Lecture 8

Atmospheric Circulation

7.1 Scales of Atmospheric Motion

The air in motion-what we commonly call wind-is invisible, yet we see evidence of it nearly everywhere we look. The wind is with us wherever we go. A breeze can sharpen our appetite when it blows the aroma from the local bakery in our direction. The wind is a powerful element. It transports heat, moisture, dust, insects, bacteria, and pollens from one area to another.

Circulations of all sizes exist within the atmosphere. Little whirls form inside bigger whirls, which encompass even larger whirls-one huge mass of turbulent, twisting eddies. For clarity, meteorologists arrange circulations according to their size. This hierarchy of motion from tiny gusts to giant storms is called the *scales of motion*. Table (8.1) lists the main scales of motion in the atmosphere. Also the figure (8.1) shows some examples of the scales.

Table (8.1) Atmospheric scales of motion

Scale Category	Time Scale	Spatial Scale	Example
microscale	seconds to minutes	< 1 km	turbulence, small cumulus clouds
mesoscale	minutes to hours to 1 day	1 to 100 km	thunderstorms, sea breeze, mountain, circulations
synoptic scale	days to weeks	100 to 5000 km	cyclones, fronts, anticyclones
planetary scale (or global scale)	weeks to months	1000 to 40000 km	planetary waves (westerlies), trade winds, El Nino

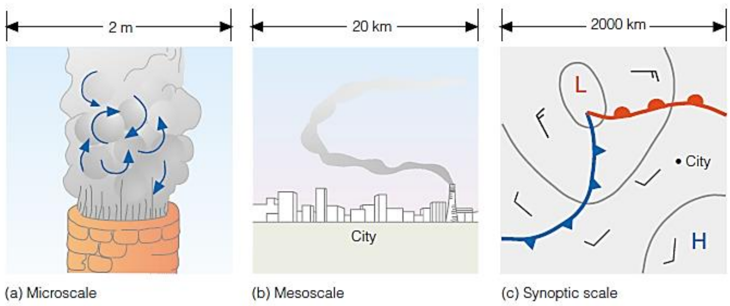

Figure (8.1) Examples of atmospheric scales, a. eddies in the smoke rising from a chimney, b. smoke moves above a city, c. low, high, and front systems.

8.2 Eddies-Big and Small

When the wind encounters a solid object, a whirl of air- or eddy-forms on the object's downwind side. The size and shape of the eddy often depend upon the size and shape of the obstacle and on the speed of the wind. Light winds produce small stationary eddies. Wind moving past trees, produces small eddies. Air flowing over a building produces larger eddies that will, at best, be about the size of the building. Wind blowing over a fairly smooth surface produces few eddies, but when the surface is rough, many eddies form.

The eddies that form downwind from obstacles can produce a variety of interesting effects. For instance, wind moving over a mountain range in stable air with a speed greater than 40 knots (20 m/s) usually produces waves and eddies, such as those shown in Fig. 8.2. We can see that eddies form both close to the mountain and beneath each wave crest. These so-called rotors have violent vertical motions that produce extreme turbulence and hazardous flying conditions.

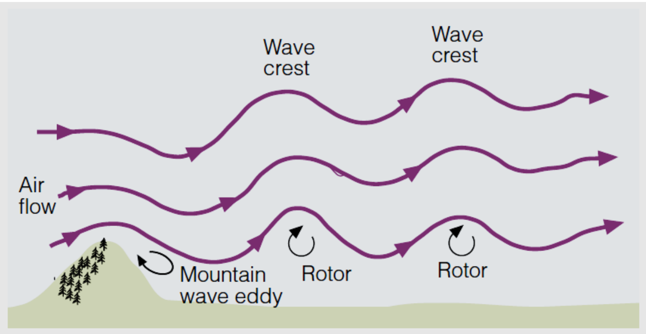

Figure (8.2) Under stable conditions, air flowing past a mountain range can create eddies many kilometers downwind from the mountain itself.

