

## 1

## Clouds

Clouds are fascinating to watch for their myriad of shapes. They are also scientifically challenging because their formation requires both knowledge about the large-scale meteorological environment as well as knowledge about the microphysical processes involved in cloud droplet and ice crystal formation.

In this chapter we introduce clouds. In Section 1.1 we highlight their importance for Earth's energy budget and the hydrological cycle. In Section 1.2 we discuss the main cloud types, with their macroscopic properties, as defined by the World Meteorological Organization (WMO), and other, less common cloud types. After this macroscopic description of clouds, we turn to their microphysical properties in Section 1.3.

## 1.1 Definition and importance of clouds

A cloud is an aggregate of cloud droplets or ice crystals, or a combination of both, suspended in air. For a cloud to be visible, the cloud particles need to exist in a sufficiently large concentration. This definition has its origin in operational weather forecasting, where observers indicate the fraction of the sky that is covered with clouds. A more precise definition of cloud cover is used when the information is derived from satellite data, which nowadays provide a global picture of the total cloud cover. Satellites define clouds on the basis of their optical depth, which is the amount of radiation (in our case from the Sun) removed from a light beam by scattering and absorption (Chapter 12).

There are several global cloud climatologies; most of them derived from satellite data, so-called satellite retrievals (Stubenrauch *et al.*, 2009). In the global annual average, roughly 70% of Earth's surface is covered with clouds. The cloud cover is 5%–15% higher over oceans than over land (Table 1.1). The oldest satellite data are from the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer, 1999), which has cloud information dating back to 1983. The ISCCP satellite picture (Figure 1.1) shows that clouds cover more than 90% of the sky in the storm tracks of the Southern Ocean and the semi-permanent Aleutian and Icelandic low pressure regions in the north Pacific and north Atlantic, respectively, as shown in Figure 1.2. High cloud amounts are also seen in the Intertropical Convergence Zone (ITCZ) between the equator and 10°–15° N and in the South Pacific Convergence Zone (SPCZ), which is a northwest to southeast oriented band starting at 120° E and the equator and extending to 120° W and 30° S, as a result of

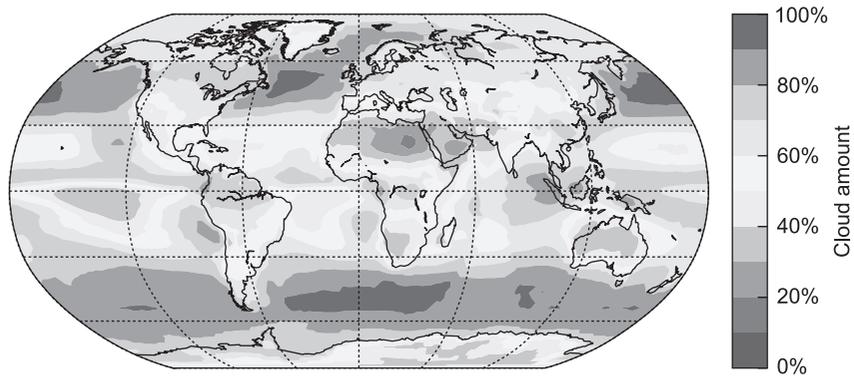


Fig. 1.1

Annual mean total cloud cover [%] averaged over 1983–2009. Data were obtained from the International Satellite Cloud Climatology Project (ISCCP) web site (<http://isccp.giss.nasa.gov/>) in December 2014 and are described in Rossow and Schiffer (1999). A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

