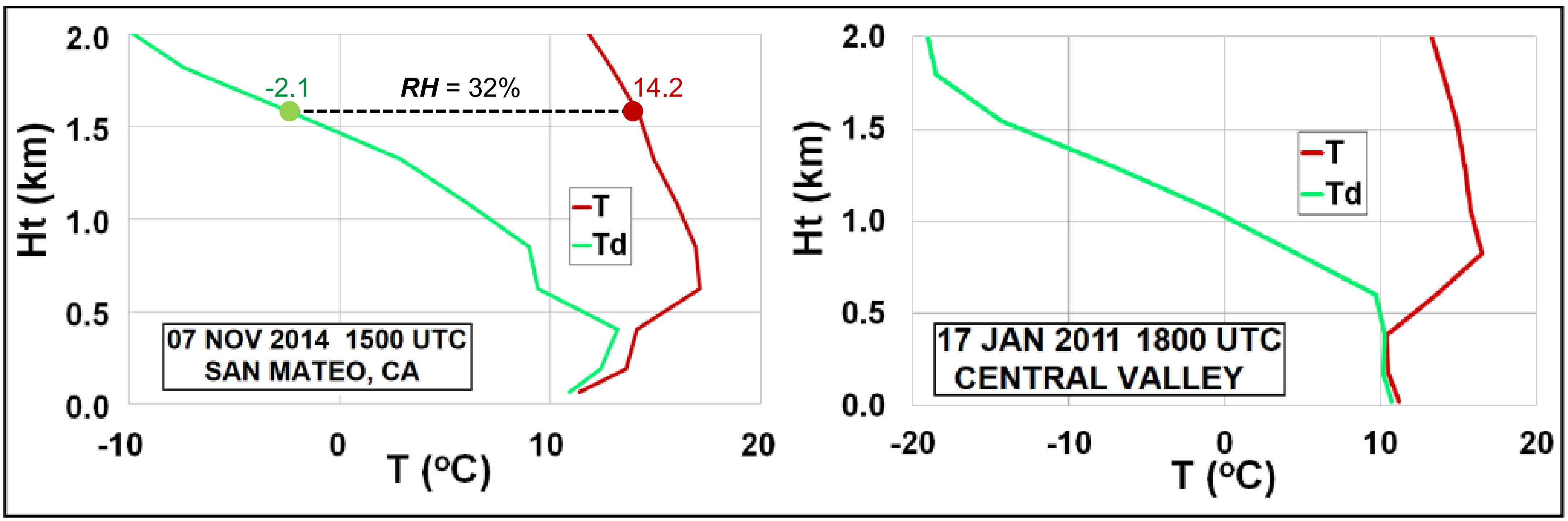


**Fig. 4-27. Soundings during radiation fog at (left) San Mateo, CA 2500 UTC 07 Nov 2014 and (right) the Central Valley 1800 UTC 17 Jan 2011. SDG.**

These were the conditions at San Mateo, CA on the morning of 07 Nov 2014 (Fig. 4-26). The sounding at 0700 PST (Fig 4-27, left side) showed a temperature inversion from $\boldsymbol{T}$ = 12°C at the surface to $\boldsymbol{T}$ = 17°C at 600 m. The air at the surface had cooled to the dew point and remained humid up to about 350 m. Higher up, the air was clear and extremely dry. At 1568 m, $\boldsymbol{T}$ = 14.2°C and $\boldsymbol{T}_d$ = -2.1°C, so RH = 32%. At 3 km (not shown) RH dipped below 1%.

Under similar conditions of clear, calm winter nights following ground-soaking rains (with similar soundings) California's Central Valley can fill with a radiation fog called *Tule Fog* (named for the tule grass widespread in the valley). The sounding for 17 Jan 2011 from the midpoint of the Central Valley (Fig. 4-27, right side) closely resembled that of the San Mateo sounding, with a nocturnal inversion just above the surface, saturated air in a thin layer just above the surface, clear, dry skies aloft, and almost calm surface winds (not shown).

