CHAPTER 21

THE CLASSIFICATION OF CLOUDS

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1 INTRODUCTION

Official synoptic weather observations have contained information of the coverage of various types of clouds since 1930. These cloud observations are based on a classification system that was largely in place by the late 1890s (Brooks, 1951). In recent years, these cloud observations have also had increased value. Besides their traditional role in helping to assess the current condition of the atmosphere and what weather may lie ahead, they are also helping to provide a long-term record from which changes in cloud coverage and type associated with climate change might be discerned that might not be detectable in the relatively short record of satellite data (Warren et al., 1991). This article discusses what a cloud is, the origin of the classification system of clouds, and contains photographs of the most commonly observed clouds.

2 WHAT IS A CLOUD?

As defined by the World Meteorological Organization (1969), a cloud is an aggregate of minute suspended particles of water or ice, or both, that are in sufficient concentrations to be visible—a collection of "hydrometeors," a term that also includes in some cases, due to perspective, the precipitation particles that fall from them.

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Clouds are tenuous and transitory. No single cloud element, even within an extensive cloud shield, exists for more than a few hours, and most small clouds in the lower atmosphere exist for only a few minutes. In precise numbers, the demarcation between a cloud and clear air is hard to define. How many cloud drops per liter constitute a cloud? When are ice crystals and snow termed "clouds" rather than precipitation? When are drops or ice crystals too large to be considered "cloud" particles, but rather "precipitation" particles?

These questions are difficult for scientists to answer in unanimity because the difference between cloud particles and precipitation particles, for example, is not black and white; rather they represent a continuum of fallspeeds. For some scientists, a 50-μm diameter drop represents a "drizzle" drop because it likely has formed from collisions with other drops, but for others it may be termed a "cloud" drop because it falls too slowly to produce noticeable precipitation, and evaporates almost immediately after exiting the bottom of the cloud. Also, the farther an observer is from falling precipitation, the more it appears to be a "cloud" as a result of perspective. For example, many of the higher "clouds" above us, such as cirrus and altostratus clouds, are composed mainly of ice crystals and even snowflakes that are settling toward the Earth; they would not be considered a "cloud" by an observer inside them on Mt. Everest, for example, but rather a very light snowfall. Some of the ambiguities and problems associated with cloud classification by ground observers were discussed by Howell (1951).

3 ORIGIN OF THE PRESENT-DAY CLOUD CLASSIFICATION SYSTEM

The classification system for clouds is based on what we see above us. At about the same time at the turn of the 19th century, the process of classifying objectively the many shapes and sizes of something as ephemeral as a cloud was first accomplished by an English chemist, Luke Howard, in 1803, and a French naturalist, Jean Baptiste Lamarck, in 1802 (Hamblyn, 2001). Both published systems of cloud classifications. However, because Howard used Latin descriptors of the type that scientists were already using in other fields, his descriptions appeared to resemble much of what people saw, and because he published his results in a relatively well-read journal, *Tilloch's Philosophical Magazine*, Howard's system became accepted and was reproduced in books and encyclopedias soon afterward (Howard, 1803).

Howard observed, as had Lamarck before him, that there were three basic cloud regimes. There were fibrous and wispy clouds, which he called *cirrus* (Latin for hair), sheet-like laminar clouds that covered much or all of the sky, which he referred to as *stratus* (meaning flat), and clouds that were less pervasive but had a strong vertical architecture, which he called *cumulus* (meaning heaped up). Howard used an additional Latin term, *nimbus* (Latin for cloud), meaning in this case, a cloud or system of clouds from which precipitation fell. Today, *nimbus* itself is not a cloud, but rather a prefix or suffix to denote the two main precipitating clouds, *nimbostratus* and *cumulonimbus*. The question over clouds and their types generated such enthusiasm among naturalists in the 19th century that an ardent observer and member of the British Royal Meteorological Society, Ralph Abercromby, took two voyages around the world to make sure that no cloud type had been overlooked!

The emerging idea that clouds preferred just two or three levels in the atmosphere was supported by measurements using theodolites and photogrammetry to measure cloud height at Uppsala, Sweden, as well as at sites in Germany and in the United States in the 1880s. These measurements eventually led H. Hildebrandsson, Director of the Uppsala Observatory, and Abercromby to place the "low," "middle," and "high" cloud groupings of Howard more systematically in their own 1887 cloud classification. At this time, *cumulus* and *cumulonimbus* clouds were placed in a fourth distinct category representing clouds with appreciable updrafts and vertical development.

