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

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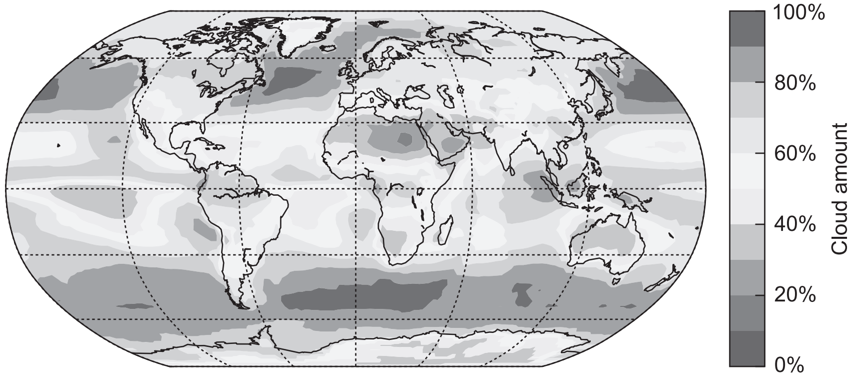

Fig. 1.1 Annual mean total cloud cover [%] averaged over 1983–2009. Data were obtained from the International Satellite Cloud Climatology Project (ISCCP) web site (http://isccp.giss.nasa.gov/) in December 2014 and are described in Rossow and Schiffer (1999). A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

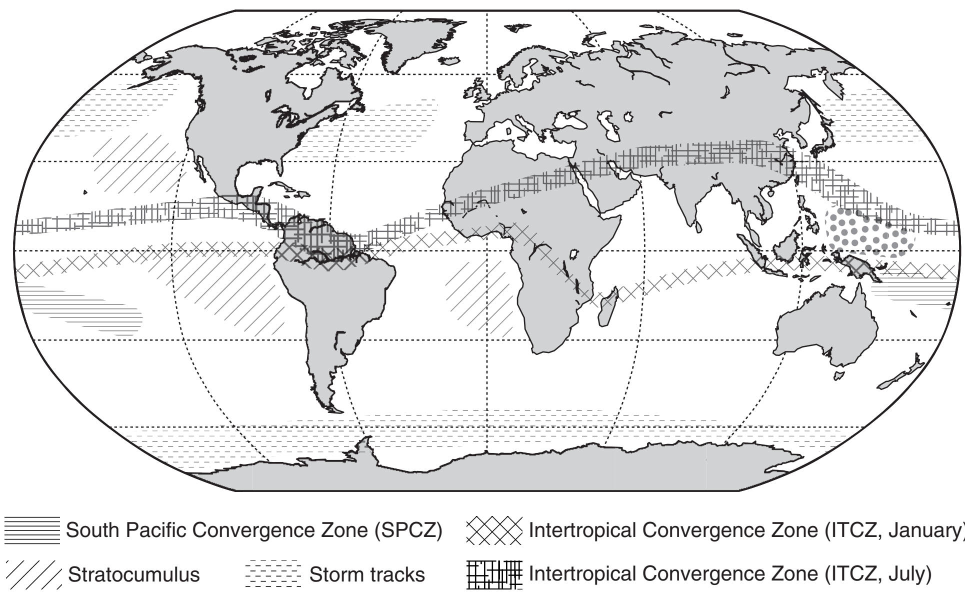

Fig. 1.2 Schematic of the regions where clouds occur most often.

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

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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 tuberose 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

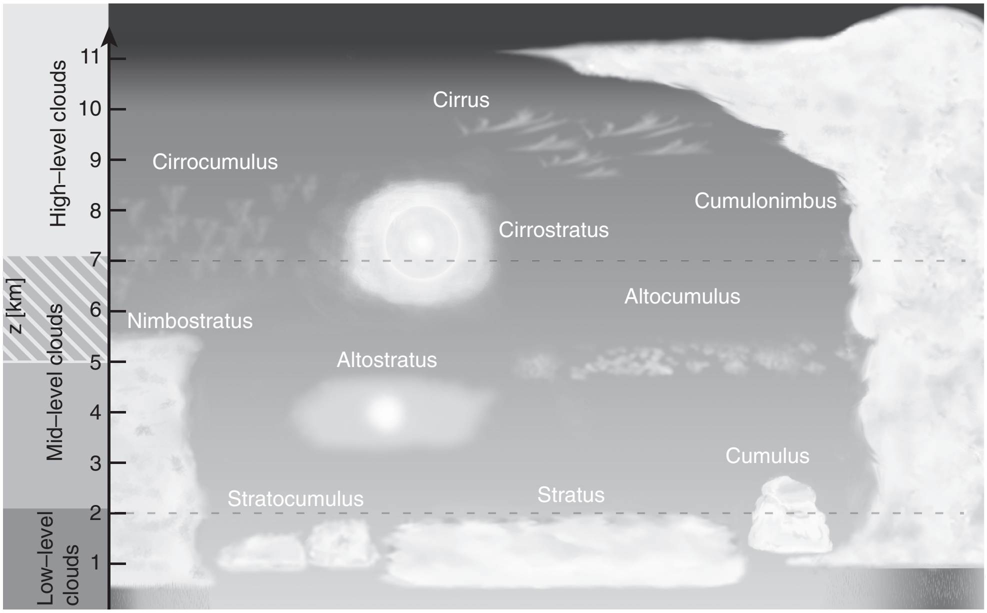

Fig. 1.3 Schematic figure of the ten cloud types according to WMO and as described in Table 1.1. A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

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.

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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.

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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)	
Altocumulus (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 μm and 0.25 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 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.

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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

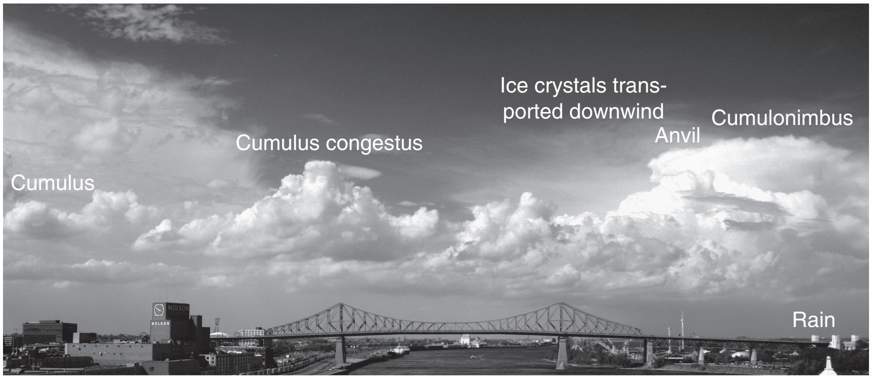

Fig. 1.5 Photograph of cumulus clouds in different stages of development, taken by Fabian Mahrt.