8.3 Thermal Circulation

Consider the vertical distribution of pressure shown in Fig. 8.3a. The isobars all lie parallel to the earth’s surface; thus, there is no horizontal variation in pressure (or temperature), and there is no pressure gradient and no wind. Suppose the atmosphere is cooled to the north and warmed to the south (Fig. 8.3b). In the cold, dense air above the surface, the isobars get closer together, while in the warm, less dense air, they spread farther apart. This dipping of the isobars produces a horizontal pressure gradient force (PGF) aloft that causes the air to move from higher pressure toward lower pressure. At the surface, the air pressure remains unchanged until the air aloft begins to move. As the air aloft moves from south to north, air leaves the southern area and “piles up” above the northern area. This redistribution of air reduces the surface air pressure to the south and raises it to the north. Consequently, a pressure gradient force is established at the earth’s surface from north to south and, hence, surface winds begin to blow from north to south.

We now have a distribution of pressure and temperature and a circulation of air, as shown in Fig. 8.3c. As the cool surface air flows southward, it warms and becomes less dense. In the region of surface low pressure, the warm air slowly rises, expands, cools, and flows out the top at an elevation of about 1 km above the surface. At this level, the air flows horizontally northward toward lower pressure, where it completes the circulation by slowly sinking and flowing out the bottom of the surface high. Circulations brought on by changes in air temperature, in which warmer air rises and colder air sinks, are termed thermal circulations.

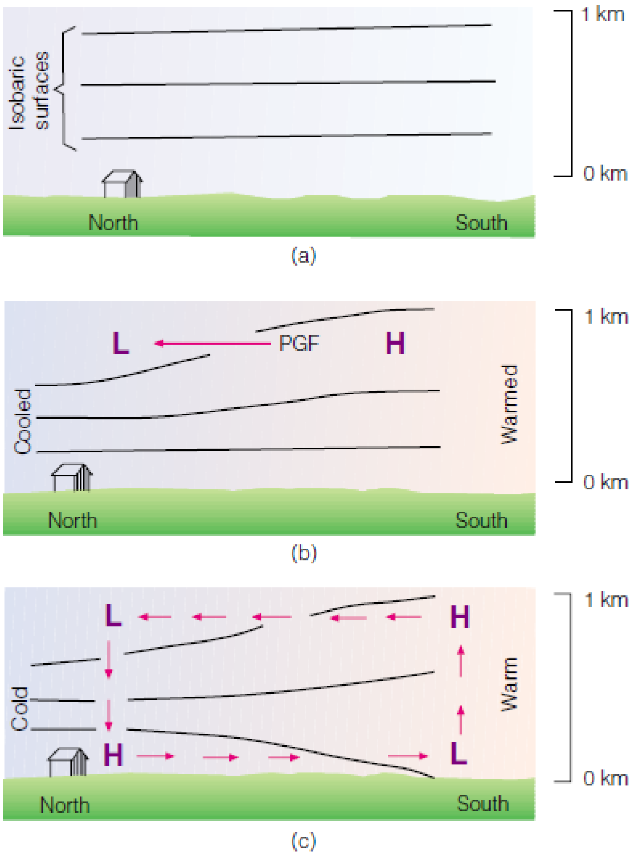

Figure (8.3) A thermal circulation produced by the heating and cooling of the atmosphere near the ground. The H's and L's refer to atmospheric pressure. The lines represent surfaces of constant pressure (isobaric surfaces).

8.4 Sea and Land Breezes

The sea breeze is a type of thermal circulation. The uneven heating rates of land and water cause these mesoscale coastal winds. During the day, the land heats more quickly than the adjacent water, and the intensive heating of the air above produces a shallow thermal low. The air over the water remains cooler than the air over the land; hence, a shallow thermal high exists above the water. The overall effect of this pressure distribution is a sea breeze that blows from the sea toward the land (see Fig. 8.4a). At night, the land cools more quickly than the water. The air above the land becomes cooler than the air over the water, producing a distribution of pressure, such as the one shown in Fig. 8.4b. With higher surface pressure now over the land, the wind reverses itself and becomes a land breeze—a breeze that flows from the land toward the water. Temperature contrasts between land and water are generally much smaller at night, hence, land breezes are usually weaker than their daytime counterpart, the sea breeze. Look at Fig. 7.4 again and observe that the rising air is over the land during the day and over the water during the night.

