2

INTRODUCTION TO THE EARTH'S ATMOSPHERE

Chapter Highlights:

- ✓ Meet the earth's atmosphere: the weather maker.
- ✓ Learn why oxygen decreases with elevation.
- ✓ Weather fronts defined.
- ✓ How to use an altimeter for 'on-the-mountain' forecasting.

Meet the Atmosphere

We will start our study of mountain weather by looking at the structure of earth's atmosphere. This is important because the phenomenon we call weather, is caused by simple changes in the condition of the atmosphere: that is changes in temperature, air pressure, moisture, and wind. The atmosphere is of course the layer of air that surrounds the earth which extends up to an altitude of about 800 km (500 miles). Meteorologists like to separate the atmosphere into four sub-regions, from the earth's surface upward they are the: troposphere, stratosphere, mesosphere, and the thermosphere (figure 2.1). This classification is based primarily on the change in temperature with height within each region.

The gas that we call 'air' is made up of 78% nitrogen, 21% oxygen, and 1% of trace gases like argon, carbon dioxide, water vapor, and helium to name a few. It's important to note that the percentage of these gases remains fixed throughout the entire troposphere and lower stratosphere. For example, the air on the summit of Mt. Rainier (4,392 m) or K2 (8,613 m) still contains 78% nitrogen, 21% oxygen, and 1% trace gases. What does change however is the density of air (Figure 2.2). <u>Air density decreases as elevation increases</u>. As a result, there is less air and hence less available oxygen for a climber to breathe as they ascend. In practical terms this means that on the summit of Mt. Rainier, a climber has approximately 57% of the oxygen available at sea-level, and on the summit of K2, only about 32%.

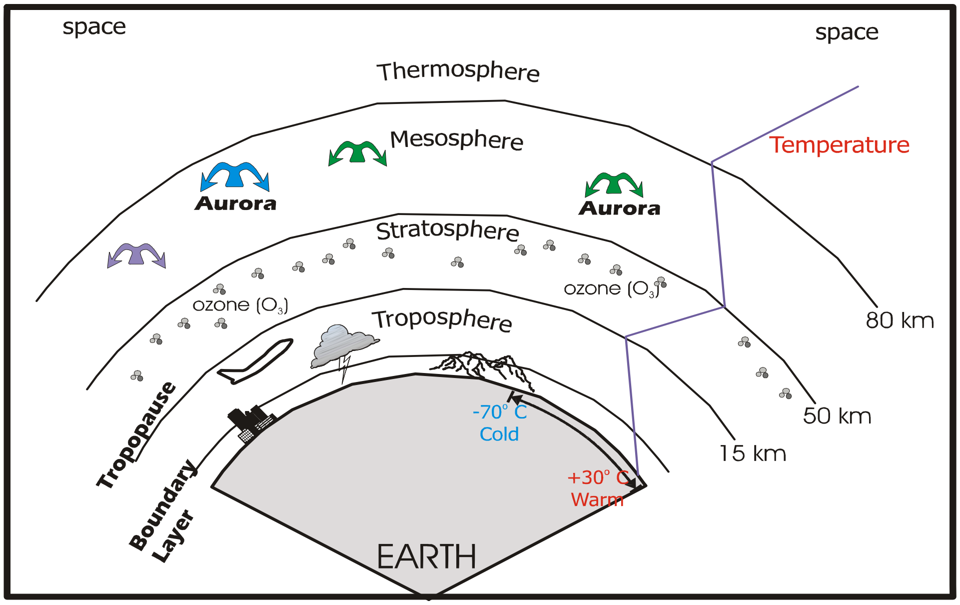


Figure 2.1- Schematic of the earth's atmosphere.

Troposphere:

The region that interests us the most is the lowest one, the troposphere; because it's only here that significant amounts of moisture and hence clouds are found. Above 16 km (10 miles) the air is too cold and too thin to contain very much moisture, so the weather that affects the earth is restricted primarily to the troposphere.

For the most part the troposphere is heated from the ground up. Since the surface of the earth consists of water, rock, dirt, vegetation, snow, etc. the air above these different materials can have widely differing temperature and moisture contents. This in turn leads to the generation of what we call *air masses* , very large-slowly moving-masses of air that have different temperatures, densities, and moisture. Polar air masses for example are cold and dry, while air masses that originate over the tropical oceans are warm and moist.