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 fallstreaks, 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

Fig. 1.6 (a) Altostratus, As, (b) altocumulus, Ac, (c) cirrus uncinus, Ci, (d) cirrostratus, Cs, with a 22° halo, and (e) cirrocumulus, Cc. Photographs taken by Robert David (a), Fabian Mahrt (b), (e) and Blaz Gasparini (c), (d). A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

individual cloud elements are identifiable and intersected by small areas of blue sky. Cirrostratus appears as a whitish veil, having a waveless structure where no individual cloud elements can be identified. A distinct characteristic of Cs is the appearance of a halo (Figure 1.6d). Lastly, cirrus consists of delicate filaments. These three cloud genera and the associated species are solely comprised of ice crystals. Because of the decrease of water vapor with height in the troposphere, cirrus clouds have a much lower water content than mid-level or low-level clouds. Thus cirrus clouds are generally not optically dense enough to produce shading, except when the Sun is near the horizon (Rangno, 2015).

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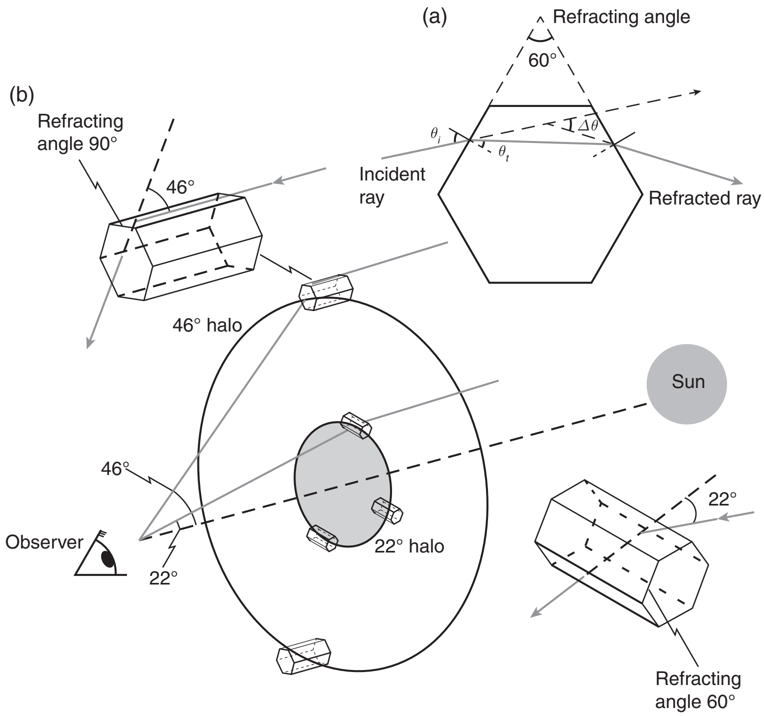

Fig. 1.7 Schematic of halo formation: (a) plan view of the refraction of light in a hexagonal ice crystal and (b) schematic of the formation of 22° and 46° halos.

Small ice crystals can be advected by the wind, causing cirrus clouds to become vertically sheared, as is the case for the cirrus uncinus shown in Figure 1.6c, with characteristic hooks at their upwind ends. However, not all high-level clouds are characterized by this fibrous pattern. Like cumulus clouds, the cirrocumuli shown in Figure 1.6e consist of individual cloud cells rather than of thin ice particle streamers. In fact this cloddy structure characterizes an early stage of cirrus development. When the cloud edges and the ice crystals are advected away from their initial cell, a fibrous appearance develops (Houze, 2014).

One characteristic of cirrus clouds, when viewed from the ground, is that they can produce halos (Figure 1.6d). A halo is an optical phenomenon consisting of a bright ring around the Sun. Figure 1.7a exemplarily shows the trace of a light ray through a hexagonal ice crystal with a refracting angle of 60° (perpendicular to the paper plane), where the incident ray deviates by $\Delta\theta$ from its original path. Light rays are concentrated in the vicinity of the angle of minimum deviation because here changes in the angle of the incident ray lead to hardly any change in the deviation angle. These concentrated rays appear as a bright ring around the Sun with an angular radius of 22° for visible radiation and prism angles of 60°. At angles smaller than the minimum deviation angle no light is refracted, so that the sky is darker inside the 22° halo (Jeske, 1988, Figure 1.7b). Not every cirrostratus produces a halo because it takes a sufficient number of hexagonal ice crystals to be aligned with their z-axes perpendicular to the Sun for the 22° halo, as shown in Figure 1.6d, to be seen. Occasionally a 46° halo also forms, caused by prism angles of 90°, which are found when the light rays enter a side (prism face) of the hexagonal ice crystal and leave it through the bottom (basal face) of the hexagonal crystal. The 90° angle between the prism and basal face causes the 46° halo to be much fainter than the 22° halo since most energy is lost in reflection.

In addition to in-situ-formed high-level clouds, Cbs leave stratiform anvil cirrus behind in their dissipating stage (Chapter 10). Deep convection transports moisture and condensate from the lower troposphere to the upper troposphere, causing anvil cirrus to have a higher ice water content than in-situ-formed cirrus. In addition, anvil cirrus often has a larger vertical extent, and since the ice crystals were formed in regions lower down in the cloud. During transport they have had time to grow to larger sizes than ice crystals in in-situ-formed cirrus (Heymsfield *et al.*, 2013). Because of their larger ice water content, they have a higher optical depth than in-situ-formed cirrus.

1.2.5 Other cloud types

There are some additional cloud types that are not included in the WMO cloud atlas. A cloud type that is restricted to isolated and sharp mountain peaks, such as the Matterhorn in Switzerland or Mount Everest in Nepal, is the banner cloud (Figure 1.8a). It is a cloud plume that extends downwind from such an isolated obstacle even on otherwise cloud-free days. Banner clouds form because an obstacle in a horizontal flow causes the air masses to split: part of the air is forced vertically upward over the obstacle while the remaining air diverges horizontally around it. The diverging air masses cause a lee vortex with a horizontal axis to form. This lee vortex is associated with pronounced upwelling close to the leeward face of the mountain (Voigt and Wirth, 2014). If this air is sufficiently moist, the contained water vapor will condense before the air reaches the top of the mountain and thus forms a banner cloud. This mechanism requires that the air forming the banner cloud on the leeward side of the mountain originates from lower levels than the air on the windward side. If this is not the case, a cloud would also form on the windward side (Schween *et al.*, 2007). After the cloud has been formed, it experiences the main wind flow around the mountain and hence is advected by it, leading to the formation of an elongated banner.

