1

Observation of clouds

1.1 Water vapor in the atmosphere

The clouds in our atmosphere are a condensed form of water (water droplets and ice particles) suspended in air. Such a system is called an aerosol. Naturally, the necessary constituent in air for forming clouds is water vapor. Thus it is important for us to understand the general situation of water vapor in our atmosphere.

Water vapor is so pervasive in our daily life that many do not know that its concentration is actually quite small. Table 1.1 lists the five major gaseous constituents and their volume concentrations in the Earth's atmosphere. Water vapor ranks fourth after N_2, O_2, and Ar.

Water vapor is also different from the other four gases in another important aspect: whereas the concentrations of N_2, O_2, Ar, and CO_2 remain fairly constant from place to place, the concentration of H_2O is highly variable. The layer immediately above the warm tropical ocean surface is literally steaming with water vapor; the highest value is ~ 4% (tropical Indian Ocean), whereas the surface layer over the Sahara Desert in North Africa or the Taklimakan Desert in western China is close to 0%. Thus, even though the water vapor concentration in the whole atmosphere is more than that of CO_2, as shown in Table 1.1, there are places in the world where its concentration is less than that of CO_2.

Water vapor concentration also varies with height. In general, water vapor is most concentrated near the surface, and it becomes more and more dilute with height. This occurs naturally because the source of water vapor is at the Earth's surface, mainly the world's oceans, while rivers, lakes, polar ice sheets and glaciers also serve a minor role. Globally, the air in tropical regions generally contains more water vapor than in middle and higher latitudes. Fig. 1.1 shows the variation of zonal mean water vapor mixing ratio with latitude and altitude. The mixing ratio, in units of $g\ kg^{-1}$, is the number of grams of water vapor per kilogram of dry air and is a form of *absolute humidity.*

Table 1.1 *The five most concentrated gaseous constituents of the Earth's atmosphere.*

Name	Concentration (volume)
Nitrogen (N_2)	78.084%
Oxygen (O_2)	20.946%
Argon (Ar)	0.934%
Water vapor (H_2O)	~ 0.4%
Carbon dioxide (CO_2)	0.039%

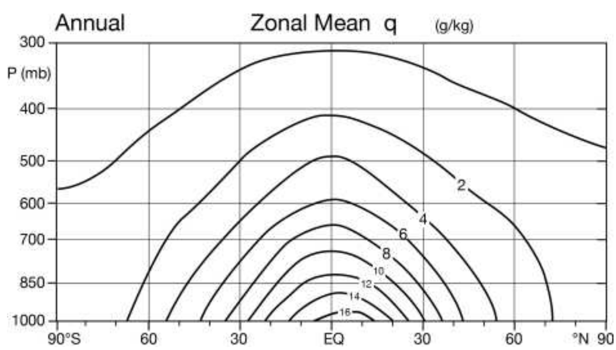

Fig. 1.1 Zonal mean water vapor mixing (g kg^{-1}) field as a function of latitude and altitude (in pressure units).

Another unusual characteristic of water vapor is that it can condense into either liquid or solid form in our atmosphere, a feat that no other gas in our natural environment can achieve. Indeed, water is the only natural substance that is present in all three phases in the Earth's surface environment – water vapor is of course ubiquitous in the atmosphere, but clouds consist of both liquid water droplets and ice particles. Liquid water oceans cover about 70% of the Earth's surface, along with many rivers and lakes. A large amount of ice exists in glaciers in high mountains and ice caps in polar regions.

This peculiar character of water makes the behavior of our atmosphere especially complicated and difficult to study. The phase change of water involves the release or consumption of latent heats that directly impacts the weather process, making accurate weather prediction difficult because it is not easy to predict precisely where, when, and how much condensation will occur. Condensation also makes the accurate estimate of moisture in the atmosphere a difficult task because it is difficult to measure accurately how much condensate there is in the atmosphere. The current estimates of cloud amounts and precipitation contain very large errors. The details of the cloud distribution (both horizontally and vertically) influence the radiation budget of the Earth–atmosphere system and should be considered carefully in any climate studies.