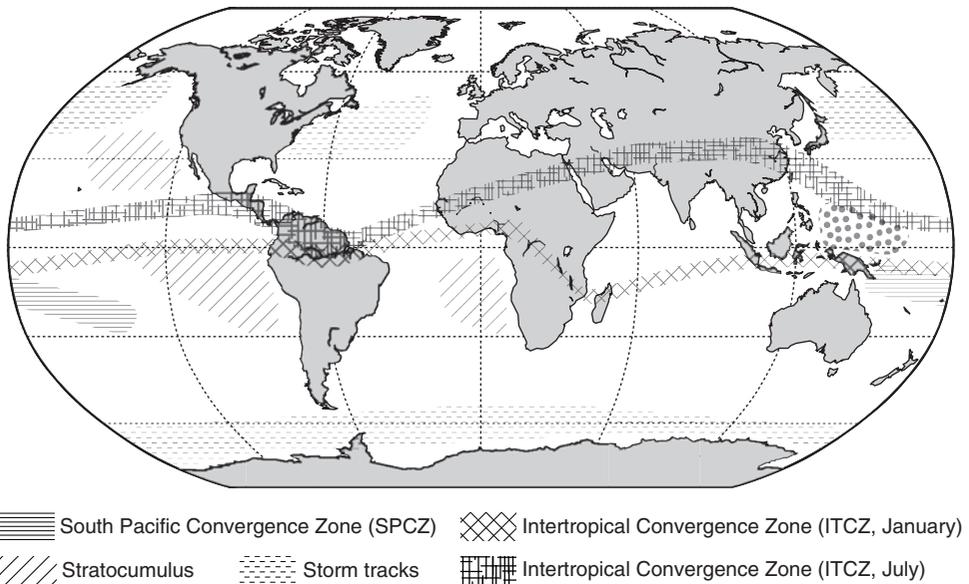


Fig. 1.2

Schematic of the regions where clouds occur most often.

convective activity. The location of the ITCZ has an annual cycle that follows the position of the Sun's zenith but is modulated by the distribution of land masses; see Figure 1.2.

The extensive cloud cover off the west coasts of North and South America and Africa is associated with stratiform clouds that form under subtropical high pressure systems over cold ocean currents. Apart from these regions, the subtropics are characterized by small cloud amounts, in particular over the main deserts, such as the Sahara and the Kalahari as well as the desert and arid regions of Australia and the Arabian Peninsula. Satellite retrievals still have problems in identifying clouds over ice-covered surfaces. Therefore

cloud amounts over polar regions are rather uncertain. In addition, the area of lower cloud amount over the Indian Ocean seen in Figure 1.1 is an artifact due to the poorer satellite coverage in this region.

Clouds are an integral part of Earth's atmosphere and are a major factor in Earth's radiation budget. Their influence on the radiation budget, i.e. their radiative impact, differs for the solar (shortwave) and terrestrial (longwave) radiation and depends on the cloud type and altitude, as will be discussed in Chapter 11.

As part of the hydrological cycle, clouds deliver water from the atmosphere to Earth's surface as rain or snow (Section 9.6). Precipitation removes soluble gases and aerosol particles (Chapter 5) from the atmosphere and deposits them onto the surface. Moreover, clouds provide a medium for aqueous-phase chemical reactions, meaning reactions that take place inside cloud droplets. As an example, sulfate aerosols can be produced by oxidation of gaseous sulfur dioxide upon its uptake into cloud droplets. Furthermore, vertical motions associated with clouds, called updrafts and downdrafts, largely determine the vertical redistribution of trace species, temperature and moisture.

## 1.2 Macroscopic cloud properties and cloud types

Clouds can be grouped into three basic categories, following the French naturalist Jean Baptiste Lamarck (Lamarck, 1802) and English chemist Luke Howard (Howard, 1803), namely cumulus, stratus and cirrus. The Latin term “cumulus” means heap or pile and denotes dense isolated clouds, which appear as white tuberos flowers, composed of individual cloud elements. In a group of cumulus clouds the individual clouds are disconnected from each other. The tower-like structure of cumulus clouds indicates that they usually extend farther in the vertical than in the horizontal. In fact, cumulus clouds form due to convection, i.e. the rising of air masses in locally unstable air. Therefore cumulus clouds are often referred to as convective clouds, where their vertical extent is given by the depth of the instability. In contrast, stratus clouds represent clouds with dimensions that are much larger in the horizontal than in the vertical, as indicated by “stratus”, which means flat. Consequently, they appear as uniform cloud layers when seen from Earth's surface. When stratus clouds cover the whole sky, the sky appears gray and may not have any structure. In contrast with cumulus clouds, stratus clouds are usually formed by large-scale vertical air motions in statically stable air (Rogers and Yau, 1989), i.e. there is little internal vertical motion. Cumulus and stratus can consist entirely of cloud droplets, of ice crystals or of both, depending on temperature and other parameters as will be discussed in Chapters 7 and 8.

