Lecture 7

Clouds and Precipitation

6.1 Introduction

Clouds, spectacular features in the sky, add beauty and color to the natural landscape. As they form, vast quantities of heat are released into the atmosphere. Clouds help regulate the earth's energy balance by reflecting and scattering solar radiation and by absorbing the earth's infrared energy. And, of course, without clouds there would be no precipitation. But clouds are also significant because they visually indicate the physical processes taking place in the atmosphere; to a trained observer, they are signposts in the sky.

6.2 Cloud Development and Stability

Clouds form as air rises, expands, and cools. Basically, the following mechanisms are responsible for the development of the majority of clouds we observe:

1. surface heating and free convection.
2. topography.
3. widespread ascent due to the flowing together (convergence) of surface air.
4. uplift along weather fronts.

6.3 Convection and Clouds

Some areas of the earth's surface are better absorbers of sunlight than others and, therefore, heat up more quickly. The air in contact with these “hot spots” becomes warmer than its surroundings. A hot “bubble” of air-a thermal-breaks away from the warm surface and rises, expanding and cooling as it ascends. If the rising air cools to its saturation point, the moisture will condense, and the thermal becomes visible to us as a cumulus cloud. the air motions are downward on the outside of the cumulus cloud. The downward motions are caused in part by evaporation around the outer edge of the cloud, which cools the air, making it heavy. Therefore, we have rising air in the cloud and sinking air around it. Since subsiding air greatly inhibits the growth of thermals beneath it, small cumulus clouds usually have a great deal of blue sky between them (see Fig. 7.1).

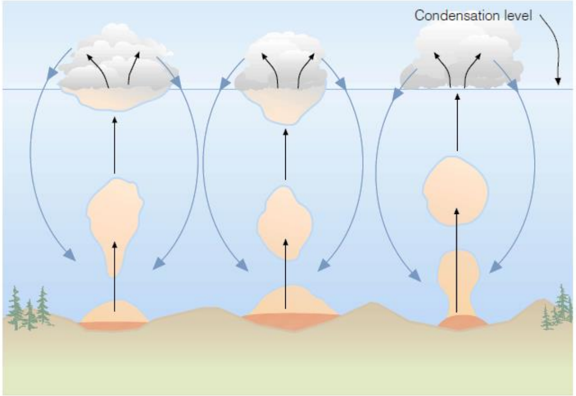

Fig. 7.1 Cumulus clouds form as hot, invisible air bubbles detach themselves from the surface, then rise and cool to the condensation level. Below and within the cumulus clouds, the air is rising. Around the cloud, the air is sinking.

The stability of the atmosphere plays an important part in determining the vertical growth of cumulusclouds. For example, if a stable layer (such as an inversion) exists near the top of the cumulus cloud, the cloud would have a difficult time rising much higher, and it would remain as a “fair-weather” cumulus cloud. However, if a deep, conditionally unstable layer exists above the cloud, then the cloud may develop vertically into a towering cumulus congestus with a cauliflowerlike top.

When the unstable air is several kilometers deep, the cumulus congestus may even develop into a cumulonimbus (see Fig. 7.2). Notice in Fig. 7.2 that the distant thunderstorm has a flat anvil-shaped top. The reason for this shape is due to the fact that the cloud has reached the stable part of the atmosphere, and the rising air is unable to puncture very far into this stable layer. Consequently, the top of the cloud spreads laterally as high winds at this altitude (usually above 10,000 m) blow the cloud’s ice crystals horizontally.

Fig. 7.2 Cumulus clouds developing into thunderstorms in a conditionally unstable atmosphere

6.4 Topography and Clouds

Horizontally moving air obviously cannot go through a large obstacle, such as a mountain, so the air must go over it (orographic uplift). Often, large masses of air rise when they approach a long chain of mountains. This lifting produces cooling, and if the air is humid, clouds form. Clouds produced in this manner are called orographic clouds. An example of orographic uplift and cloud development is given in Fig. 7.3. Notice that, after having risen over the mountain, the air at the surface on the leeward (downwind) side is considerably warmer than it was at the surface on the windward (upwind) side. The higher air temperature on the leeward side is the result of latent heat being converted into sensible heat during condensation on the windward side. In fact, the rising air at the top of the mountain is considerably warmer than it would have been had condensation not occurred.