On longer time scales, the condensation of water also plays very important roles. In our atmosphere, clouds can produce precipitation, which represents one of the most powerful forces to shape the surface of the Earth. Precipitation forms rivers and glaciers that eliminate rugged high mountains and produce deep valleys over geological time scales. In fact, it was the formation of rain at the beginning of the current (secondary) atmosphere that dissolved most of the CO_2, SO_2, and other water-soluble gases that were present in the ancient atmosphere and led to our current nitrogen-dominated atmosphere. In contrast, the clouds in the atmosphere of our neighboring planets, Venus and Mars, do not produce rain, and consequently their atmospheres are very "dry" and dominated by CO_2 (see, for example, Walker, 1977).

1.2 Where do clouds occur in the atmosphere?

Although the mixing ratio of water vapor is an index of absolute humidity, the high value of mixing ratio alone does not necessarily mean lots of clouds. Rather, the occurrence of clouds depends more on the *relative humidity*, which measures the degree of saturation and hence the likelihood of condensation of the air.

Almost all (more than 99%) of the water vapor resides in the troposphere, with the stratosphere containing less than 1%. Thus, it is not surprising that almost all clouds that we encounter daily from a small fair-weather cumulus to very large cumulonimbus occur entirely within the troposphere. Even the clouds of very strong storm systems, such as hurricanes and tornadoes, are basically confined within the troposphere. Fig. 1.2 shows this situation graphically. Specific cloud types will be discussed later in the chapter.

Occasionally, we do see clouds in the stratosphere, but they are normally not water clouds. Rather, they are made mostly of sulfuric or nitric acid aerosol particles and are called *nacreous clouds* or *mother-of-pearl* clouds because they exhibit brilliant iridescent colors due to the diffraction of sunlight by the aerosol particles. Such clouds are particularly common in the stratosphere of polar regions, and hence are called polar stratospheric clouds (PSCs). They may play an important role in the depletion of stratospheric ozone in Antarctica and produce the "ozone hole" phenomenon.

Another kind of clouds, called *noctilucent* (night-glowing) clouds, occur even higher up – in the mesosphere. When they do appear, they can be seen as very high bright clouds even though it is already dark on the surface. They appear to be bright at night because the Sun is still shining on them due to their altitude. These clouds are not made of water either and are not the subject of this book.