Howard's modified classification system was re-examined at the International Meteorological Conference at Munich in 1891 followed by the publication of a color cloud atlas in 1896 (Hildebrandsson et al., 1896). At this point, the definitions of clouds were close to their modern forms. Additional international committees made minor modifications to this system in 1926 that were realized with the publication of the 1932 International Cloud Atlas. Little change has been made since that time.

The most comprehensive version of the classification system was published in two volumes (International Cloud Atlas) by the World Meteorological Organization in 1956 (WMO, 1956). Volume I contained the cloud morphology and Volume II consisted of photographs. An abridged Atlas published in 1969 consisted of combined morphology and photographs. The descriptions of clouds and their classifications (Volume I) were published again in 1975 by the WMO (WMO, 1975). In 1987, a revised Volume II of photographs (WMO, 1975) was published that included photographs of clouds from more disparate places than in the previous volumes.

4 THE CLASSIFICATION OF CLOUDS

There are ten main categories or genera into which clouds are classified for official observations (e.g., British Meteorological Office, 1982; Houze, 1993): *cirrus*, *cirrostratus*, *cirrocumulus*, *altostratus*, *altocumulus*, *nimbostratus*, *stratocumulus*, *stratus*, *cumulus*, and *cumulonimbus*. Table 1 is a partial list of the nomenclature used to describe the most commonly seen species and varieties of these clouds. Figures 1 to 13 illustrate these main forms and their most common varieties or species.

Within these ten categories are three cloud base altitude regimes: "high" clouds, those with bases generally above 7 km above ground level (AGL); "middle-level" clouds, those with bases between 2 and about 7 km AGL; and "low" clouds, those with bases at or below 2 km AGL. The word "about" is used because clouds with certain visual attributes that make them, for example, a middle-level cloud, may actually have a base that is above 7 km. Similarly, in winter or in the Arctic, high clouds with cirriform attributes (fibrous and wispy) may be found at heights below 7 km. Also, some clouds that are still considered low clouds (e.g., *cumulus* clouds) can have bases that are a km or more above the general low cloud upper base limit of

TABLE 1 The Ten Cloud Types and Their Most Common Species and Varieties.

Genera	Species	Varieties
Cirrus (Ci)	Uncinus, fibratus, spissatus, castellanus	Intortus, radiatus, vertebratus
Cirrostratus (Cs)	Nebulosus, fibratus	
Cirrocumulus (Cc)	Castellanus, floccus lenticularis	Undulatus
Altocumulus (Ac)	Castellanus, floccus, lenticularis	Translucidus, opacus, undulatus, perlucidus
Altostratus (As)	None	Translucidus, opacus
Nimbostratus (Ns)	None	None
Stratocumulus (Sc)	Castellanus, lenticularis	Perlucidus, translucidus opacus
Stratus (St)	Fractus, nebulosus	
Cumulonimbus (Cb)	Calvus, capillatus	
Cumulus (Cu)	Fractus, humilis, mediocris, congestus	

Letters in parentheses denote accepted abbreviations.
Source: From World Meteorological Organization, 1975.

2 km AGL. Therefore, these cloud base height boundaries should be considered somewhat flexible. Note, too, that what is classified as an *altocumulus* layer when seen from sea level will be termed a *stratocumulus* layer when the same cloud is seen by an observer at the top of a high mountain because the apparent size of the cloud elements, part of the definition of these clouds, becomes larger the nearer one is to the cloud layer. The definitions are made on the basis of the distance of the observer from the cloud.

The classification of clouds is also dependent on their composition. This is because the composition of a cloud, all liquid, all ice, or a mixture of both, determines many of its visual attributes on which the classifications are founded (e.g., luminance, texture, color, opacity, and the level of detail of the cloud elements). For example, an *altocumulus* cloud cannot contain too many ice crystals and still be recognizable as an *altocumulus* cloud. It must always be composed largely of water drops to retain its sharp-edged compact appearance. Thus, it cannot be too high and cold. On the other hand, wispy trails of ice crystals comprising *cirrus* clouds cannot be too low (and thus, too warm). Therefore, having the ability to assess the composition of clouds (i.e., ice vs. liquid water) visually can help in the determination of a cloud's height.