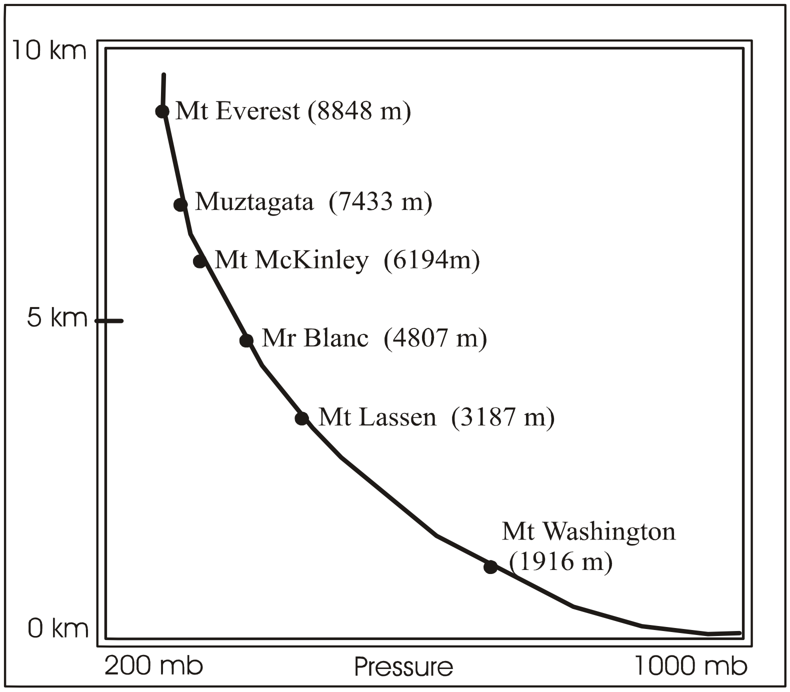


Figure 2.2- Change in pressure with change in elevation.

Since the troposphere is heated from the ground up, air temperatures within the troposphere generally decrease with height. The rate at which it decreases varies from about 4° C to about 10° C per kilometer (11° to 18° F per mile), and is termed the *lapse rate*. As you might imagine, the lapse rate at a given location changes as air masses pass through the area and as the air next to the ground heats up during the day and cools off at night.

Air masses move around and frequently collide with each other. Since cold air is denser than warm air, the colder air mass slides beneath the warmer air mass–with interesting results, as we shall shortly see. It's in regions of interacting air masses that most of our planet's stormy weather occurs.

It takes considerable energy to heat large masses of air, of course this energy comes from the sun. Considerably more sunlight reaches the tropics than anywhere else on the planet. In fact, if it weren't for the movement of air masses, the tropics would be considerably hotter than they already are, while the higher latitudes would be much cooler. Keep in mind that ocean currents also help distribute the heat from the tropics to higher latitudes. Nevertheless, a large temperature difference exists between the tropics and the mid-latitudes, which in turn produces an equator-to-mid latitude movement of air known as the Hadley Cell (Figure 2.3). The Hadley Cell sort of works like an air conveyor belt-heat energy from the tropics is transport to the mid-latitudes of both the northern and southern hemispheres.

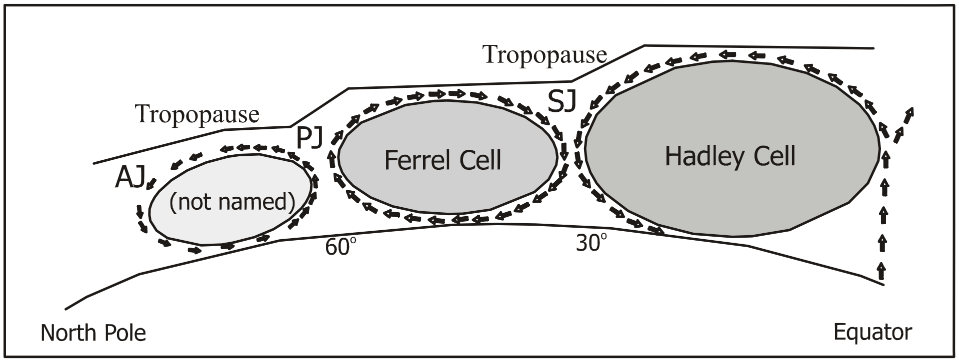


Figure 2.3- north-to-south cross section of hemispheric circulation systems.
AJ= Arctic Jet, PJ= Polar Jet, SJ= Sub-tropical Jet.