Notice also in Fig. 7.3, that the dew-point temperature of the air on the leeward side is lower than it was before the air was lifted over the mountain. The lower dew point and, hence, drier air on the leeward side is the result of water vapor condensing and then remaining as liquid cloud droplets and precipitation on the windward side. This region on the leeward side of a mountain, where precipitation is noticeably low, and the air is often drier, is called a rain shadow.

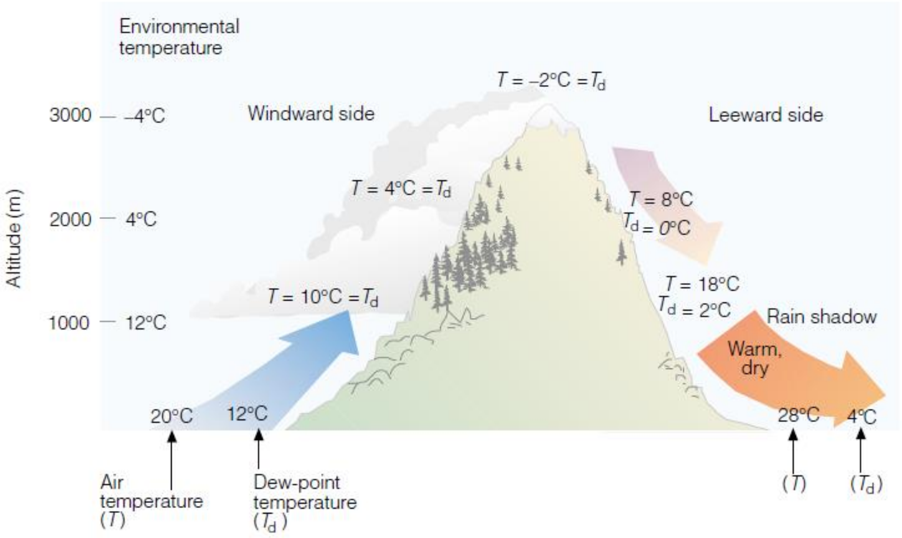

Fig. 7.3

Orographic uplift, cloud development, and the formation of a rain shadow.

6.5 Precipitation Processes

The cloudy weather does not necessarily mean that it will rain or snow. In fact, clouds may form, last for many days, and never produce precipitation. How, then, do cloud droplets grow large enough to produce rain? And why do some clouds produce rain, but not others?

In Fig. 7.4, we can see that an ordinary cloud droplet is extremely small, having an average diameter of 0.02 mm. Also, notice in that the diameter of a typical cloud droplet is 100 times smaller than a typical raindrop. Clouds, then, are composed of many small droplets-too small to fall as rain. These minute droplets require only slight upward air currents to keep them suspended.

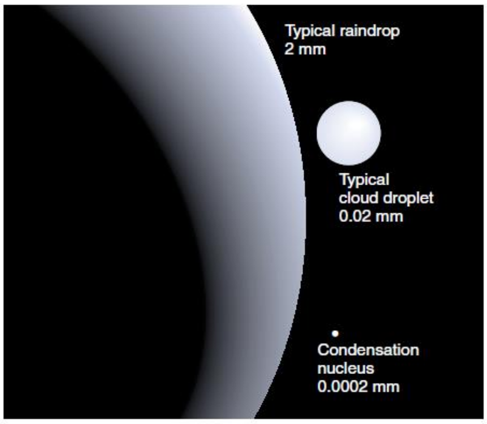

Fig. 7.4 Relative sizes of raindrops, cloud droplets, and condensation nuclei.

The condensation begins on tiny particles called *condensation nuclei*. The growth of cloud droplets by condensation is slow and may take several days for this process alone to create a raindrop. It is evident, then, that the condensation process by itself is entirely too slow to produce rain. Yet, observations show that clouds can develop and begin to produce rain in less than an hour. Since it takes about 1 million average size cloud droplets to make an average size raindrop, there must be some other process by which cloud droplets grow large and heavy enough to fall as precipitation.