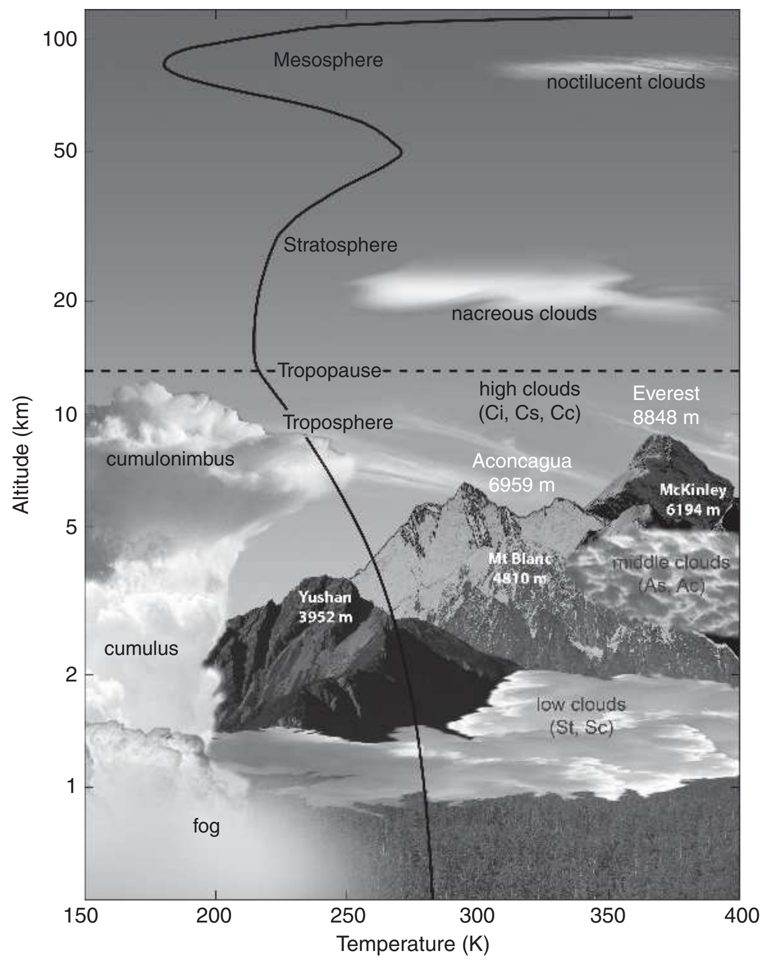

Fig. 1.2 A schematic guide of the height level of various cloud types. The solid curve represents the vertical temperature profile of the atmosphere. The elevations of a few mountains are indicated as a reference. Note that the height is in logarithmic scale.

1.3 Conventional classifications of clouds

The central point of scientific classification is to identify one or more suitable characteristics of the subject as the basis for classification. The two main characteristics upon which the conventional cloud classification scheme is based are (1) cloud visual texture and (2) cloud-base height. The visual texture of clouds is based on that seen by the observer on the ground. This scheme was originally introduced by the British meteorologist Luke Howard in 1803 and has since been modified and expanded; it was adopted by the World Meteorological Organization

(WMO) in 1956 after some modifications. Since the subject of cloud types is usually covered in more elementary meteorology textbooks, our discussion here will be brief.

The most commonly used scheme classifies clouds into four different height categories and three different basic textures. The three basic texture categories are the cirriform, stratiform, and cumuliform. Cirriform is only used to describe high clouds whose texture resembles curly hair or fibers. Stratiform clouds are clouds with more or less uniform, layer-like structure that tend to cover a large part or even the whole sky. Cumuliform clouds, on the other hand, have a patchy structure that looks like cells or fish scales. They can cover either a large part or just a small part of the sky. The reason they look like that has something to do with their dynamical environment. It is common to list the height groups and then to distinguish different types in that group according to their visual texture appearance. Each type may also have subtypes, which will not be discussed in this book, and sometimes it is not easy to determine exactly what designation a cloud should have. It is also possible that a cloud is undergoing transition from one type to another, and the designation may become ambiguous.

1.3.1 High clouds (base height greater than 6000 m)

This group consists of three types – cirrus (often abbreviated as Ci), cirrostratus (Cs), and cirrocumulus (Cc). Conventionally, all high clouds are thought to consist completely of ice crystals, although this notion has been called into question lately, as some observations have suggested that the liquid state in the form of aqueous solution droplets may exist in high clouds. Figs. 1.3–1.5 show the typical cases of the cirrus, cirrostratus, and cirrocumulus, respectively. Although “cirri” refers to the filament texture, in reality only cirrus has that characteristic when observed from the ground. Cirrostratus occasionally exhibits that characteristic but usually appears as a relatively uniform layer, but cirrocumulus never has that curly hair texture.

Fig. 1.3 shows a typical cirrus cloud with the clear texture of curly hair. This texture indicates the presence of wind shear at that level, and the falling ice crystals carried by the wind form the virga filaments. The filaments can be short, like the ones shown here, or very long, and may stretch across the whole sky.

Fig. 1.4 shows an example of a cirrostratus cloud. It has some recognizable curls but also a layer feature that is usually not easy to see if it is thin. The surest sign of the presence of Cs in the sky is the halo, a white circle around the Sun or Moon, as seen in this photograph. The sky inside the circle is slightly darker than outside. The Sun here is blocked by the satellite dish. But the presence of a Sun halo in this case positively identifies the cirrostratus layer in addition to the curls.