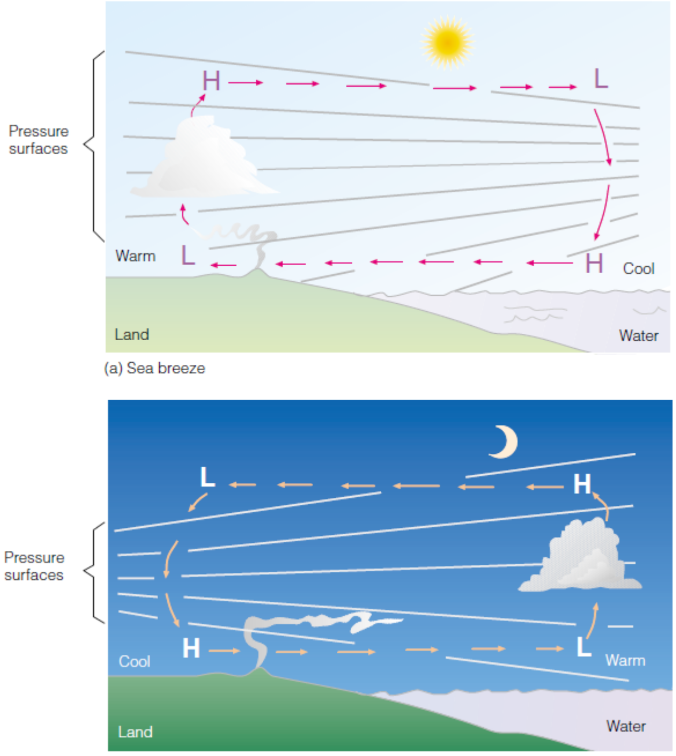

Figure (8.4) Development of a sea breeze and a land breeze. (a) At the surface, a sea breeze blows from the water onto the land, whereas (b) the land breeze blows from the land out over the water. Notice that the pressure at the surface changes more rapidly with the sea breeze. This situation indicates a stronger pressure gradient force and higher winds with a sea breeze.

8.5 Mountain and Valley Breezes

Mountain and valley breezes develop along mountain slopes. Observe in Fig. 8.5 that, during the day, sunlight warms the valley walls, which in turn warm the air in contact with them.

The heated air, being less dense than the air of the same altitude above the valley, rises as a gentle upslope wind known as a valley breeze. At night, the flow reverses. The mountain slopes cool quickly, chilling the air in contact with them. The cooler, more-dense air glides downslope into the valley, providing a mountain breeze. (Because gravity is the force that directs these winds downhill, they are also referred to as gravity winds, or nocturnal drainage winds.) This daily cycle of wind flow is best developed in clear, summer weather when prevailing winds are light. When the upslope valley winds are well developed and have sufficient moisture, they can reveal themselves as building cumulus clouds above mountain summits.

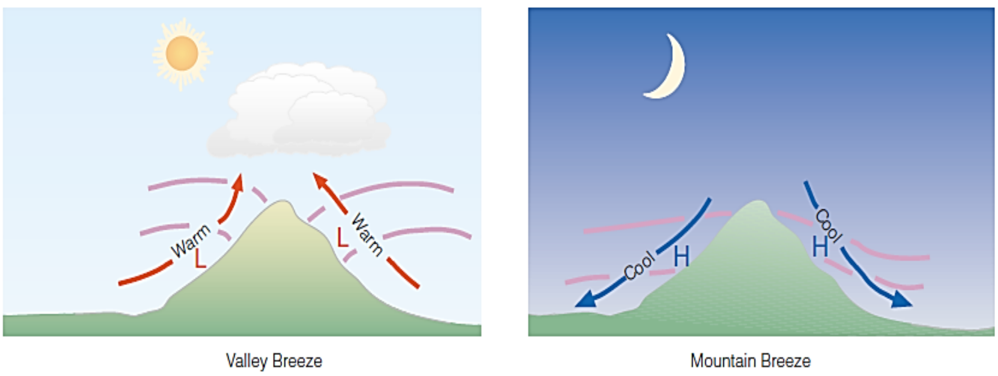

Figure (8.5) Valley breezes and mountain breezes (The L's and H's represent pressure, whereas the purple lines represent surfaces of constant pressure.)