Lastly, the word “cirrus” means hair or curl and is used to describe clouds that appear wispy and fibrous, composed of delicate filaments. Cirrus clouds consist purely of ice crystals, which give them their characteristic hair-like appearance. Cirrus clouds have horizontal dimensions that are much larger than their vertical dimension. Because of their low ice water content (Table 1.3), they appear almost transparent. Ice crystals can leave the cirrus clouds as precipitation, which causes the cloud edges to become optically thin and

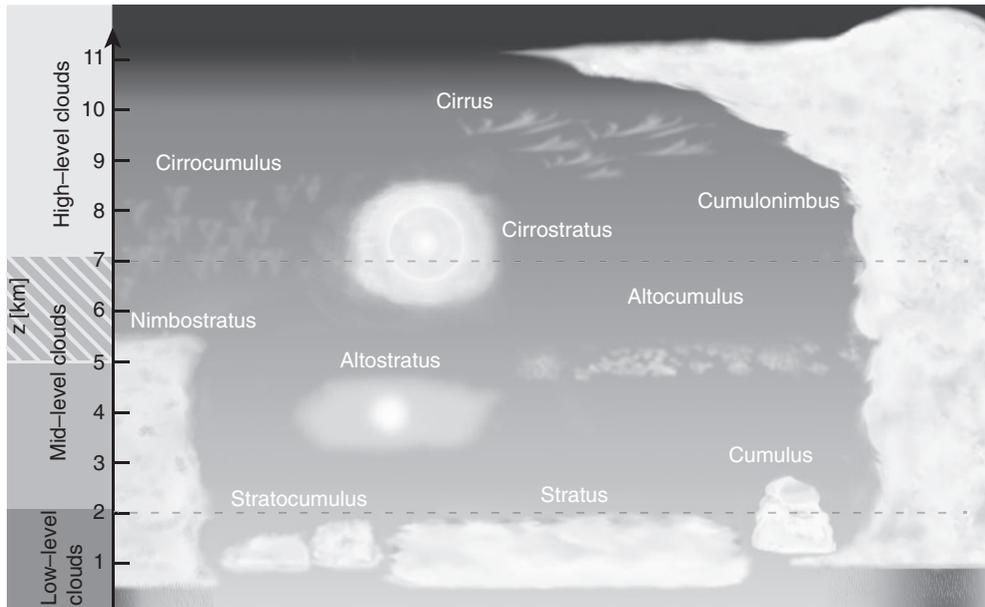


Fig. 1.3

Schematic figure of the ten cloud types according to WMO and as described in Table 1.1. A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

to appear diffuse (Penner *et al.*, 1999). In contrast, cloud droplets are much smaller than ice crystals (Table 1.3) and do not leave the cloud as precipitation until they have grown to raindrop size. Therefore the edges of cumuliform clouds (see below) are quite sharp as long as they consist of cloud droplets.

The WMO further distinguishes clouds in these three categories and specifies them first in terms of the cloud type they belong to, also called “genera”. This defines the main category to which a cloud belongs (WMO, 1975). On the basis of the cloud shape, i.e. the arrangement of the elements that compose it, a cloud type can be further subdivided into “species”. Finally the concept of “varieties” allows one to characterize the spatial arrangement of the macroscopic cloud elements and the associated degree of transparency. Here we confine ourselves to a description of clouds only in terms of genus and species.

A cirrus cloud can be subdivided into the species “uncinus” or “floccus”. Cirrus uncinus describes a cloud which has a comma-like shape (Figure 1.6c). Cirrus floccus, however, occurs as small tufts of cloud.