Other important attributes for identifying a cloud are: How much of the sky does it cover? Does it obscure the sun's disk? If the sun's position is visible, is its disk sharply defined or diffuse? Does the cloud display a particular pattern such as small cloud elements, rows, billows, or undulations? Is rain or snow falling from it? If so, is the rain or snow falling from it concentrated in a narrow shaft, suggesting heaped cloud tops above, or is the precipitation widespread with little gradation, a characteristic that suggests uniform cloud tops? Answering these questions will allow the best categorization of clouds into their ten basic types.

Figure 1 Cirrus (*fibratus*) with a small patch of *cirrus spissatus* left between the trees.

4.1 High Clouds

Cirrus, *cirrostratus*, and *cirrocumulus* clouds (Figs. 1, 2, and 3, respectively) comprise high clouds. By WMO definition, they are not dense enough to produce shading except when the sun is near the horizon, with the single exception of a thick patchy *cirrus* species called *cirrus spissatus* in which gray shading is allowable.[1] *Cirrus* and *cirrostratus* clouds are composed of ice crystals with, perhaps, a few momentary exceptions just after forming and when the temperature is higher than $-40°$C. In this case, droplets may be briefly present at the instant of formation. The bases of *cirrus* and *cirrostratus* clouds, composed of generally low concentrations of ice crystals that are about to evaporate, are usually colder than $-20°$C. The coldest cirriform clouds (i.e., *cirrus* and *cirrostratus*) can be $-80°$ C or lower in deep storms with high cloud tops (> 15 km above sea level) such as in thinning anvils associated with high-level outflow of thunderstorms.

Because of their icy composition, *cirrus* and *cirrostratus* clouds are fibrous, wispy, and diffuse. This wispy and diffuse attribute is because the ice crystals that comprise them are overall in much lower concentrations (often an order of magnitude or more) than are the droplet concentrations in liquid water clouds. In contrast, droplet clouds look hard and sharp-edged with the details of the tiniest elements clearly visible. The long filaments that often comprise cirriform clouds are caused by

[1] Many users of satellite data refer to *cirrus* or *cirriform* those clouds with cold tops in the upper troposphere without regard to whether they produce shading as seen from below. However, many such clouds so described would actually be classified as *altostratus* clouds by ground observers. This is because such clouds are usually thick enough to produce gray shading and cannot, therefore, be technically classified as a form of cirrus clouds from the ground.

Figure 2 Cirrostratus (*nebulosus*), a relatively featureless ice cloud that may merely turn the sky from blue to white.

the growth of larger ice crystals that fall out in narrow, sloping shafts in the presence of changing wind speeds and directions below the parent cloud. As a result of the flow settling of ice crystals soon after they form, mature *cirrus* and *cirrostratus* clouds are, surprisingly, often 1 km or more thick, although the sun may not be appreciably dimmed (e.g., Planck et al., 1955; Heymsfield, 1993).

Cirrus and *cirrostratus* clouds often produce haloes when viewed from the ground whereas thicker, mainly ice clouds, such as altostratus clouds (see below) cannot. This is because the cirriform clouds usually consist of small, hexagonal prism crystals such as thick plates, short solid columns—simple crystals that refract the sun's light as it passes through them. On the other hand, *altostratus* clouds are much deeper and are therefore composed of much larger, complicated ice crystals and snowflakes that do not permit simple refraction of the sun's light, or, if a halo exists in its upper regions, it cannot be seen due to the opacity of the *altostratus* cloud. The appearance of a widespread sheet of cirrostratus clouds in wintertime in the middle and northern latitudes has long been identified as a precursor to steady rain or snow (e.g., Brooks, 1951).

Cirrocumulus clouds are patchy, finely granulated clouds. Owing to a definition that allows no shading, they are very thin (less than 200 m thick), and usually very short-lived, often appearing and disappearing in minutes. The largest of the visible cloud elements can be no larger than the width of a finger held skyward when observed from the ground; otherwise it is classified as an *altocumulus* or, if lower, a *stratocumulus* cloud.