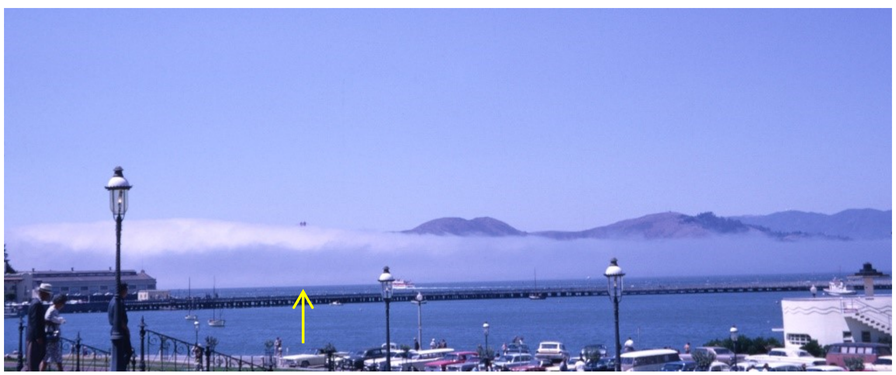

**Fig. 4-28. Advection fog pours through the Golden Gate as a long tongue covering all of the Golden Gate Bridge except the top of the north tower. Robert Gedzelman**

Because the Tule fog covers such a large area (at times it extends westward to San Francisco), and because the valley is almost entirely hemmed in by mountains (except at San Francisco), it may persist for days until a strong wind blows it away and dissipates it. In addition to the low, weak winter sun and short winter days that provide little heating to burn off the fog, the high albedo of the extensive fog adds to its persistence, because reflected sunlight is wasted in that it does not contribute to warming and evaporating the fog.

Advection fog, which forms when warm, moist air blows over a cold surface, is the type of fog that so often covers San Francisco. It blows in from the Pacific through the Golden Gate, often extending a long tongue 'clear' across the San Francisco Bay, as in Fig. 4-28, where it covers all of the Golden Gate Bridge but the tippy top of the north tower (indicated by the yellow arrow).

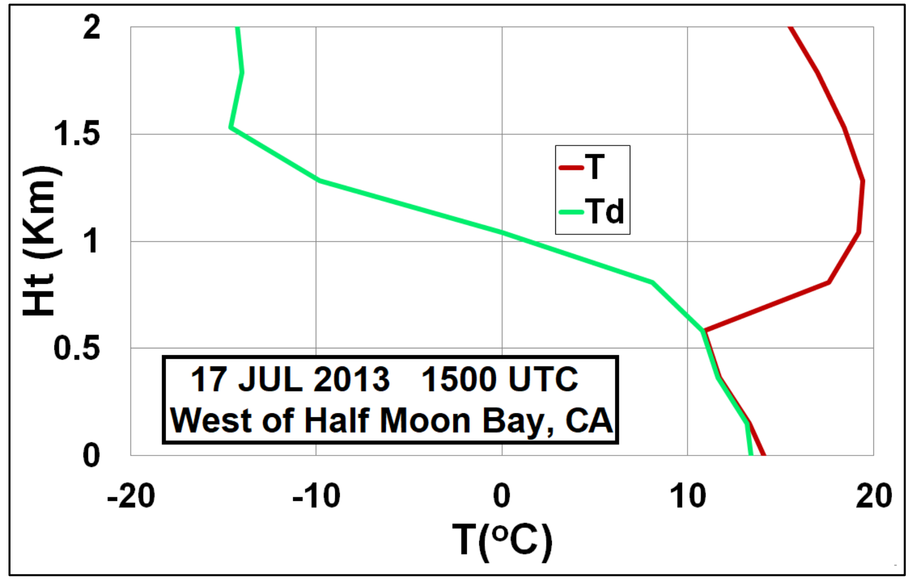


**Fig. 4-29. Sounding for the advection fog of 17 July 2013 at 1500 UTC west of Half Moon Bay, CA. SDG.**

California's advection fog and low stratus can extend up more than 1 km. That is high enough to pour over the Coast Range and then cascade as an enormous but harmless tsunami of fog when the wind has a component from the west. That was the case on the morning of 17 July 2013, when The sounding (Fig. 4-29) showed that the fog topped out at almost 600 m, just above the summit of Montara Mountain, the highest point on the Coast Range from San Francisco to Half Moon Bay. In Fig. 4-30, the fog can be seen cascading down the slopes after surmounting the crest of the Coast Range just east of Half Moon Bay, and indeed, it moved fast enough to be seen in real time. The long, parallel stretch lines were likely caused by horizontal roll vortices similar to the roll vortices that produce cumulus cloud streets (see Fig. 6-29, Fig. 6-31). They reveal the direction of the moving fog as it plunged downslope and then, like the splash of a breaking wave, rebounded on the right before evaporating completely. The rough, corrugated outlines of the fog testified that the flow was turbulent.