Another rarely observed cloud type is the so-called roll cloud that can be seen above the light horizon (Figure 1.8b). It is characterized by strong updrafts in front of it and down-drafts at its rear causing it to appear as if rolling. This cloud type occurs in connection with land–sea breezes (Section 9.6) and thunderstorm activity. Roll clouds are frequently observed in Australia, where they are associated with the land–sea breeze. The only place where they seem to occur regularly is over the southern part of the Gulf of Carpentaria in northern Australia in the southern hemispheric spring. Because such a cloud typically arrives in the morning at the coast of Queensland, it is also called “morning glory cloud”. Roll clouds can also occur in connection with thunderstorms but are isolated from the thunderstorm cell from which they develop. They indicate the leading edge of thunder-storm outflow (Chapter 10). The roll cloud forms horizontally because of the circulating

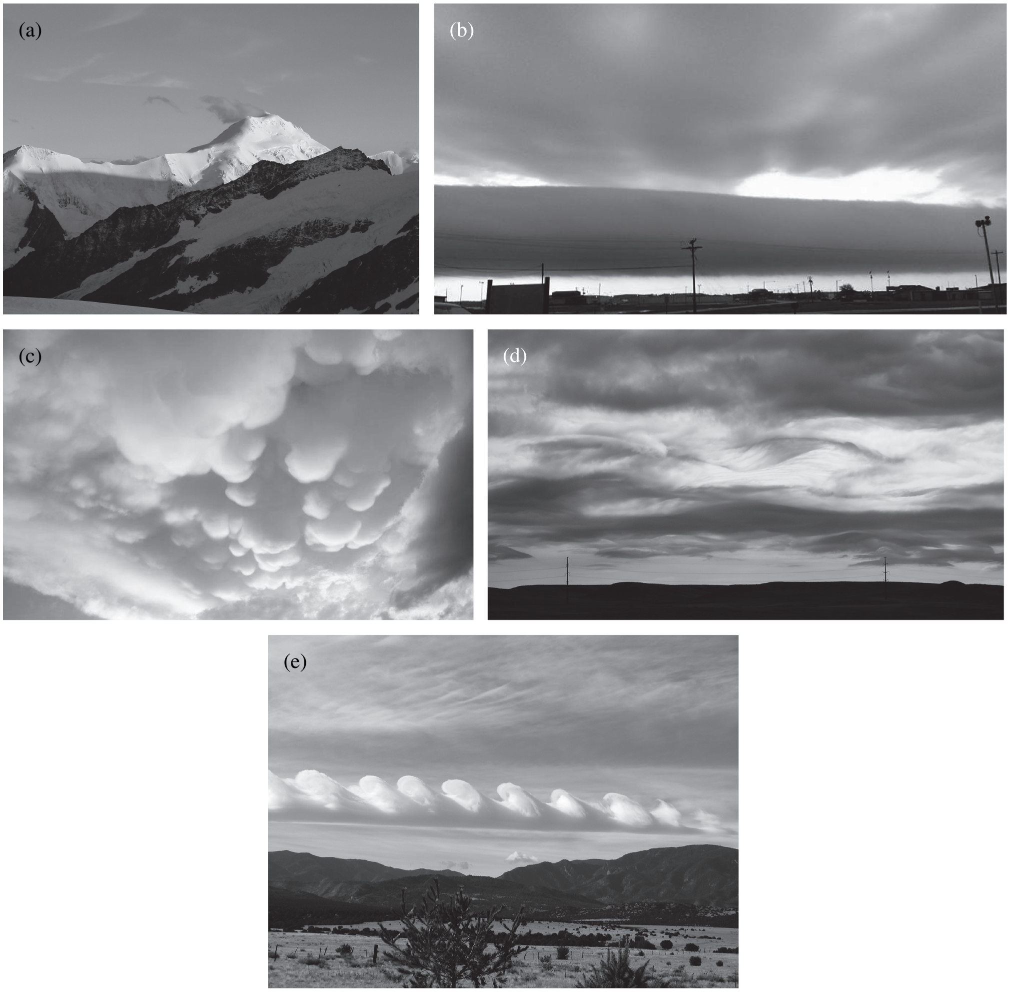

Fig. 1.8 (a) Banner cloud, (b) roll cloud (the dark shape above a light horizon), (c) mammatus cloud, (d) asperatus cloud and (e) Kelvin–Helmholtz wave cloud. Photographs taken by Larissa Lacher (a), Sandra LaCorte (b), Robert David (c), Christian Grams (d) and Laurie Krall (e). A black and white version of this figure will appear in some formats. For the color version, please refer to the plate section.

(rolling) air masses. Along the direction in which the thunderstorm is moving a (cold) front is formed at the leading edge of the storm. It forces the warm air to be lifted and, if it is sufficiently moist, a roll cloud forms.

Mammatus clouds are a rare example of clouds in sinking air (Figure 1.8c). The term "mammatus" refers to the cellular pattern of pouches hanging underneath the cloud base, caused by negative buoyancy. Mammatus clouds typically develop below the anvil of a thunderstorm. The high concentration of heavy hydrometeors (Section 1.3.2) in anvils exerts a gravitational force, so that the air in the anvil starts sinking. The warming of the subsiding air and the associated decrease in relative humidity leads to evaporation or sublimation of the hydrometeors. This in turn causes cooling of the air owing to the latent heat consumption of evaporation or sublimation and counteracts the warming due to

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subsidence. If the amount of energy required for evaporation or sublimation is sufficient to cool the sinking air below the temperature of the surrounding air, the air will continue to sink. The subsiding air with the evaporating or sublimating hydrometeors eventually appears below the cloud base as rounded pouch-like structures.

A similar feature is seen in the so-called asperatus cloud (Figure 1.8d). The term "asperatus" means roughened or agitated and refers to their wavy cloud base. This unique feature distinguishes them from all other cloud types. Asperatus clouds are most closely related to undulatus clouds. Their wavy cloud base again indicates sinking cloudy air. They are particularly common in the Great Plains in North America during the morning or midday after thunderstorms. Even though asperatus clouds appear dark and storm-like, they are harmless leftovers of thunderstorms and will dissipate.

A Kelvin–Helmholtz instability arises from small perturbations at the interface of two fluids with different velocities, an example of which is waves on a lake or ocean. Such an instability can also occur within one medium. In the atmosphere the resulting waves form along the interface between two atmospheric layers with a sufficiently large difference in velocity. The instability is manifested in the form of Kelvin–Helmholtz billows (Figure 1.8e) if the air that originates from the more moist lower layer is lifted high enough for the air to reach saturation and condense.