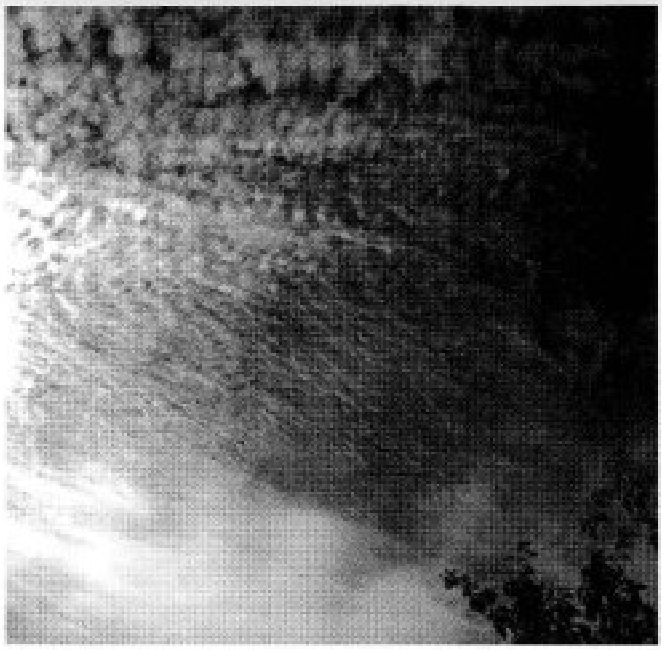

Figure 3 Cirrocumulus: the tiniest granules of this cloud can offer the illusion of looking at the cloud streets on a satellite photo.

Cirrocumulus clouds are composed mostly or completely of water droplets. The liquid phase of these clouds can usually be deduced when they are near the sun; a corona or irisation (also called iridescence) is produced due to the diffraction of sunlight by the cloud's tiny (<10-μm diameter) droplets. However, many *cirrocumulus* clouds that form at low temperatures ($<-30°C$) migrate to fibrous *cirriform* clouds within a few minutes, causing the granulated appearance to disappear as the droplets evaporate or freeze to become longer-lived ice crystals that fall out and can spread away from the original tiny cloudlet.

4.2 Middle-Level Clouds

Altocumulus, *altostratus*, and *nimbostratus* clouds (Figs. 4, 5, 6, and 7, respectively) are considered middle-level clouds because their bases are located between about 2 and 7 km AGL (see discussion concerning the variable bases of *nimbostratus* clouds below). These clouds are the product of slow updrafts (centimeters per second) often taking place in the middle troposphere over an area of thousands of square kilometers or more. Gray shading is expected in *altostratus*, and is generally present in *altocumulus* clouds. *Nimbostratus* clouds by definition are dark gray and the sun cannot be seen through them. It is this property of shading that differentiates these clouds from high clouds, which as a rule can have no shading.

Figure 4 Altocumulus translucidus is racing toward the observed with an altocumulus lenticularis cloud in the distance above the horizon. Cirrostratus nebulosus is also present above the altocumulus clouds.

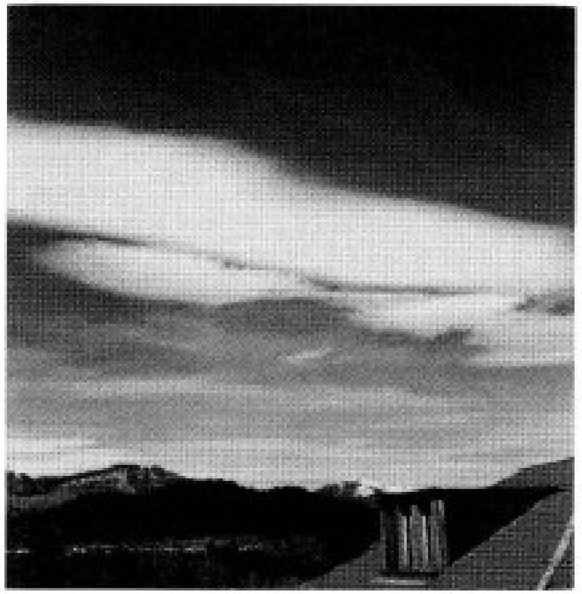

Figure 5 Altocumulus lenticularis: these may hover over the same location for hours at a time or for just a few minutes. They expand and shrink as the grade of moisture in the lifted air stream waxes and wanes.