Fig. 4-30. Advection fog pours over the coast range from Half Moon Bay on 17 July 2013. After crashing like a breaking wave it rebounds on the right. SDG.

San Francisco's advection fog is just one case of the persistent fogs and low clouds that form off the west coasts of all the continents from about 15° to 45° latitude as persistent winds of initially warm air blow over persistent cold coastal ocean waters upwelled from the depths by those same persistent winds (see Chapter 5).

Another notable example of advection fog occurs over the cold Labrador Current on the Grand Banks of Newfoundland when air blows from the warm waters of the Gulf Stream just to the south. The Grand Banks and Point Reyes, CA are among the foggiest places in the world with fog over 200 days a year.

Upslope fog is the only type of fog that forms or is enhanced by rising air. When air rises up mountain slopes, it can produce a range of cloud genera including cumulus, cumulonimbus and altocumulus lenticularis (mountain wave clouds) when seen from a distance, as at Machu Picchu on 29 Dec 1999 (Fig. 4-31), where cumulus covered the surrounding mountain tops. But observers located just below cloud base can see right in front of their eyes wispy shreds of fog condensing out of thin air and sweeping upward into the cloud. Of course, observers above cloud base will be in fog and not see much of anything.

A combination of upslope and radiation fog occurs when the wind blows uphill over lands that seem level but, in fact, involve a considerable change in elevation over a long enough stretch. One notable case of such fog occurs when winds blow from the east over the Great Plains, which rise almost a mile from the Mississippi River to the Front Range of the Rocky Mountains.

Steam fog forms when cold air settles or blows over warm streams, rivers, ponds, lakes, seas, and oceans. It is the most complex and the most dynamic form of fog, motion being and inherent part of its essence. The first step in the formation process can be like radiation fog or advection fog. On clear, calm nights the ground cools the air which then slides downhill and settles over river valleys or lakes. The favorite season for this to happen is fall, when 1: waters still retain the warmth of summer, 2: lengthening nights give time for increased cooling of the air, and 3: polar air masses behind cold fronts bring the first frigid air to previously warm areas.

**Fig. 4-31. Upslope fog forming as cumulus clouds that cover the mountains surrounding Machu Picchu 29 Dec 1999. SDG.**

A striking scene of steam fog covered the Hudson River on the morning of 12 Dec 1988 (Fig. 4-32). The fog boiled up turbulently, reaching heights up to 20 or 30 m before evaporating into the clear air above. The fog followed a dramatic change in the weather. A cold front had passed through overnight and driven temperature down to -15°C by dawn. Prior to that time the weather had been unseasonably warm for weeks and the Hudson River had been made even hotter by the massive outflow of hot water ejected from the reactors of the Indian Point nuclear power plant.

Many beautiful scenes of steam fog cover streams and lakes on similar cold, clear mornings following cold front passages in the fall. And once the gusty, post frontal winds have settled down as they do especially on clear nights, the slow, downslope drift of cold air settling over the lake is often sufficient to allow the production the fog and leave the still water mirror smooth to reflect the foliage on

**Fig. 4-32. Arctic Sea Smoke over the Hudson River on 12 Dec 1988. SDG.**

the surrounding hills (Fig.4-33). Similar steam fog covered Fairfield Lake in Sapphire, NC for 8 consecutive days in mid-Oct 2024, after a cold dome of high pressure and clear skies settled over the SE United States. The boiling steam fog gleamed in the morning Sun, lasting for two to three hours after sunrise until burning off each day as the air warmed. Under these conditions steam fog and radiation fog occur nearby or together (see Fig. 4-37 and the painting by Rubens, Fig. 15-18).