At the top of the troposphere, and dividing it from the stratosphere is a region called the tropopause. It's not a distinct boundary, but rather a transition zone. The tropopause is not located at a constant height over the entire globe; it varies with latitude and from season-to-season. The height of the tropopause ranges from about 17 km (10.6 miles) in the tropics to about 8 km (5 miles) in the polar regions. Although we won't be discussing jet-stream winds until a later chapter, it's worth noting that some of the strongest winds found anywhere in the lower atmosphere occur in the vicinity of the tropopause. As a result, a general rule-of-thumb is as follows: the higher you climb the more likely you are to encounter strong winds. In addition, taller mountains located at higher latitudes tend to experience stronger winds then a mountain of similar height located further south.

Stratosphere:

The stratosphere differs from the troposphere in a very significant manner; in this region temperatures increase with height. In addition, the stratosphere contains a significant amount of ozone that absorbs large amounts of the sun's ultraviolet radiation and so protects plants and animals from these harmful rays. The elevated warm layer of air above the troposphere is important because it acts as a lid on how much energy can be transported from the earth's surface to outer space. There is very little moisture in the stratosphere, but thin ice clouds do form from time-to-time. In short, weather in the stratosphere has little direct effect on mountain weather.

Mesosphere and Thermosphere:

These two regions are the domain of high-energy particles arriving via the solar wind, that is particles that travel from the outer layers of the sun. This is where the aurora borealis (Northern Lights) and the aurora australis (Southern Lights) are produced. Air in these regions has such a low density that virtually no weather is generated here.

Weather Fronts

In the lower troposphere, two neighboring air masses often have large differences in temperature. These pronounced contrast in temperatures (the technical term is- *temperature gradient*) are found along the boundaries between the two air masses. It's in these boundary zones, which we call *fronts*, that one air mass tends to be lifted over the other (Figure 2.4). This is important because rising air is essential for the development of clouds and rain or snow. The rate or speed of frontal lifting is small when compared to an air mass's horizontal speed, however it's still enough to generate clouds over large areas of the earth's surface.

Most fronts vary in length from about 500 km (300 miles) to over 1000 km (600 miles), while the width is a more modest 50-100 km (30-60 miles). A front is recognized as a change in wind direction, temperature, moisture, or sea-level pressure from one side of the front to the other. There are four types of fronts: cold, warm, stationary and occluded. Fronts typically form in conjunction with a developing storm (i.e. low-pressure system simply called a 'low'). They are named according to the direction in which the coldest air is moving with respect to the frontal boundary. It is important to note that 'cold' air and 'warm' air are relative terms. The important point is that there is a significant temperature difference between the two air masses. There is no criteria that says that 'cold' air has to be below a certain temperature, or that 'warm' air has to be warmer than a specified temperature.

A cold front is produced when cold air overtakes and slides underneath warm air which is ahead of it. A warm front occurs when warm air overtakes cold air, but in this case the warmer air moves over the top of the cooler air. Remember that cold air clings to the earth's surface because it's denser and therefore heavier then warm air. Sometimes warm and cold air move parallel to the frontal boundary, forming what we call a stationary front. As the name implies, there's very little relative movement between the two air masses. The fourth and final type is an occluded front. In this case cold air moves counterclockwise around the center of a mature storm, effectively undermining all of the warmer air that used to be near the ground.

A mature storm can have more than one front, in fact most have a cold and a warm front. The warm front is usually positioned several hundred kilometers to the east of the cold front. The four types of fronts we've just described occur most often during the winter months, in the middle and high latitudes. In the tropics, airmass fronts