Figure 6 Altostratus translucidus overspreads the sky as a warm-frontal system approaches Seattle. The darker regions show where the snow falling from this layer (virga) has reached levels that are somewhat lower than from regions nearby.

Figure 7 Nimbostratus on a day with freezing level at the ground. Snowfall is beginning to obscure the mountain peaks nearby and snow reached the lower valley in the foreground only minutes later.

Altostratus and *altocumulus* are different from one another in the same way that *cirrus* and *cirrostratus* clouds are different from *cirrocumulus* clouds; in *altocumulus* clouds, droplets predominate, giving them a crisp, sharper-edged look. With *altostratus* clouds, ice crystals and snowflakes dominate or comprise the entire cloud, giving it a diffuse, fibrous look. The observation of *altocumulus* and *altostratus* clouds in the sky has long been a marker for deteriorating weather in the hours ahead.

In spite of its name, *altocumulus* clouds are generally rather flat clouds that strongly resemble *stratocumulus* clouds. An exception to this overall laminar architecture is in those species of *altocumulus* called *castellanus* and *floccus*. In these forms, *altocumulus* clouds resemble miniature, lofted *cumulus* clouds that usually occur in rows or patches rather than in widespread layers.

Altocumulus clouds are distinguished from *cirrocumulus* because they are lower and the cloud elements in *altocumulus* are, or appear to be from the ground, several times larger than those in *cirrocumulus* clouds. For example, the elements of an *altocumulus* cloud are typically the width of three fingers held skyward at the ground. Also, shading toward the center of the thicker elements is usually present in *altocumulus* clouds, a property that is not allowed in the classification of *cirrocumulus* clouds. *Altocumulus* clouds are distinguished from *stratocumulus* because they are higher above ground level than *stratocumulus* (at least 2 km) and because the individual cloud elements in *altocumulus* are, or appear to be from the ground, smaller than those in *stratocumulus*.

In spite of the gray shading that may be present, *altocumulus* clouds are rarely more than 1 km thick. This is because the concentrations of drops in them are relatively high (typically 50,000 or more per liter) compared with fibrous ice clouds whose particle concentrations may only be only tens to a few thousand per liter. This density of particles produces an optical depth in which the sun's disk can be obscured (optical depth of 4 or more) by an *altocumulus* cloud layer only 300–500 m thick.

Altocumulus clouds sometimes sport patchy "virga." *Virga* is light precipitation that falls from a cloud but does not reach the ground because it evaporates. Because virga is almost always caused by falling snow, it appears fibrous, often with striations or long filaments that often far surpass the depth of the cloud from which it is falling. Virga, because it is comprised of falling snow, can appear to be quite dense. *Altocumulus* clouds with virga are predominantly those clouds whose temperatures are lower than −10° C (Heymsfield, 1993). However, at the same time, they are rarely colder than about −30° C. This is because at very low temperatures they are likely to take on the attributes of ice clouds such as *cirrus* or its thicker brethren, *altostratus*.

The species of *altocumulus* clouds called *altocumulus castellanus* has always had a special significance in meteorology because these clouds reveal a conditionally unstable lapse rate in the middle troposphere. Instability of this sort has been viewed as a marker for likely releases of deeper convection in the hours ahead. Occasionally, *castellanus* clouds group and enlarge into higher based *cumulus* and *cumulonimbus* clouds.

When the winds are relatively strong aloft (greater than about 20 m s^{-1}) and moderately moist, but stable lapse rate conditions are present, a species of *altocumulus* called *lenticularis* (lens or almond-shaped) clouds (Fig. 5) may form over or downwind of mountains. *Altocumulus lenticularis* clouds can hover over the same location for minutes to hours while expanding and shrinking in response to fluctuations in the relative humidity of the air mass being lifted over the terrain. Because the conditions under which these clouds form are most often associated with advancing short wave troughs in the middle and upper atmosphere and their accompanying regions of low pressure, *lenticularis* clouds are usually precursors to deteriorating weather.