1.3 Microphysical cloud properties

Besides the classification according to their form and altitude of occurrence, clouds can also be characterized in terms of their microphysical properties. Examples that can readily be observed and have been reported for different cloud types are the number concentrations, sizes and types of the hydrometeors within a cloud and its phase (liquid, ice or a mixture of both).

1.3.1 Cloud phase

Warm clouds consist purely of liquid water (cloud droplets, drizzle drops and raindrops). Their temperature can be above or below 0 °C as long as ice particles are absent. Warm clouds can exist down to temperatures close to −38 °C, below which water freezes homogeneously. We use the terms warm and liquid clouds synonymously. Cold clouds can consist purely of ice crystals (ice clouds) or they can contain a mixture of ice crystals and cloud droplets (mixed-phase clouds). Mixed-phase clouds can be found between 0 °C and −38 °C and pure ice clouds can occur at all temperatures below 0 °C.

Observations of the phase (liquid, mixed-phase, ice) of clouds with temperatures between 0 and −38 °C vary quite drastically. Clouds over the Arctic Ocean have been found to contain liquid water down to temperatures as low as −34 °C (Intrieri *et al.*, 2002). On the contrary, Sassen *et al.* (2003) observed an altocumulus cloud over Florida that was glaciated, meaning that it consisted of ice crystals even at temperatures between −5 and −8 °C. Cloud-phase observations from 11 years of ground-based lidar data over Leipzig, Germany, between 0 to −40 °C showed liquid clouds 42%, ice clouds 46% and mixed-phase clouds 12% of the time (Seifert *et al.*, 2010).

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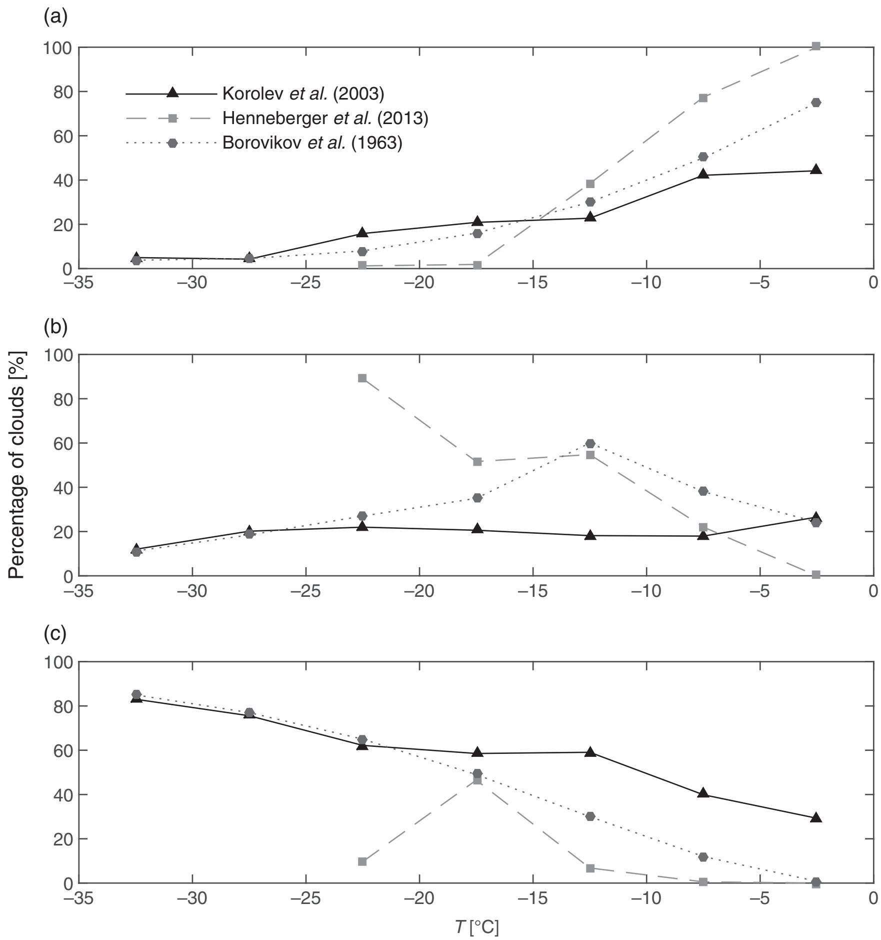

Fig. 1.9 Percentage of (a) liquid water, (b) mixed-phase and (c) ice clouds between −35 and 0 °C as composed from three different studies: frontal clouds over Canada (updated from Korolev *et al.*, 2003), various clouds over Israel (Borovikov *et al.*, 1963) and orographic clouds in the Swiss Alps (updated from Henneberger *et al.*, 2013). No clouds colder than −25 °C were sampled by Henneberger *et al.*

A composite of the percentage of occurrence of liquid water, ice and mixed-phase clouds between −35 and 0 °C obtained from three different in-situ studies is shown in Figure 1.9. A large variation exists between the different data sets. The occurrence of liquid clouds decreases with decreasing temperature, starting with between 40% and 100% of the time at temperatures above −5 °C and decreasing to below 30% at temperatures below −15 °C. A small fraction of liquid clouds is still found at temperatures below −30 °C.

Mixed-phase clouds have been observed over the entire temperature range. Their frequency of occurrence peaks between −20 and −25 °C with more than 80% in the orographic clouds studied in the Swiss Alps in the dataset extended from Henneberger *et al.* (2013). Their occurrence exceeds 50% between −10 and −15 °C in the clouds sampled over Israel and in the Swiss Alps but remains below 30% at all temperatures in the frontal clouds sampled over Canada by Korolev *et al.* (2003).

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Table 1.2 Typical sizes and size ranges of hydrometeors in millimeters.

Size parameter	Typical value	Typical range
Cloud droplet radius	0.005	0.002–0.025
Drizzle drop radius	0.1	0.025–0.25
Raindrop radius	1	0.25–5
Ice crystal length	0.1	0.001–1.5
Snowflake maximum dimension	10	0.1–100
Graupel radius		< 2.5
Hailstone radius		> 2.5

The frequency of occurrence of ice clouds increases with decreasing temperature, starting from between 0 to 30% at temperatures above −5 °C to more than 80% at temperatures colder than −30 °C, in data sets obtained over Canada and Israel. Their frequency of occurrence drops to ∼10% below −20 °C in the orographic clouds studied in the Swiss Alps. These differences in occurrence can be explained by differences in their formation mechanisms. The sampled orographic clouds probably encountered rather high updraft velocities and hence high supersaturation, which permitted the simultaneous existence of cloud droplets and ice crystals (Sections 7.1 and 8.3).