In total, ten exclusive cloud types exist according to the WMO. They are shown in Figure 1.3. It has proven useful to divide these cloud types into subgroups on the basis of the height at which they occur. The subgroups contain low-level, mid-level and high-level clouds, respectively. Here “level” refers to the altitude of the cloud base above mean sea level. Cloud base heights differ for clouds in polar regions, mid-latitudes and tropical regions and so this term should be considered somewhat flexible. Another important characteristic of clouds is their vertical extent, given by the distance between cloud base and cloud top.

In order to distinguish the various cloud types it helps to ask the following questions: How much of the sky is covered by this cloud? Is the Sun visible and, if so, is the Sun's disk sharply defined or diffuse? Is rain or snow falling from the cloud? If so, is the precipitation widespread or concentrated in narrow shafts? Are particular patterns such as small cloud elements, rolls or undulations visible or does the cloud base appear uniformly gray? Table 1.1 summarizes the ten main cloud types along with their abbreviations, their appearances, their base heights above Earth's surface as well as their global annual averages.

In general, the annual mean cloud coverage is higher over the ocean, 68%, as compared with that over land, 54%. The coverage of stratus, stratocumulus and cumulus clouds is 8%–10% higher over the oceans (Table 1.1) and their cloud bases are at lower altitudes because of the higher relative humidity in the oceanic boundary layer. Cirrus clouds have a larger coverage over land, however. This could be due to a real physical difference or to difficulties in observing cirrus clouds over the oceans (Eastman *et al.*, 2011). One physical explanation for a higher cirrus coverage over land areas is cirrus formation caused by gravity waves triggered when air flows over mountains.

### 1.2.1 Low-level layered clouds

Stratus (St) and stratocumulus (Sc) clouds (Figure 1.4d, e) comprise the low-level layered cloud types. These clouds are shallow stratiform clouds, usually less than 1 km in vertical extent (Rangno, 2002). In terms of appearance St cannot be distinguished from “high fog”, a phenomenon that is common in Alpine valleys. While clouds form due to adiabatic expansion and cooling in rising air parcels or air masses (Section 2.2), fog forms as a result of isobaric cooling and it touches the ground.

Most commonly, fog forms by radiative cooling at night and it occurs most often in the early mornings during autumn and winter. This fog is called radiation fog. At night, the longwave radiation emitted from Earth's surface causes the air to cool. If it is sufficiently moist, the relative humidity can reach 100% with respect to water, allowing condensation to set in. Usually fog does not extend much in the vertical (a few hundred meters at most) so that heating by solar radiation during the day causes the fog droplets to evaporate and the fog to disappear. During winter, when the solar radiation reaching the fog layer is not strong enough to dissipate it, high fog may persist for days. Other types of fog are advection fog, which occurs when moist air passes over a cooler surface, and mixing fog, which occurs when two air masses with different temperatures and high relative humidity mix. An example of mixing fog is steam fog, discussed in Chapter 4.

Stratocumulus clouds show some degree of patchiness, which is why cumulus enters the name. In contrast with cumuliform clouds they are layered and have flattened cloud tops. While neighboring cumuliform clouds can be seen as clearly separate from each other, individual stratocumulus cloud elements are connected, forming a cloud layer. In contrast with stratus clouds, which are purely gray, stratocumulus clouds consist of a pattern of gray and white colors, where the rounded air masses of individual cloud elements can be recognized.

**Table 1.1** The ten cloud types and their acronyms, according to the WMO definition, along with fog. Their typical altitude ranges in polar regions (pr), mid-latitudes (ml) and tropical regions (tr) and their characteristic features (WMO, 1975) are given. Global annual averages of the amounts of the different cloud types obtained from satellite observations (Raschke *et al.*, 2005) and from surface observations over land (1971–2009) and ocean (1954–2008), and their average base heights in km above the surface, are taken from Eastman and Warren (2013) and Khvorostyanov and Curry (2014).