**Fig. 4-33. Steam fog rising in turbulent eddies over Fairfield Lake, NC on 24 Oct 2019. SDG.**

Dramatic cases of steam fog, known as Arctic Sea Smoke, occur when Arctic air behind cold fronts or frigid, downslope, katabatic winds from the Greenland and Antarctic Ice Sheets pour over the ocean. The Arctic Sea Smoke in Fig. 4-34 occurred on 11 Feb 1986

**Fig. 4-34. Arctic Sea Smoke as Arctic air pours over the Gulf Stream east of Cape Hatteras, NC on xx Feb 1986 during the GALE Experiment. SDG.**

when polar air flowed over the Gulf Stream east of Cape Hatteras, NC. The research plane flew in the clear space just above the tops of the steam fog but below the bases of the cumulus clouds.

This wild, epic-appearing scene has an almost curious cause. The rising plumes of fog, some of which swirled up as steam devils (akin to dust devils), evaporated within about 100 m of the surface but the now invisible plumes remained warm enough to continue rising buoyantly high enough to reach the condensation level, whereupon the cumulus formed. All this occurred under conditions of gale-speed winds that amplified the apparent turbulence.

The turbulent motions and appearance of steam fog stands in sharp contrast with the smooth appearance of radiation and advection fogs, where the airflow is laminar (except when it cascades over a ridge and into a valley) because it is cooled from below and lacks buoyancy.

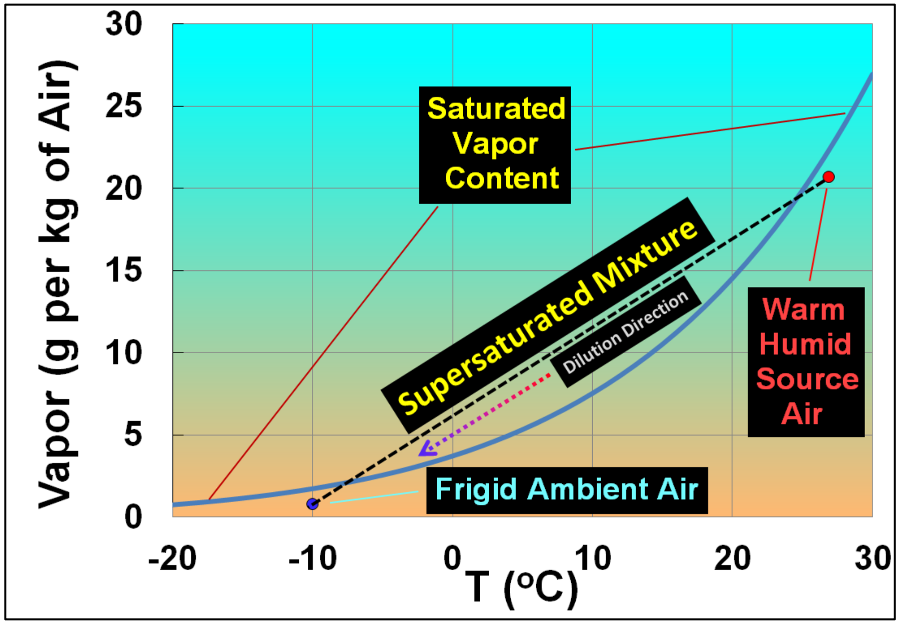


**Fig. 4-35. Saturated vapor content and the formation process of steam fog. The mixture of enough warm, humid, but unsaturated source air with frigid,, dry ambient air can be supersaturated. SDG.**

So much for appearances! It is time to explain how steam fog forms.

The encounter of cold air with warm water is only the first step in the formation of steam fog. The second step involves what happens to the cold air when it encounters the warm water surface. Steam fog would never occur if the warm surface were dry because warming by itself can only cause evaporation. But since the warm water surface is wet it not only heats the air but also charges it with vapor, and increases the relative humidity.

That leads to the third step in the formation of steam fog. No sooner does the humidified, heated air swirl up from the water surface, than it encounters colder, drier air aloft and begins to mix with it.