Even though all the complexities of how rain is produced are not yet fully understood, two important processes stand out: (1) the collision-coalescence process and (2) the ice-crystal (or Bergeron) process.

6.6 Collision and Coalescence & the Bergeron Process

In order for cloud droplets, which are very small, to become rain drops, they have to increase in size almost a million times. Indeed, for even a cloud droplet to form, complicated processes must take place allowing for the conversion of water vapor to liquid water. Often times in the atmosphere this process would be virtually impossible without the presence of aerosols. Before we look at this process involving cloud condensation nuclie (CCN), let us first examine the case without them, known as homogeneous nucleation.

We have said before that the process of the change of state from vapor to liquid is called condensation. Also, this will occur when the relative humidity reaches 100%, or when the vapor pressure equals the saturation vapor pressure. However, pure water will condense only when levels of saturation reach upwards of 120% (20% supersaturation). The reason being that the spherical shape a water droplet forms is a very unstable structure, hence resisting formation of the droplet. It is not until these high levels of saturation are reached that the forcing will overcome this resistance known as surface tension.

The process known as heterogeneous nucleation involves "polluting" the pure water with aerosols, or CCN. By adding CCN, water is allowed to condense with much lower values of supersaturation.

Now that cloud droplets have formed, we will try to understand how they can grow to the size of a raindrop. One such way is through collision and coalescence. Cloud droplets will be carried by air currents within the cloud, and if they bump into each other, it is called a collision. However, if they collide then stick together, that is called coalescence. Although this process is important, especially in the tropics and in increasing the size of raindrops, it falls short of being the primary mechanism for the formation of raindrops. There is another more effective process was discovered by Bergeron.

The Bergeron process relies primarily on the fact that the saturation vapor pressure with respect to ice is less than the saturation vapor pressure with respect to water. Another important fact is that pure water droplets do not freeze at 0°C! Again, because of surface tension and the structure of water, to get a pure water droplet to freeze requires a temperature of -40°C.

Liquid water that is cooler than 0 °C is called supercooled. In the atmosphere, similar to CCN, there exist freezing nuclei. In contrast to CCN, freezing nuclei are not plentiful in the atmosphere because there structure must be similar to the structure of an ice crystal. Most of the naturally occurring freezing nuclei "activate" at about -10° C. These freezing nuclei allow for the cloud droplets to freeze around them. Because of the relative sparseness of the freezing nuclei, ice crystals and supercooled water droplets can coexist at the same time. This is where the Bergeron's primary fact becomes important.

The following chart illustrates the differences in saturation vapor pressures of water.

The Bergeron process can be summarized as such: The air reaches saturation and some of the resulting droplets will come in contact with freezing nuclei (assuming they have reached the activation temperature). We will now have a combination of ice crystals and supercooled water droplets. From the perspective of the supercooled droplets, the air is in equilibrium at saturation, but from the perspective of the ice crystals, the air is supersaturated. Therefore, water vapor will sublimate on the ice crystals. Since the amount of water vapor in the air has decreased, and from the perspective of the supercooled water droplet, the air is subsaturated, the supercooled water will evaporate until the air once again reaches saturation. The process then continues. In short summary, the ice crystal grows through sublimation at the expense of the supercooled water droplet. (Ref: http://weather.cod.edu/sirvatka/bergeron.html)

6.7 Cloud Seeding and Precipitation

The primary goal in many experiments concerning cloud seeding is to inject (or seed) a cloud with small particles that will act as nuclei, so that the cloud particles will grow large enough to fall to the surface as precipitation. The first ingredient in any seeding project is, of course, the presence of clouds, as seeding does not generate clouds. However, at least a portion of the cloud (preferably the upper part) must be supercooled because cloud seeding uses the icecrystal process to cause the cloud particles to grow. Some of the first experiments in cloud seeding were conducted the late 1940s. To seed a cloud, they dropped crushed pellets of dry ice (solid carbon dioxide) from a plane. Because dry ice has a temperature of -78^{o}C, it acts as a cooling agent. Small pellets dropped into the cloud cool the air to the point where droplets are able to change into ice in an instant. The newly formed ice crystals then grow larger at the expense of the nearby liquid droplets and, upon reaching a sufficiently large size, fall as precipitation.