With *altostratus* clouds (Fig. 6), the dominance of ice causes a diffuse, amorphous appearance with striations or fallstreaks (virga) on the bottom; an observer is usually viewing relatively low concentrations of precipitation particles rather than a cloud per se. *Altostratus* clouds are rarely less than 2 km thick and often have tops at the same heights as *cirrus* and *cirrostratus* clouds. Because of this great altitude range, they are considerably colder and span a much greater temperature range than do *altocumulus* clouds. They also, by definition, cover the entire sky or at least wide portions of it; they are not patchy clouds. Precipitation is usually imminent when *altostratus* clouds are moving in because they are a sign that a widespread slab of air is being lifted, usually that due to an approaching cyclone and its frontal system (Brooks, 1951).

The relatively low concentrations of large particles in some *altostratus* clouds (often tens per liter) can allow the sun's position to be seen as though looking through ground or fogged glass: the sun's position is apparent, but the outline of its disk is not. This may be the case (*translucidus* variety) even when the cloud layer is two or more kilometers thick.

Somewhat surprisingly, when the top of an *altostratus* cloud layer is warmer than about −30 to −35°C, it is not uncommon to find that the top is comprised of a thin droplet cloud virtually identical to an *altocumulus* cloud layer that is producing virga. The survival, growth, aggregation, and breakup of ice crystals spawned by these cold, liquid clouds over a great depth usually obscures the ice-producing droplet cloud top in these cases. These kinds of situations were dubbed "the upside-down storm" when first noticed in the mid-1950s because the coldest part of the cloud (the top) was liquid and the warmer regions below were comprised of ice (Cunningham, 1957).

Optical phenomena seen from the ground with *altostratus* clouds are limited to *parhelia* ("sun dogs"). They are usually observed in thin portions of *altostratus* when the sun is low in the sky. Parhelia are bright, colored highlights, which sometimes rival the brightness of the sun, that are located 22° from the sun's position. They are most noticeable in the morning or before sunset.

However, since the composition of the uppermost regions of the deepest *altostratus* clouds are virtually identical to *cirriform* ice clouds with simpler, smaller ice crystals, haloes are often observed in the uppermost portions of deep *altostratus* clouds.

Nimbostratus clouds (Fig. 7) are virtually identical to *altostratus* clouds in their composition except that their bases are usually perceived from the ground as lower than in *altostratus* (from which it has usually derived due to a downward thickening). Therefore, they often appear somewhat darker than *altostratus* clouds and, by definition, do not allow the sun to be seen through them. The perceived base of *nimbostratus* is caused by snowflakes that are melting into raindrops. This apparent base of the cloud is a result of the greater opacity of snow particles giving the impression of a bottom or sharp increase in thickness of the cloud at the melting level. Thus, the base of an amorphous, precipitating *nimbostratus* cloud might be perceived at mid-levels on a day when the freezing level is high (above 2 km) such as in southern latitudes or the tropics, or be perceived as low when the freezing level is low as in northern latitudes in the winter. Generally, the bottom of *nimbostratus* clouds is obscured by lower detached clouds such as *stratus fractus*, or *stratocumulus*.

Nimbostratus clouds produce relatively steady precipitation that often continues for hours at a time. They are not clouds responsible for passing showers with periods of sun in between. The tops of dark, steadily precipitating *nimbostratus* clouds can be as shallow as 2–3 km and even be above freezing in temperature, or they may reach into the upper regions of the troposphere (to *cirriform* cloud levels) and be as cold as −80°C. At elevations above the freezing level *nimbostratus* is largely composed of ice crystals and snowflakes, though embedded thin (supercoooled) droplet cloud layers similar to *altocumulus* clouds are relatively common. Also, similar to *altostratus* clouds, when the temperature at the top of *nimbostratus* clouds is above about −30° to −35°C, a thin droplet cloud layer may be found in which the first ice crystals form.

A broken-to-overcast layer of shallow *stratus* or *stratocumulus* clouds often resides at the bottom of *nimbostratus* clouds. However, while usually not precipitating themselves, these lower cloud layers are important in enhancing the amount of rain or snow that falls from *nimbostratus* clouds. This enhancement occurs because of the accretion or riming of the relatively small cloud drops in the lower clouds by the rapidly falling precipitation-sized particles. This enhancement is especially evident in hilly or mountainous regions. However, just the existence of lower clouds even with drops too small to be collected by the faster falling precipitation indicates enhanced precipitation at those locations compared with cloud-free locations. This is because where there are no lower clouds, the precipitation is likely to be subject to a degree of evaporation, and the drops or snowflakes are slightly smaller in comparison to those locations where clouds exist below the *nimbostratus* and there is no evaporation through the depth of the cloud.