1.3.2 Size distributions and water contents

Cloud particles are also called hydrometeors, but the term "hydrometeor" is more general as it also includes precipitation particles that leave the cloud. Therefore cloud particles are sometimes also referred to as cloud hydrometeors. Typical sizes and size ranges of the various hydrometeors are summarized in Table 1.2. Cloud droplets are the smallest cloud particles, with a typical radius of 5 μm and a range in radius between 2 and 25 μm. Drops between 25 and 250 μm in radius are called drizzle drops. Raindrops are of millimeter size.

In the ice phase, some hydrometeors such as ice crystals and snowflakes are better described in terms of a maximum dimension because their shapes can deviate significantly from a spheroid. Ice particles cannot be categorized by size as neatly as liquid hydrometeors. Ice crystal lengths range between 1 μm and 1.5 mm, which overlaps with the maximum dimension of snowflakes, between 0.1 mm and 10 cm. Only rimed hydrometeors can be separated by size, graupel denoting particles with radii less than 2.5 mm and hailstones anything larger.

The various cloud types consist of differing types of hydrometeors, which have differing size distributions. The number size distributions (also referred to as number distributions or size distributions for brevity) of cloud droplets and ice crystals are commonly described in terms of a three-parameter gamma distribution $n_N(r)$, given as

$$n_N(r) = N_0 r^{\mu} \exp(-\Lambda r). \tag{1.1}$$

Here r is the radius of the hydrometeor and N_0, Λ and μ are the intercept, slope and shape parameters, respectively. Frozen hydrometeors are described either in terms of

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their equivalent radius, i.e. the radius of the water sphere that results when the frozen hydrometeor is melted, or in terms of their maximum dimension.

By integrating over the size distribution, the number concentration N_x in m^{-3} and the mass mixing ratio q_x in kg per kg of air (from now on referred to as kg kg^{-1} for simplicity) of the different hydrometeors, cloud droplets, ice crystals, raindrops, snowflakes, graupel or hailstones, indicated by subscript x, can be obtained as

$$N_x = \int_0^\infty n_N(r)dr = \int_0^\infty N_0 r^\mu \exp(-\Lambda r)\, dr, \tag{1.2}$$

$$q_x = \int_0^\infty m(r) n_N(r)dr = \int_0^\infty m(r) N_0 r^\mu \exp(-\Lambda r)\, dr, \tag{1.3}$$

where $m(r)$ is the hydrometeor mass as a function of the hydrometeor radius r. Raindrops and snowflakes tend to follow an exponential distribution (Chapter 9), which is equivalent to a gamma distribution with shape parameter zero (i.e. $\mu = 0$).

Instead of mass mixing ratios, in-situ observations often report water content, for example the liquid water content (LWC) or ice water content (IWC). These refer to the amount of water or ice per cubic meter of air and are usually given in g m^{-3}.

The formation of precipitation depends on the water content of a cloud as well as on the cloud droplet or ice crystal number concentration. The LWC and IWC together with the cloud droplet and ice crystal number concentration determine the average sizes of the cloud droplets and ice crystals. In addition to being important for the initiation of precipitation-sized particles, the sizes of hydrometeors also determine the optical properties of the cloud, for instance the fraction of the sunlight that it reflects back to space (Chapter 12).

Typical values and ranges of these microphysical properties for the cloud types introduced above are summarized in Table 1.3. Generally, the smallest cloud droplets and the highest number concentrations N_c of cloud droplets are found in clouds over land. The value of N_c is determined by the number concentration of aerosol particles that serve as cloud condensation nuclei (CCN) (Chapter 6). Generally CCN concentrations are higher over land. In addition, N_c depends on the water vapor excess over the equilibrium value, the so-called supersaturation. Supersaturation is produced by adiabatic cooling in rising air parcels and thus is determined by the updraft velocity (Chapter 7). Updraft velocities are generally higher over land than over ocean because the land heats up more quickly than the ocean owing to its smaller heat capacity. This is turn produces more buoyancy and higher vertical velocities, which activates more and smaller aerosol particles (Chapter 6). Therefore cloud droplets of the same cloud genera are generally more numerous and smaller over land than over oceans.

An example of typical observed cloud droplet number concentrations in marine and continental cumuli is given in Figure 1.10 (Squires, 1958). It shows that N_c is much smaller in marine cumuli than in continental cumuli because there are fewer CCN in marine air. In addition, the typically lower updraft velocities in marine air cause lower supersaturations. Therefore only the larger aerosol particles, which are less numerous (Chapter 5), can become activated and form cloud droplets (Chapter 6). As a result, N_c rarely exceeds 200 cm^{-3} in marine cumuli, while N_c reaches up to 950 cm^{-3} in continental cumuli. Owing to the lower N_c values in marine clouds, cloud droplets experience less competition for the available water vapor. Therefore cloud droplets are capable of growing to larger sizes more

Table 1.3 Typical macroscopic and microphysical properties for various cloud types (compiled from the WMO cloud atlas (WMO, 1975), Pruppacher and Klett (1997), Miles *et al.* (2000), Lehmiller *et al.* (2001), Quante (2004), Deierling and Petersen (2008), Krämer *et al.* (2009), Cotton *et al.* (2011), Wood (2012), Khvorostyanov and Curry (2014) and Linda Schlemmer, personal communication); "oc" refers to clouds over oceans and "la" to clouds over land.

Parameter	Typical value	Typical range
Fog		
N_c [cm^{-3}]	150	1–600
Cloud droplet radius [µm]	7.5	1–15
LWC [g m^{-3}]	< 0.2	0.05–0.5
Vertical velocity [m s^{-1}]	0.01	
Vertical extent [km]	0.1	0.05–0.6
Lifetime [h]	4	2–6
St, Sc: rain (Sc), drizzle (Sc,St), snow possible		
N_c [cm^{-3}]	75 (oc), 290 (la)	10–300 (oc), 40–1000 (la)
Cloud droplet radius [µm]	7 (oc), 4 (la)	2–12.5
LWC [g m^{-3}]	0.2	0.1–0.6 (oc), 0.05–0.5 (la)
Vertical velocity [m s^{-1}]	0.01	
Vertical extent [km]	0.5	0.2–0.7 (oc), 0.2–0.9 (la)
Lifetime [h]	6	2–12
Cu hum, Cu med		
N_c [cm^{-3}]		100–1000
Cloud droplet radius [µm]	14 (oc), 6 (la)	2–25
LWC [g m^{-3}]	0.3	0.2–1
Vertical velocity [m s^{-1}]		1–3
Vertical extent [km]	1.5	
Lifetime [min]	20	10–40
Cu con: rain, snow and graupel possible		
LWC [g m^{-3}]		0.5–2.5
Vertical velocity [m s^{-1}]		3–10
Vertical extent [km]	5	
Lifetime [min]	30	20–45
Cb: rain (always), snow, graupel and hail possible		
LWC [g m^{-3}]		1.5–14
Vertical velocity [m s^{-1}]		5–50
Vertical extent [km]	9	6–12
Lifetime [min]	60	45–180
Ns: rain (always), snow and ice pellets possible		
LWC [g m^{-3}]		0.2–0.5
Vertical velocity [m s^{-1}]	1	1–2
Vertical extent [km]	4	2–10
Lifetime [h]		6–12