Fig. 4-35 illustrates the surprising fact that the **mixture** of two **un**saturated samples of air can be **super**saturated (above the saturated curve) provided the temperature difference between the warm, humid source air and the frigid ambient air is large enough. As the warm, humid but unsaturated air moves away from the source it mixes with more and more ambient air and is progressively diluted and cooled. Supersaturation is due to the fact that the **saturated** vapor content of the source air decreases exponentially as it is cooled and diluted while the **actual** vapor content of the mixture decreases linearly.

The following example, based on Fig. 4-35, illustrates the principle. Mix 1 kg of warm, humid source air at $T$ = 27°C and vapor content = 21 g/kg with 1 kg of frigid, ambient air at $T$ = -10°C and vapor content = 1 g/kg. Each kg of the resulting mixture air has the average temperature, $T$ = 8.5°C and average vapor content = 11 g/kg. But at $T$ = 8.5°C vapor capacity is only 6.7 g/kg, so several grams of vapor must condense.

Supersaturation is greatest when the mixture contains roughly equal parts of source air and ambient air. Ultimately, as the source air moves further from the source and mixes with more and more ambient air, the mixture is so dilute it resembles the ambient air and becomes unsaturated (RH falls below 100%) so that the steam evaporates and disappears.

Even though steam fog almost always forms overnight and evaporates by midmorning, there is at least one situation in which steam fog forms in the heat of the day. During a brief afternoon shower the falling rain will not only cool the air as it evaporates it will also wet the still hot blacktop pavement of roads. So, once again we have the classic conditions for steam fog – a hot surface and cool air above. But no sooner does the hot pavement dry than the steam fog over it disappears.

Steam fog is the form of fog that we produce simply by breathing so long as the outside air is cold enough. When we inhale, the air in our lungs and windpipe is heated to near body temperature (37°C) and

**Fig. 4-36. Steam fog made by throwing powdered dry ice in a tub of hot water. SDG.**

charged with vapor by contact with the wet tissues. Steam does not form immediately upon leaving our mouths but only after mixing begins. Thus it does not appear until it is a few cm away from our mouths. Then, as the source air continues mixing with the ambient air and becomes progressively diluted it disappears, usually within a meter or two.

The densest steam fog is created by powdering dry ice (to increase its surface area) and throwing it into a tub of hot water (Fig. 4-36). As the mixture bubbles furiously, the dry ice cools hot, vapor-charged bubbles of air. The temperature difference between dry ice (-78.5°C) and the hot water (ε 40°C) is so great and causes so much cooling that it produces an enormous number and concentration of tiny fog droplets, which can reduce visibility to 1 cm or less.

The dense fog in Fig 4-36 spreads out atop the table in a manner similar to how a thunderstorm downburst or the leading edge of a sandstorm advances across the ground (see Fig. 7.5), and it cascades down when it reaches the edge, ultimately evaporating.

Thus an important bonus feature of dry ice fog is that it can make normally invisible air motions visible.

## 4.6 Cloud and Fog Gallery

**Fig. 4-37. Radiation fog forms in the valleys and sinks towards Fairfield Lake, NC where steam fog boils up over the warm water, all while condensation trails (*contrails*) cross the sky on 19 Oct 2018. SDG.**

**Fig. 4-38. Cirrus uncinus off to the races over Boynton Beach, FL 30 Jan 2024. SDG.**

**Fig. 4-39. Cloud color vs height and viewing angle Cheyenne, WY28 Aug 2024. The optical thickness of the light path from Sun to cloud to observer is shortest for the white cirrus, intermediate for the near horizon golden clouds and longest for the underlit red base of the stratocumulus. Jan Curtis.**

**Fig. 4-40. A field of cumulus mediocris and its reflection at Fairfield Lake, NC 26 Jul 2025. SDG.**

**Fig. 4-41. Shade vs. Light, Cheyenne, WY 08 Jun 2018. The shaded protuberances under the optically thick cumulonimbus are almost black while the sunlit clouds near the horizon are white Jan Curtis.**

**Fig. 4-42. Altocumulus stratiformis undulatus with clouds at wave crests and clearings at troughs Boynton Beach, FL10 Jan 2023. SDG.**

**Fig. 4-43. Valley fog and stratus Mont Blanc Massif 17 Aug 2007. SDG.**