Cumulonimbus clouds (see below) may also be embedded in *nimbostratus* clouds. The presence of such clouds within *nimbostratus* is evident by sudden gushes of much heavier rain and sometimes lightning within a context of relatively steady rain.

4.3 Low Stratiform Clouds

Stratocumulus and *stratus* clouds (Figs. 8 and 9, respectively) are low-based, shallow stratiform clouds, almost always less than 1 km thick. They are composed of droplets unless the cloud top is cooler than about −5 to −10° C in which case ice crystals may form (Hobbs and Rangno, 1985). *Stratocumulus* clouds differ from *stratus* clouds because they have a rather lumpy appearance at cloud base with darker and lighter regions due to embedded weak convection. Also, their bases tend to be higher, and more irregular in height than those of *stratus* clouds. *Stratus* presents a smoother, lower, more uniform sky than do *stratocumulus* clouds because the internal convective overturning that produces lighter and darker regions is slight. Drizzle (precipitation comprised of drops < 500-μm diameter that nearly float in the air) is likely to form when the cloud droplet concentrations are lower than about 100 cm^{-3}. Therefore, drizzle is common from both *stratus* and *stratocumulus* clouds at sea and along and inland of coastlines in onshore flow because in such situations the air is clean and there are relatively few cloud condensation nuclei on which droplets can form. However, recent measurements have also shown that drizzle and light rain producing shallow clouds with low droplet concentrations are much more common at inland locations in winter than was once believed (e.g. Huffman and Norman, 1988). Since such clouds are often supercooled in winter, they pose a severe potential for aircraft icing and freezing rain or drizzle at the ground.

Figure 8 Stratocumulus: note the uneven bases of this cloud layer. The darker regions show where there is enhanced modest convection and higher liquid water content.

Figure 9 Stratus: the clouds intercept hills only a few hundred meters above sea level. Note here the uniformity of this cloud layer compared with *stratocumulus* in Fig. 8.

4.4 Convective Clouds

Cumulus and *cumulonimbus* clouds (Figs. 10, 11, 12, and 13, respectively) are convective clouds created when the temperature decreases rather rapidly with increasing height. Differential heating and converging air currents in this circumstance can therefore send plumes of warmer air skyward with relative ease. Convective clouds are limited in coverage compared with stratiform clouds and, except for the anvil portions of *cumulonimbus* clouds, rarely cover the entire sky or do so only for short periods. This coverage characteristic differentiates, for example, *stratocumulus* clouds with their linked cloud bases covering large portions of the sky, and similar-sized *cumulus* clouds that by definition must be relatively scattered into isolated clouds or small clusters with large sky openings.

Cumulus clouds have a size spectrum of their own that ranges from *cumulus fractus*, those first cloud shreds that appear at the top of the convective boundary layer, to *congestus* size (more than about 2 km deep). Between these sizes are *cumulus humilis* and *cumulus mediocris* clouds, clouds that range between about 1 and 2 km in depth, respectively. The tops of these larger clouds are marked by sprouting portions called turrets that represent the growing and usually warmer parts of the cloud. Individual turrets are generally one to a few kilometers wide, although in strong storms individual turrets may coalesce into groups of many turrets to form

Figure 10 In this busy sky, *cumulus mediocris* is at the center, with *cumulus humilis* in the distance, and *cumulus congestus* on the horizon at left. Also present in this photo is *altocumulus translucidus* (left center), *cirrocumulus* (top center), and *cirrus uncinus* (center above *cumulus* and right center).

Figure 11 Cumulonimbus calvus: this rapidly changing and expanding *cumulonimbus* cloud is in the short-lived calvus stage where fibrousness of the top is just beginning to be apparent. No strong rainshaft has yet appeared below base, though the careful eye can see that considerable ice has already formed aloft (right half of cloud). An intense rainshaft emerged below cloud base a few minutes after this photograph was taken.

Figure 12 Cumulus congestus, *cumulonimbus calvus*, and *cumulonimbus capillatus*. In this line of convection north of Seattle, WA, (nonprecipitating) *cumulus congestus* clouds comprise the left side of the line, while in the center a taller single turret has emerged and reached the *cumulonimbus calvus* stage. The right third of the photograph shows a *cumulonimbus capillatus*, the stage that follows the calvus stage. In the capillatus stage, in this instance consisting of a conglomerate of turrets, the tops have lost their compact cumuliform look and are clearly fibrous and icy. Strands of precipitation are falling below the bases of both types of *cumulonimbus* clouds.

a large, tightly packed, and hard-appearing cauliflower mass that roils upward with little turret differentiation.