Table 1.3 (Continued)

Parameter	Typical value	Typical range
Ac, As: rain, snow, ice pellets		
N_c [cm^{-3}]	100	30–1000
Cloud droplet radius [μm]	4	2–10
LWC, IWC [g m^{-3}]	0.2	0.01–0.5
Vertical velocity [m s^{-1}]	<0.5 (As), <1 (Ac)	0.01–1
Vertical extent [km]	0.5 (Ac), 1 (As)	0.2–0.7 (Ac), 1–3 (As)
Lifetime [h]		6–12
Cc, Ci, Cs		
N_i [cm^{-3}]	0.2	10^{-4}–10
Ice crystal length [μm]	100	1–1500
IWC [g m^{-3}]	0.02	10^{-4}–0.5
Volume mean ice crystal radius [μm]	20	2–80
Vertical velocity [m s^{-1}]	0.1	0.01–1.5
Vertical extent [km]		0.2–0.4 (Cc), 0.1–3 (Cs)
Lifetime [h]		0.2–12

quickly in marine clouds than in continental clouds. In the marine cumuli shown in Figure 1.10b, cloud droplets grow up to 30 μm in radius at higher altitudes whereas they remain below 10 μm in radius in the continental cumuli at all altitudes (Figure 1.10c).

Similar differences, in terms of size distribution and number concentration, to those between marine and continental clouds are found between polluted and clean clouds. An example of an observed size distribution of cloud droplets (N_c) and drizzle drops (N_d) in marine clouds off the coast of Nova Scotia, Canada, is shown in Figure 1.11 (Peng *et al.*, 2002). These data are sorted according to their aerosol concentration (N_a), measured with an instrument which sampled aerosol radii larger than 0.07 μm. In this study, clouds with $N_a < 300$ cm^{-3} were considered clean and those with $N_a > 300$ cm^{-3} were considered polluted. The polluted clouds have average concentrations $N_a = 810$ cm^{-3}, $N_c = 260$ cm^{-3} and $N_d = 8 \times 10^{-4}$ cm^{-3}. In contrast, the clean clouds have average concentrations $N_a = 160$ cm^{-3}, $N_c = 70$ cm^{-3} and $N_d = 9.4 \times 10^{-3}$ cm^{-3}.

Figure 1.11 shows that the concentration of small cloud droplets (with $r < 5$ μm) is larger in the polluted clouds than in the clean clouds. At a radius of about 7.5 μm the curves intersect so that the concentration of larger drops is larger in the clean clouds. The gap in the data between radii 25 μm and 55 μm is caused by use of different instruments to obtain the size distributions and their respective measurement size ranges.

The differences between clean versus polluted or marine versus continental clouds show that "typical" cloud droplet size distributions for a given cloud type do not exist. In addition to differences in aerosol concentration and vertical velocity at the cloud base, clouds of the same cloud type can have different values of the temperature at the cloud base, which determines the growth rate of the cloud droplets (Chapter 7). They can also experience different levels of mixing with the ambient air (Chapter 4). Lastly, they could have been sampled at different stages of their life cycle and at different heights above cloud base. Therefore, large variations exist between the individual size distributions of the various cloud types.

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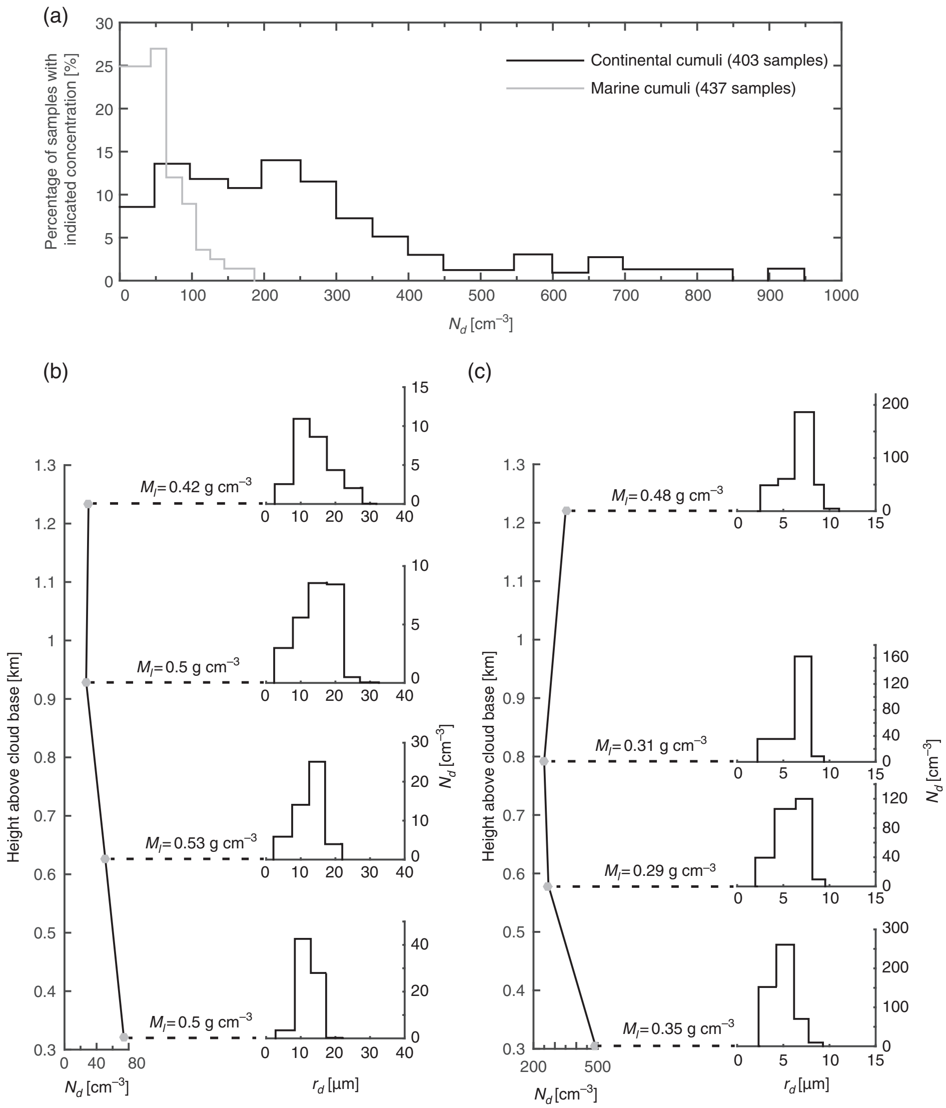