In 1947, silver iodide (AgI) was used as a cloud-seeding agent. Because silver iodide has a crystalline structure similar to an ice crystal, it acts as an effective ice nucleus at temperatures of –4°C and lower.

6.8 Precipitation in Clouds

In cold, strongly convective clouds, precipitation may begin only minutes after the cloud forms and may be initiated by either the collision-coalescence or the ice-crystal process. Once either process begins, most precipitation growth is by accretion.

Although precipitation is commonly absent in warmlayered clouds, such as stratus, it is often associated with such cold-layered clouds as nimbostratus and altostratus.

This precipitation is thought to form principally by the ice-crystal process because the liquid water content of these clouds is generally lower than that in convective clouds, thus making the collision-coalescence process much less effective. Nimbostratus clouds are normally thick enough to extend to levels where air temperatures are quite low, and they usually last long enough for the ice-crystal process to initiate precipitation.

6.9 Precipitation Types

Up to now, we have seen how cloud droplets are able to grow large enough to fall to the ground as rain or snow. While falling, raindrops and snowflakes may be altered by atmospheric conditions encountered beneath the cloud and transformed into other forms of precipitation that can profoundly influence our environment.

RAIN Most people consider rain to be any falling drop of liquid water. To the meteorologist, however, that falling drop must have a diameter equal to, or greater than, 0.5 mm to be considered rain. Fine uniform drops of water whose diameters are smaller than 0.5 mm are called drizzle. Most drizzle falls from stratus clouds; however, small raindrops may fall through air that is unsaturated, partially evaporate, and reach the ground as drizzle. Occasionally, the rain falling from a cloud never reaches the surface because of the rapid evaporation (called virga).

Beneath a cumulonimbus cloud, which normally contains large convection currents, it is entirely possible that one side of a street may be dry (updraft side), while a heavy shower is occurring across the street (downdraft side). Continuous rain, on the other hand, usually falls from a layered cloud that covers a large area and has smaller vertical air currents. These are the conditions normally associated with nimbostratus clouds.

6.10 Measuring Precipitation

Any instrument that can be used to collect and measure rainfall is called a rain gauge. A standard rain gauge is commonly used to measure rainfall. This instrument consists of a funnel-shaped collector attached to a long measuring tube (see Fig. 7.5).

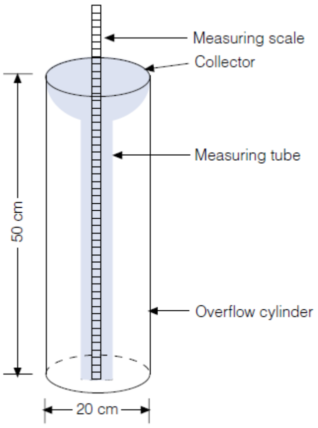

Fig. 7.5 Components of the standard rain gauge

The depth of snow in a region is determined by measuring its depth at three or more representative areas.

6. 11 Doppler Radar and Precipitation

Atmospheric scientists use radar to examine the inside of a cloud much like physicians use X-rays to examine the inside of a human body. Essentially, the radar unit consists of a transmitter that sends out short, powerful microwave pulses. When this energy encounters a foreign object-called a target-a fraction of the energy is scattered back toward the transmitter and is detected by a receiver. The returning signal is amplified and displayed on a screen, producing an image or “echo” from the target. The elapsed time between transmission and reception indicates the target’s distance. The brightness of the echo is directly related to the amount (intensity) of rain falling in the cloud. So, the radar screen shows not only where precipitation is occurring, but also how intense it is. Typically the radar image is displayed using various colors to denote the intensity of precipitation within the range of the radar unit.