Prior to reaching the *cumulonimbus* stage, *cumulus* clouds are therefore composed of droplets and contain very few precipitation-sized particles. Precipitation, however, usually begins to develop in *cumulus congestus* clouds if they are more than about 3 km thick over land and about 1.5 to 2 km thick over the oceans (Ludlum, 1980; Wallace and Hobbs, 1977). The precipitation that falls may be caused by collisions with coalescence of cloud drops in the upper portions of the cloud or it may be a result of the formation of ice particles in clouds with cooler bases. However, in the winter, even small *cumulus* clouds with tops colder than about −10 to −15° C can produce virga, snow flurries, or even accumulating amounts of snow. These kinds of small, cold-based, and precipitating *cumulus* clouds are found in winter in such locations as the Great Lakes of the United States, off the east coasts of the continents, and over high mountains or desert regions (Rangno and Hobbs, 1994).

Figure 13 Cumulonimbus capillatus incus: this well-known species of *cumulonimbus* cloud also has a fibrous and icy top, but it is marked by a noticeable flattening there. Incus translates to "anvil." These types of *cumulonimbus* clouds suggest that the convection has spanned the entire troposphere.

If significant precipitation begins to develop in deep *cumulus* clouds, they quickly take on the visual attributes of *cumulonimbus* clouds (Figs. 11–13)—a strong precipitation shaft is seen below cloud base with a cloud top that is soft, fibrous, fraying, or wispy. The visual transition to a softer, fibrous appearance in the upper portion of *cumulus* clouds is caused by the lowering of the concentrations of the particles from hundreds of thousands per liter of relatively small cloud droplets (< 50-μm diameter), to only tens to hundreds per liter of much larger (millimeter-sized) precipitation-sized particles (rain drops or ice particles). These larger particles tend to fall in filaments and help produce a striated appearance.

In the period while this transformation is taking place and the fibrousness is just becoming visually apparent in the upper portions of a *cumulus congestus* cloud, the cloud is entering a short-lived period of its lifecycle when it is referred to as a *cumulonimbus calvus* ("bald") cloud. At this same time, a concentrated precipitation shaft may not be present yet or is just emerging below the cloud base (Fig. 11).

When the fibrousness of the upper portion of the cloud is fully apparent, the *cumulonimbus* cloud has transitioned to a *cumulonimbus capillatus* (hair) in which most or all of its upper portion consists of ice crystals and snowflakes (Figs. 12 and 13). In the tropics or in warm humid air masses, this visual transformation also occurs but can be due solely to the evaporation of the smaller drops leaving drizzle and raindrops rather than ice and snow in smaller *cumulonimbus* clouds. *Cumulo-*

nimbus capillatus clouds span a wide range of depths, from miniature versions only about 2 km deep in polar air masses over the oceans, to as much as 20 km in the most severe thunderstorms in equatorial regions, eastern China in the summer, and the plains and southeast regions of the United States. If a pronounced flattening of the top develops into a spreading anvil then the cloud has achieved the status of a *cumulonimbus capillatus incus* (incus meaning "anvil").

Hail or graupel (soft hail) are usually found, if not at the ground, then aloft in virtually all *cumulonimbus* clouds that reach above freezing level. Updrafts may reach tens of meters per second in *cumulus* and *cumulonimbus* clouds, particularly in warm air masses. These updrafts lead to large amounts of condensation and liquid water content. Depending on how warm the cloud base is, the middle and upper building portions of deep *cumulus* clouds might contain 1 to 5 $g\,m^{-3}$ of condensed water in the form of cloud droplets and raindrops. Supercooled water concentrations of these magnitudes are sufficient to cause a buildup of about 1 cm or more of ice buildup on an airframe for every one to two minutes in cloud. Therefore, they are avoided by aircraft. *Cumulonimbus* clouds are the only clouds, by definition, that produce lightning. If lightning is observed, the cloud type producing it is automatically designated a *cumulonimbus*.

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