8.6 Katabatic Winds

Although any downslope wind is technically a katabatic wind, the name is usually reserved for downslope winds that are much stronger than mountain breezes. Katabatic (or fall) winds can rush down elevated slopes at hurricane speeds, but most are not that intense and many are on the order of 10 knots or less. The ideal setting for a katabatic wind is an elevated plateau surrounded by mountains, with an opening that slopes rapidly downhill. When winter snows accumulate on the plateau, the overlying air grows extremely cold. Along the edge of the plateau the cold, dense air begins to descend through gaps and saddles in the hills, usually as a gentle or moderate cold breeze. If the breeze, however, is confined to a narrow canyon or channel, the flow of air can increase, often destructively, as cold air rushes downslope like water flowing over a fall.

8.7 Global Winds

Up to now, we have seen that local winds vary considerably from day to day and from season to season. As you may suspect, these winds are part of a much larger circulation- the little whirls within larger whirls. Indeed, if the rotating high- and low-pressure areas are like spinning eddies in a huge river, then the flow of air around the globe is like the meandering river itself. When winds throughout the world are averaged over a long period, the local wind patterns vanish, and what we see is a picture of the winds on a *global scale*-what is commonly called the *general circulation of the atmosphere*.

8.8 General Circulation of the Atmosphere

Before we study the general circulation, we must remember that it only represents the average airflow around the world. Actual winds at any one place and at any given time may vary considerably from this average. The underlying cause of the general circulation is the unequal heating of the earth’s surface. We learned previously that, averaged over the entire earth, incoming solar radiation is roughly equal to outgoing earth radiation.

8.8.1 Three-Cell Model

If we allow the earth to spin, the simple convection system breaks into a series of cells as shown in Fig. 8.6a. The tropical regions receive an excess of heat and the poles a deficit. A surface high-pressure area is located at the poles, and a broad trough of surface low pressure exists at the equator. From the equator to latitude 30^o, the circulation closely resembles that of a *Hadley cell*, as does the circulation from the poles to about latitude 60^o.

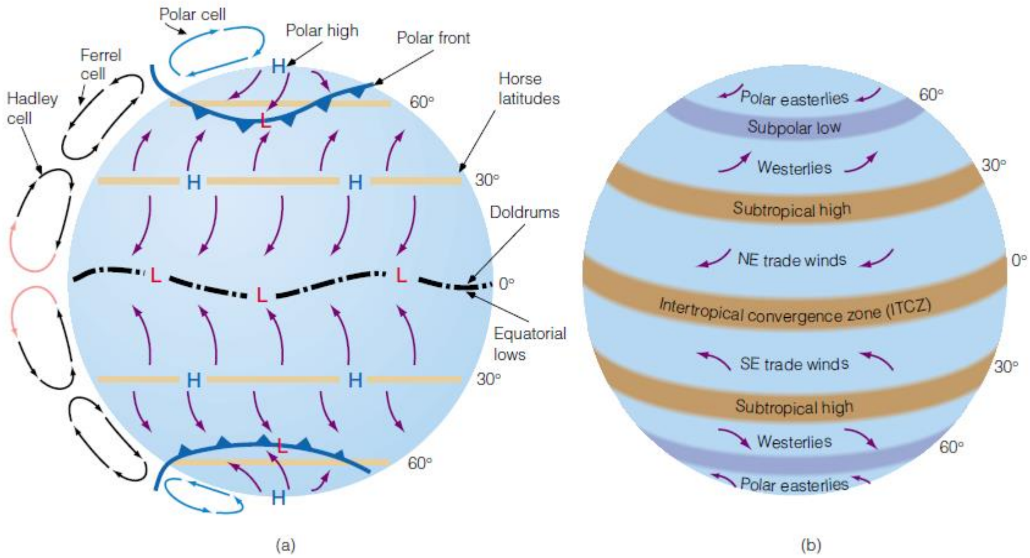

Figure (8.6) Diagram (a) shows the idealized wind and surface-pressure distribution over a uniformly water-covered rotating earth. Diagram (b) gives the names of surface winds and pressure systems over a uniformly water-covered rotating earth.