Cloud type/genera	Description	Amount [%]		Base height [km]	
		Land	Ocean	Land	Ocean
Fog	a “cloud” that touches the ground	1	1	0	0
Low-level layered clouds: 0–2 km (pr, ml, tr)		17	35		
Stratus (St)	very low, gray, uniform layer; Sun outline very distinct when visible	2–5	2–13	0.5	0.4
Stratocumulus (Sc)	low, gray–white, patch or layer with elements, rolls or rounded masses	8–13	14–22	1	0.6
Low-level with vertical extent: 0–2 km (pr, ml, tr)		14	24		
Cumulus (Cu)	white, detached, dense elements with shape outlines and vertical growth	5–8	13–15	1.1	0.6
Cumulonimbus (Cb)	very deep, dense and precipitating, with flattened top	3–5	2–6	1	0.5
Nimbostratus (Ns)	gray, dark, diffuse, uniform cloud with steady precipitation	2–4	3–5		0.1–3
Mid-level clouds: 2–4 km (pr), 2–7 km (ml), 2–8 km (tr)		21	24		
Altostratus (As)	uniform or striated gray/blue sheet; Sun can be seen as through translucent glass, i.e. there is no clear outline	4–12	6–7	3–5	(ml)
Alto cumulus (Ac)	gray or white broken sheets, elements, bands, rounded masses	5–17	3–18		2–6 (ml)
High-level clouds: 3–8 km (pr), 5–13 km (ml), 6–18 km (tr)		6–22	6–14		
Cirrus (Ci)	detached white filaments or patches with fibrous appearance or silky sheen				7–10 (ml)
Cirrostratus (Cs)	thin white translucent veil, either fibrous or smooth in appearance (halo)				6–8 (ml)
Cirrocumulus (Cc)	thin white sheet or patch without shading, composed of very small ripples, grains				6–8 (ml)
Total cloud cover		54	68		

Stratus and stratocumulus clouds tend to produce drizzle in clean air masses that are characterized by low concentrations of aerosol particles. These are primarily found over the oceans in the absence of anthropogenic pollution. Drizzle denotes light rain and has drop radii between  $25\ \mu\text{m}$  and  $0.25\ \text{mm}$  (Table 1.2). They are large enough to fall by the action of gravity but are still smaller than raindrops, with radii between  $0.25$  and  $5\ \text{mm}$  (Houze, 1993). Rain and drizzle formation will be discussed in Chapter 7. Sometimes drizzle inhibition over the oceans can be observed in so-called ship tracks, which owe their existence to exhaust from ships. Ship tracks are visible as bright lines (Figure 1.4f). They broaden with time, i.e. with increasing distance from the moving ship, due to the turbulent mixing of environmental air masses with the ship track. This causes the dilution of the ship



Fig. 1.4

(a) Cumulus humilis, Cu hum, (b) cumulonimbus, Cb, (c) nimbostratus, Ns, (d) stratus, St, (e) stratocumulus, Sc, as viewed from above, and (f) satellite image of ship tracks off Europe's Atlantic coast (MODIS Land Rapid Response Team). Photographs taken by Fabian Mahrt (a), (b), (d), (e) and Larissa Lacher (c). A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

track until it either evaporates or cannot be distinguished from the background cloud any longer.

Ship exhausts create a much higher number concentration of aerosol particles than is normally found over the oceans. As will be discussed in Chapter 6, a higher number concentration of aerosol particles causes the cloud to consist of more cloud droplets; this normally implies that the droplets will be smaller as more of them have to compete for the water vapor available for condensation. In Chapter 7 we will see that it takes much longer for small droplets to form precipitation than for large droplets. The time it takes for precipitation formation in a cloud with a high cloud droplet number concentration, such as in a ship track, can be longer than the lifetime of the cloud, so that it dissipates before any precipitation has been formed.

Also, graupel particles may be formed in stratus and stratocumulus clouds (Table 1.3). Graupel refers to heavily rimed snow particles, also called snow pellets when their radius is less than 2.5 mm; above this radius heavily rimed snow particles are called hailstones (Table 1.2). Hailstones may be spheroidal, conical or irregular in shape.