Fig. 1.10 Observed cloud droplet number concentrations in marine and continental cumuli. (a) Percentages of marine and continental cumuli with indicated droplet concentrations. (b), (c) Change in the droplet concentration and size distribution with height above cloud base in marine and continental cumuli; M_l denotes the liquid water content. Note the different *x*-axis scales in (b) and (c). Figure adapted from Squires (1958).

A few general differences between certain cloud types can be stated, with caution, keeping the above points in mind. As shown in Figure 1.10, cloud droplets are larger higher up in a cloud; thus one can expect that as a fair weather cumulus continues to develop into a cumulus congestus, the cloud droplets become larger and fewer in number, mainly owing to their growth by collision–coalescence between cloud droplets (Section 7.2). Also, a comparison of stratus and stratocumulus with Cu hum and Cu med shows that cumuli have higher updraft velocities than stratus clouds, causing N_c to typically be higher in cumulus

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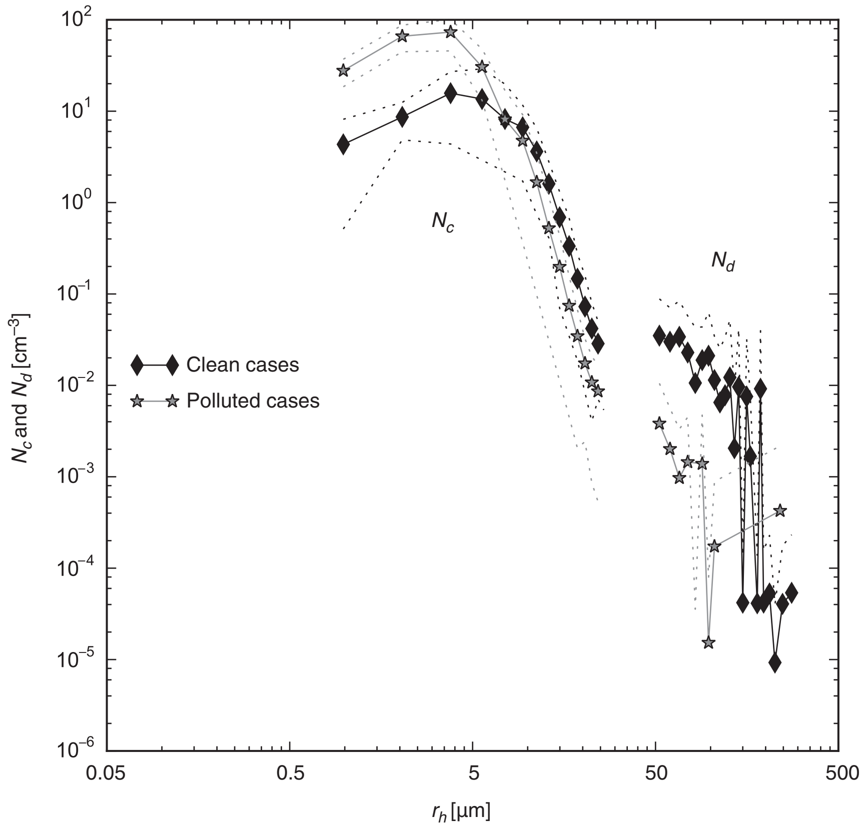

Fig. 1.11 Cloud droplet N_c and drizzle drop N_d size distributions for clean clouds (diamonds) and polluted clouds (asterisks). Each point refers to the averaged concentration over all clean or all polluted clouds. The solid and dotted lines give the averages and the standard deviations for the clean and polluted cases, respectively. The values of N_d minus one standard deviation are not shown because they extend below the lowest values shown. Figure adapted from Peng *et al.* (2002).

than in stratus and stratocumulus. Clouds which can produce precipitation (mainly Ns, Cb and Cu con) typically have broader drop size distributions, with drop radii exceeding 15 μm. In addition they often have an ice phase.

Because aerosol number concentrations decrease with altitude, the number concentration of CCN also decreases, which results in smaller cloud droplet number concentrations in mid-level clouds (Ac and As) than in the respective low-level clouds (Sc and St). As discussed above, the water vapor mixing ratio decreases exponentially with altitude in the troposphere, owing to the decrease in temperature with increasing altitude. If less water vapor is available, less can condense or deposit and form cloud droplets or ice crystals. Therefore, the liquid and ice water content also decreases with increasing height of the cloud base. The decrease of water vapor with increasing altitude is generally stronger than the decrease in the number of CCN with the result that mid-level clouds have smaller cloud droplets than low-level clouds.

Cirrus clouds are characterized by the lowest number concentrations and the largest average ice crystal size. However, there is a large spread in the microphysical properties of cirrus clouds (Tables 1.2 and 1.3). This is partly due to the different mechanisms by which cirrus clouds form and partly due to uncertainties in measurements. The variety of ice crystal shapes and sizes, as will be discussed in Chapter 8, additionally complicates the characterization of ice clouds.