Over equatorial waters, the air is warm, horizontal pressure gradients are weak, and winds are light. This region is referred to as the doldrums. Here, warm air rises, often condensing into huge cumulus clouds and thunderstorms that liberate an enormous amount of latent heat. This heat makes the air more buoyant and provides energy to drive the Hadley cell. The rising air reaches the tropopause, which acts like a barrier, causing the air to move laterally toward the poles. The Coriolis force deflects this poleward flow toward the right in the Northern Hemisphere and to the left in the Southern Hemisphere, providing westerly winds aloft in both hemispheres. Air aloft moving poleward from the tropics constantly cools by radiation, and at the same time, it also begins to converge, especially as it approaches the middle latitudes. This convergence (piling up) of air aloft increases the mass of air above the surface, which in turn causes the air pressure at the surface to increase. Hence, at latitudes near 30°, the convergence of air aloft produces belts of high pressure called subtropical highs (or anticyclones). As the converging, relatively dry air above the highs slowly descends, it warms by compression. This subsiding air produces generally clear skies and warm surface temperatures; hence, it is here that we find the major deserts of the world, such as the *Sahara*.

Over the ocean, the weak pressure gradients in the center of the high produce only weak winds. This region is sometimes called the horse latitudes. From the horse latitudes, some of the surface air moves back toward the equator. It does not flow straight back, however, because the Coriolis force deflects the air, causing it to blow from the northeast in the Northern Hemisphere and from the southeast in the

Southern Hemisphere. These winds are called *the trade winds*. Near the equator, the northeast trades converge with the southeast trades along a boundary called the intertropical convergence zone (ITCZ). In this region of surface convergence, air rises and continues its cellular journey. Meanwhile, at latitude 30^{o} not all of the surface air moves equatorward. Some air moves toward the poles and deflects toward the east, resulting in a more or less westerly air flow- called the prevailing westerlies, or, simply, *westerlies*-in both hemispheres. As this mild air travels poleward, it encounters cold air moving down from the poles. These two air masses of contrasting temperature do not readily mix. They are separated by a boundary called the polar front, a zone of low pressure- the subpolar low-where surface air converges and rises and storms develop. Some of the rising air returns at high levels to the horse latitudes, where it sinks back to the surface in the vicinity of the subtropical high. This middle cell (called the Ferrel cell, after the American meteorologist William Ferrel) is completed when surface air from the horse latitudes flows poleward toward the polar front.

8.9 Westerly Winds and the Jet Stream

Aloft, the winds above the middle latitudes in both hemispheres blow in a more or less west-to-east direction. The reason for these westerly winds is that, aloft, we generally find higher pressure over equatorial regions and lower pressures over polar regions. Where these upper-level winds tend to concentrate into narrow bands, we find rivers of fast-flowing air-what we call **jet streams**. Atmospheric jet streams are swiftly flowing air currents hundreds of kilometers long, normally less than several hundred kilometers wide, and typically less than a kilometer thick (see Fig. 8.7). Wind speeds in the central core of a jet stream often exceed 100 knots and occasionally 200 knots. Jet streams are usually found at the tropopause at elevations between 10 and 14 km although they may occur at both higher and lower altitudes.

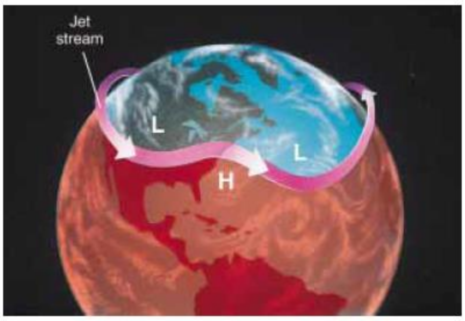

Figure (8.7) A jet stream is a swiftly flowing current of air that moves in a wavy west-to-east direction.

Homework

1. Describe the various scales of motion and give an example of each.

2. Why does a sea breeze blow from sea to land and a land breeze from land to sea?

3. What are katabatic winds? How do they form?