## 1.2.2 Low-level clouds with vertical extent

Convective clouds (cumulus and cumulonimbus) and nimbostratus clouds are characterized by a low base height and a large vertical extent. Though nimbus is the Latin word for a cloud, the term is normally used to denote precipitating clouds. Nimbostratus is always found at mid levels but can extend down to low levels or up to high levels. Since its base height is usually around 2 km, we regard it as having a low-level cloud base. Nimbostratus is a formless cloud that is almost uniformly dark gray; it is thick enough to block the sunlight. Nimbostratus is typically associated with long-lasting stratiform precipitation (Figure 1.4c) and forms when air masses are lifted along a warm front in a low pressure system. Nimbostratus clouds will be discussed in detail in Chapter 9.

Convective clouds, however, develop in unstable air due to buoyancy. In the atmosphere, stability or instability is mainly determined by the vertical temperature gradient. In an unstable atmosphere this gradient is large enough that a rising air parcel (Chapter 2) stays warmer than the surrounding air, in spite of the cooling due to adiabatic expansion. If the air is sufficiently moist, buoyantly rising air parcels can cause the formation of convective clouds, as will be discussed in Chapter 3. Upon cloud formation, the air parcel gains additional buoyancy from the latent heat released during cloud droplet activation and condensational growth (Chapters 6 and 7).

An example of a cumulus cloud, a cumulus humilis (Cu hum), is shown in Figure 1.4a. The designation “Cu hum” is a combination of the genus and the species to which the cloud belongs, where “Cu” denotes that the cloud belongs to the “cumulus” genus and “hum” indicates the species humilis. Cumulus humilis is the smallest cloud of the cumulus genus, with a vertical extent of less than 1 km. Its vertical growth can be restricted by a temperature inversion, i.e. a layer of air in which the temperature increases with increasing altitude and which terminates the upward motion of an air parcel. However, a temperature inversion is not required to stop the growth of cumuli. An air parcel stops rising when its temperature is colder than that of the environment. This height can be predicted by

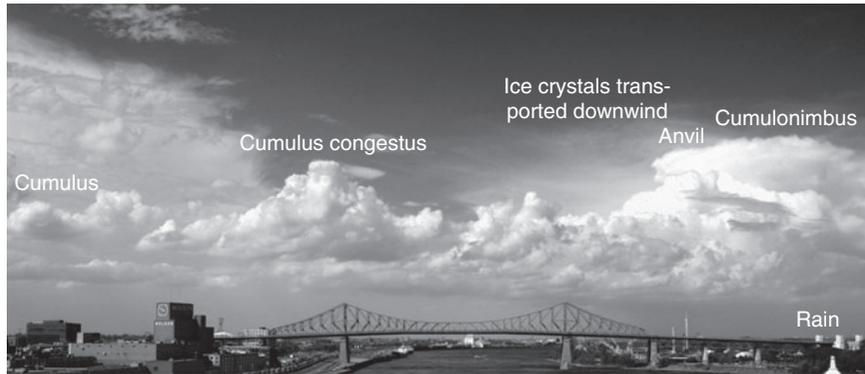


Fig. 1.5

Photograph of cumulus clouds in different stages of development, taken by Fabian Mahrt.

comparing how the environmental temperature changes with height (the ambient lapse rate) with the air parcel's lapse rate (Chapter 3).

Capping inversions or smaller ambient lapse rates cause the uniform cloud top heights of Cu hum; they are a feature of this cumulus species only. A capping inversion often coincides with the top of the planetary boundary layer, which is the lowest layer of the troposphere. Its vertical extent ranges from 50 m during wintertime in the Arctic to over a few hundred meters in mid-latitudes at night and up to 2 km in the tropics.

A cumulus cloud that has a slightly higher buoyancy than the surrounding cumuli is able to penetrate through the capping inversion. There it may develop into the slightly taller cumulus mediocris (Cu med) if the atmosphere above the inversion is unstable, allowing the cloud to extend further vertically. Taller cumuli also develop if the atmosphere is unstable throughout. Like Cu hum, Cu med clouds do not precipitate and frequently develop into cumulus congestus (Cu con, Figure 1.5). This growth occurs over the course of the day if the Sun continues to heat the surface, leading to thermally induced upward motions. Moreover, Cu con can form behind a cold front where the atmosphere becomes increasingly unstable and rising air parcels acquire more buoyancy. These clouds can grow up to heights of 6 km above their cloud bases. They appear as cauliflowers, where the cauliflower elements are indicative of the exchange between cloudy and environmental air in the form of entrainment and detrainment (Chapter 4). They may produce abundant precipitation, especially in the tropics (Johnson *et al.*, 1999). Their sharp outlines suggest that they still consist mainly of cloud droplets even at temperatures below 0 °C.