Fig. 1.5 shows an example of a cirrocumulus cloud. Both cirrocumulus and altocumulus (see below) have fish-scale-like texture, but cirrocumulus is usually

Fig. 1.3 Cirrus (Ci). Photo by P. K. Wang.

Fig. 1.4 Cirrostratus (Cs). Photo by P. K. Wang.

thinner and will not cast a shadow. The photograph shows the Sun's corona caused by the presence of the cirrocumulus.

High clouds are usually optically thin and allow sunlight (or moonlight) to shine through and they can produce spectacular optical phenomena called *halos* because of the ice crystals in them, as seen in Fig. 1.4. Halos are caused by the refraction of

Fig. 1.5 Cirrocumulus (Cc). Photo by P. K. Wang.

light by ice crystals and are different from the *coronae* that are caused by the interference of light diffracted by cloud particles, which can be either water droplets or ice particles.

Cirrus clouds also exist at the top of thunderclouds in the form of an anvil, but in that case they are considered as part of the thundercloud (cumulonimbus, see later in this section) unless they are blown away and become detached from the thundercloud.

Before the 1980s, high clouds were usually thought to be "harmless", that is, they did not seem to influence the atmospheric processes very much, although they have been used as an indicator of some weather processes. But since then it has been realized that the ice crystals in high clouds can interact strongly with solar and terrestrial radiation in both the visible and infrared bands, and can exert substantial impact on the global climate process. Cirrus clouds are now being studied more vigorously by the research community. We will have more discussions of the climatic impact of high clouds in Chapter 15.

1.3.2 Middle clouds (base height between 2000 and 6000 m)

There are two types of clouds that belong to this family: altostratus (As) and altocumulus (Ac). Examples of them are shown in Figs. 1.6 and 1.7. They consist of either water drops or a mixture of water drops and ice particles. Altostratus clouds

Fig. 1.6 Altostratus (As). Photo by P. K. Wang.

Fig. 1.7 Altocumulus (Ac). Photo by P. K. Wang.

are usually produced by large-scale lifting associated with a low-pressure system and hence may indicate the approach of bad weather. Altocumulus, on the other hand, is usually associated with good weather. Perhaps it is more useful to note that the weather is changing for the better if we observe that altostratus is gradually breaking up into patches and turning into altocumulus. This indicates that large-scale lifting, which is responsible for altostratus formation, is diminishing and is being replaced by smaller-scale weak convection indicated by the appearance of altocumulus, indicating better weather to come.

1.3.3 Low clouds (base height lower than 2000 m)

This group consists of three types: stratus (St), stratocumulus (Sc), and nimbostratus (Ns). Examples of them are shown in Figs. 1.8–1.10. They are often thick, dark, and cover a large part of the sky. Among the three, stratocumulus clouds show identifiable chunky structure, unlike stratus and nimbostratus, which are more uniform and continuous horizontally. All three can be associated with rain, although the rain intensity varies. Stratus and stratocumulus are usually associated with drizzle, light rain or no rain at all. The stratocumulus clouds sometimes form by the rain that falls from a layer of altostratus above it. Nimbostratus is always associated with rain (the prefix “nimbo” means rain) and have a more diffuse appearance at the cloud base. However, it is often difficult to distinguish nimbostratus from stratus by just looking at a photograph.

Low clouds are traditionally thought to consist of liquid droplets. However, more recent observations show that low clouds also contain ice particles when the environmental temperature is cold. Stratocumulus clouds are very common over the ocean and cover a wide area. They play an important role in the radiative balance of the Earth–atmosphere system.

Fig. 1.8 Stratus (St). Photo by P. K. Wang.

Fig. 1.9 Stratocumulus (Sc). Photo by P. K. Wang.

Fig. 1.10 Nimbostratus (Ns). Photo by P. K. Wang.

1.3.4 Clouds with vertical development

This last family of clouds has a common characteristic: they are formed in an environment of relatively strong updrafts. The normal synoptic-scale updraft is on the order of 1 cm s^{-1} (Holton, 2004). In contrast, the environment in which this