1.4 Exercises

Single/multiple choice exercises

1. Clouds form an important part of the hydrological cycle and the Earth's radiation budget. Which of the following is/are true?
   (a) In the global annual average, around 70% of the Earth's surface is covered with clouds.
   (b) The North Atlantic storm tracks, the Intertropical Convergence Zone and the subtropics are associated with high cloud amounts.
   (c) Satellites can distinguish between clouds and sea ice.
   (d) All cloud types have a net cooling effect on the Earth's surface because they reflect solar radiation.
2. Clouds are classified into three basic categories, namely cumulus, stratus and cirrus clouds. Which of the following is/are true?
   (a) Stratus clouds form in statically stable air.
   (b) Cumulus clouds usually have a larger vertical than horizontal dimension.
   (c) Cumulus and stratus clouds consist purely of cloud droplets, whereas cirrus clouds consist of ice crystals.
   (d) Clouds are often classified according to their cloud top height.
3. Low-level clouds are characterized by a low cloud base height. Which of the following is/are true?
   (a) Stratus and high fog cannot be distinguished in terms of their appearance and formation mechanisms.
   (b) Nimbostratus forms when air is lifted along a warm front and is associated with convective precipitation.
   (c) Convective clouds form in unstable air masses.
   (d) Lightning and thunder can occur in cumulonimbus and nimbostratus.
4. High-level clouds have a base height of 5–13 km in mid-latitudes. Which of the following is/are true?
   (a) Both cirrus and low stratus clouds can produce halos.
   (b) All cirrostratus produce halos.
   (c) Cirrus clouds have a high optical depth.
   (d) Gravity waves can lead to the formation of cirrus clouds.
5. Assign the following attributes to the corresponding cloud type: (1) halo, (2) convective precipitation, (3) wavy cloud base, (4) touches the ground. Cloud types: (i) stratus, (ii)

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cirrostratus, (iii) nimbostratus, (iv) cumulonimbus, (v) mammatus cloud, (vi) asperatus cloud, (vii) cumulus, (viii) fog.
(a) 1i, 2iv, 3vi, 4viii
(b) 1i, 2iii, 3v, 4viii
(c) 1ii, 2iv, 3vi, 4viii
(d) 1ii, 2iii, 3v, 4i
(e) 1ii, 2iv, 3vii, 4i

6. Clouds consist of cloud droplets and/or ice crystals. Which of the following is/are true?
   (a) Warm clouds consist purely of liquid water, and thus the temperature in these clouds is above 0 °C.
   (b) Mixed-phase clouds are the most frequent type.
   (c) The temperature in cold clouds cannot exceed 0 °C.
   (d) The number concentrations and sizes of cloud droplets and ice crystals determine optical cloud properties.
7. The microphysical properties differ for clouds over land and clouds over ocean. Which of the following is/are true?
   (a) Cloud droplets over land are usually smaller than over the ocean.
   (b) The cloud droplet number concentration in continental cumulus clouds can reach up to 950 cm^{-3}.
   (c) Cumulus clouds have an average lifetime of less than 1 hour.

Long exercises

1. Figure 1.12 shows examples of the different cloud types introduced. Which types of cloud are represented in the photographs? Describe their characteristics and classify them as either low-level, mid-level or high-level cloud.
2. Which cumulus cloud is associated with capping inversions? How does the capping inversion influence the appearance of that cloud type?
3. What is a halo and how does it form?
4. Assume a low level cloud with the following properties: vertical extent 1.5 km, horizontal extent 1 km, cloud droplet number concentration 90 cm^{-3} air and mean diameter 10 μm. Estimate the mass of the cloud by assuming that all the cloud droplets are spherical and have the same size. Take 1000 kg m^{-3} to be the density of water.
5. The average pressure at Earth's surface is 985 hPa. Knowing the radius of the Earth r_{Earth} = 6370 km and using the definition of pressure, estimate the total mass of the atmosphere.
6. Imagine a pure water cloud which consists of cloud droplets of uniform size with $r_d = 5\ \mu m$. Assume a uniform spacing of the cloud droplets, with a number concentration of $N_c = 170\ cm^{-3}$.
   (a) Calculate the average distance apart $\bar{d}$ of the cloud droplets, using

$$\frac{\bar{d}}{\bar{r}_d} = \frac{0.893}{M_l^{1/3}}, \tag{1.4}$$

   where M_l denotes the liquid water content of the cloud.

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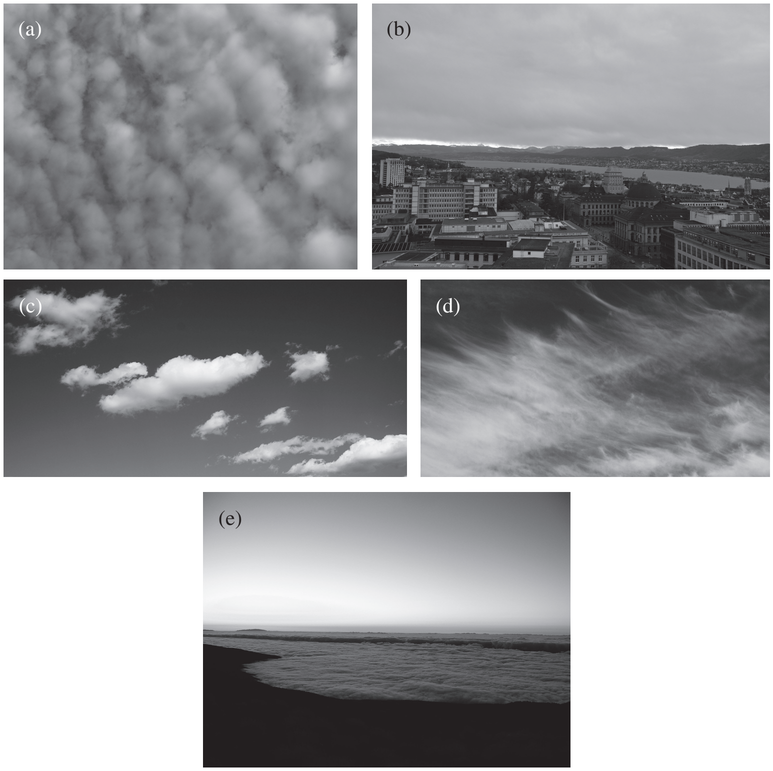

Fig. 1.12 Photographs of different cloud types, taken by Fabian Mahrt.

(b) For the same M_l as calculated above, what would happen to the average distance between cloud droplets if their number concentration was tripled?

7. Consider a developing Cb cloud in mid-latitudes that grows vertically, experiencing an updraft velocity $w = 12.5$ m s^{-1}. Assume a cloud base at 500 m.
   (a) How long does it take until the Cb cloud reaches the tropopause at 13 km?
   (b) How does this time compare with a typical time scale on which a thunderstorm forms in mid-latitude summer?
   (c) What happens once the rising air parcel (cloud top) reaches the tropopause?
8. A stratus cloud has a typical vertical velocity of $w = 0.01$ m s^{-1}. Assume typical values for the vertical extent of a stratus cloud of 900 m over land and 500 m over the ocean.
   (a) How long does it take for an air parcel to be transported up the vertical extent of the cloud, i.e. from cloud base to cloud top of the stratus cloud, over land and ocean, respectively?
   (b) How do these times compare with the lifetimes of a stratus cloud in Table 1.3? How do you explain the differences?
   (c) Now repeat the calculations for typical values of a Cu con cloud in Table 1.3 and compare with those obtained for the stratus cloud. Interpret your results.