Cumulus congestus can further develop into cumulonimbus (Cb, Figures 1.4b and 1.5) if the atmosphere becomes even more unstable and the cloud extends high enough that ice crystals form. Part of the buoyancy in cumulonimbus originates from the freezing of cloud droplets into ice crystals and the associated release of latent heat, which warms the cloud relative to its environment and hence causes further upward motion. When Cbs reach the temperature inversion of the tropopause, further ascent is stopped by the stable stratification of the stratosphere. This causes the tops to flatten and the cloud to spread out horizontally leading to the formation of an anvil. Cumulonimbus clouds which have developed an anvil are characterized by a region of active convection on the upwind side and a stratiform

anvil on the downwind side. The smooth fibrous anvils of Cbs are indicative of ice crystals falling with different speeds and sublimating below the cloud.

On a given day, it is common to observe cumuli at different stages of development (Figure 1.5) because of slight differences in buoyancy. After some time the seemingly random cumuli develop some organization, which enables the growth of taller cumuli. They in turn develop downdrafts which can either terminate their lifetime or lead to larger complexes such as multicells and supercells, as will be discussed in Chapter 10. Only Cbs can be accompanied by lightning, thunder or hail. As will be discussed in Chapter 10, the common prerequisite for lightning, thunder and hail is the coexistence of water, ice and strong updrafts.

### 1.2.3 Mid-level clouds

Mid-level clouds comprise altocumulus (Ac) and altostratus (As). They typically owe their existence to the slow upward lifting of air masses (Table 1.3) with updraft vertical velocities on the order of centimeters to tens of centimeters per second over a large area in the mid-troposphere (Rangno, 2002). Altocumulus are usually 200–700 m thick and altostratus clouds are usually 1–3 km thick (Khvorostyanov and Curry, 2014).

Like normal stratus clouds, As clouds are layered with a uniform appearance. Their cloud bases are usually at the mid level of the troposphere, while stratus clouds have base heights around 0.5 km. Even though As clouds are usually found at mid levels, they often extend higher. Moreover, As clouds have smaller optical depths than stratus clouds, i.e. they attenuate radiation less effectively and consequently appear less gray. They are low enough that the Sun's appearance is as if one were looking through translucent glass, meaning that the Sun does not have a clear outline (Figure 1.6a). However, the optical depth of As clouds is larger than that of cirrus clouds. If large-scale altostratus clouds follow cirrostratus clouds, this can often be taken as an indicator of an approaching warm front or occlusion, as will be discussed in Chapter 9.

Like other cumuliform clouds, Ac clouds are associated with local instabilities and convection. They consist of distinct cloud elements and can exist as either detached clouds (altocumulus castellanus) or as rolls in layers and patches (as shown in Figure 1.6b). Altocumulus castellanus clouds observed in the morning are a good indicator of afternoon convection. Altocumulus lenticularis provide a visualization of an oscillatory motion of the air in a statically stable atmosphere, as will be discussed in Section 3.2.

Sometimes precipitation falling from As and Ac clouds is visible in the form of fall-streaks, also called “virga”. Virga is the term for precipitation that evaporates or sublimates before it reaches the ground (Section 7.3).

### 1.2.4 High-level clouds

The three cloud genera constituting in-situ-formed high-level clouds are cirrus (Ci), cirrostratus (Cs) and cirrocumulus (Cc), as shown in Figures 1.6c to 1.6e. Cirrocumulus is a finely granulated cloud, consisting of many small, similar looking, cloud elements. These small granular structures are often arranged in a co-joined regular pattern, where the