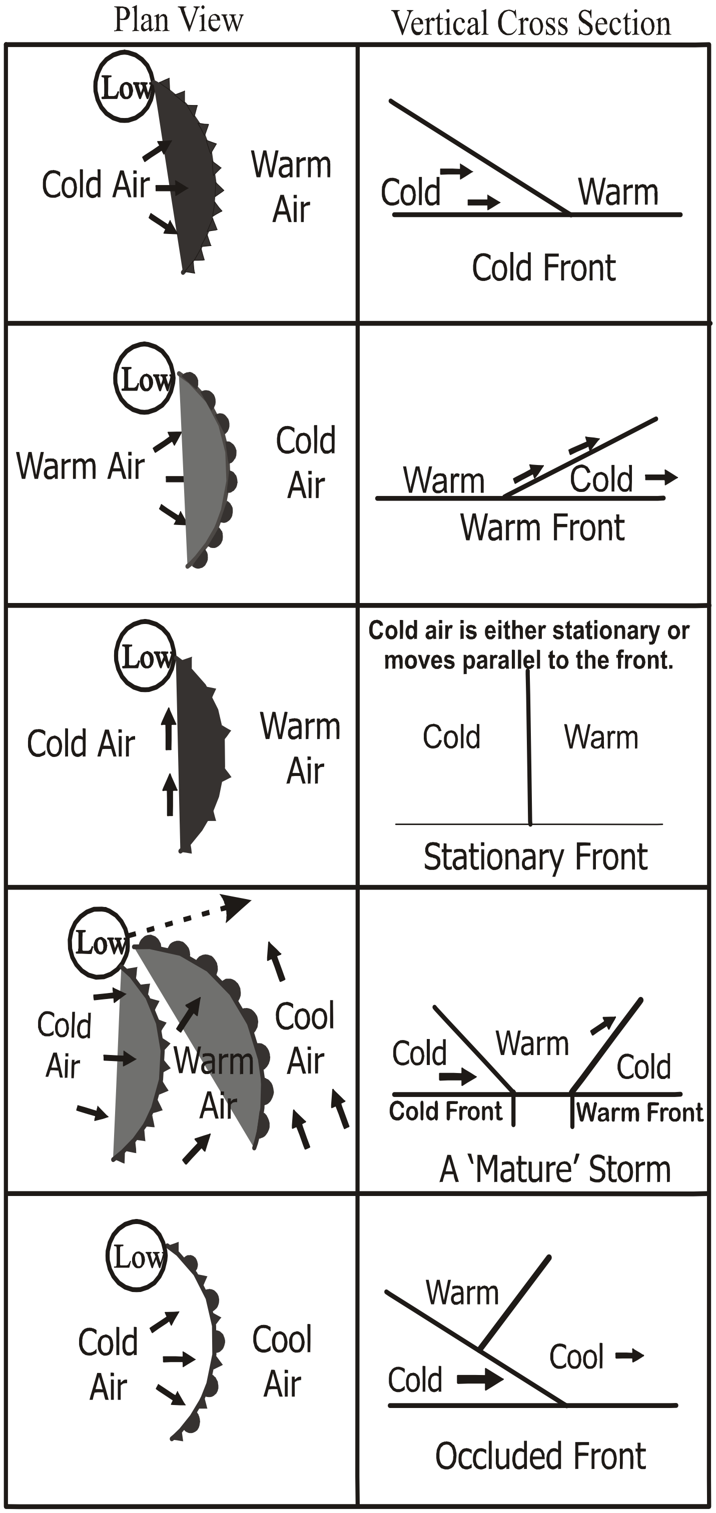


Figure 2.4- Surface Fronts.

do not often develop because there is very little temperature contrast across the uniformly warm tropical oceans.

Forces that Produce Weather

If you really want to understand how weather is generated, then you need to know what natural forces produce it. This topic can be a bit daunting to those readers who have never taken a high school or college level physics class, nevertheless, read through this section, you might surprise yourself with what you can learn.

The most easily identified force at work in the atmosphere is gravity. Here is an example how gravity helps produce weather. Imagine a parcel of air (some identifiable unit of air, suppose one meter on a side) located 3 km (1.9 miles) above the ground. This parcel has no horizontal or vertical motion and it has the same temperature as the surrounding air. Will the force of gravity cause this parcel to sink toward the ground? The answer is : no! In this scenario the downward pull of gravity is equally matched by an upward pressure force; the parcel will in fact remain stationary. However, if the parcel is warmer than the surround air, its density will be lower, and it will tend to rise. If on the other hand, the parcel is cooler then the surrounding air, it's density is higher and it will tend to sink toward the ground.

Remember that warm light air rises; while cold heavy air sinks. This turns out to be very important in the formation of clouds. For example, on a warm sunny day, air just above a large patch of bare dirt or asphalt will be heated to a temperature well above that of the surrounding air. Since it's warmer and hence lighter, the air above the dirt begins to rise above the ground; this process is called *convection*. A rising parcel of air which is heated in such a manner is often referred to as a *thermal.* As this warm parcel rises it eventually reaches an altitude where it's density matches the density of the surrounding air, at which time it comes to rest.

As you gain elevation in the mountains for example, atmospheric pressure– the weight of air above your head–decreases, as the density of air decreases. A good analogy is the pressure that a swimmer experiences on a dive to the bottom of a swimming pool. The water pressure at any given depth in the pool is the total weight of the water pressing down on the swimmer; the deeper the swimmer, the higher the pressure.

At sea-level, air pressure is on average around 1013 millibars (mb). At an altitude of 5.5 km (3.4 miles) it's only about half that. Table 2.1 shows the atmospheric pressure that a climber would experience while on the summit of a few selected mountains. Note that the decrease in pressure with increasing elevation is not linear (would not be a straight line if these values were plotted on a piece of paper and a line segment connected each value). The vertical distance between the 1000 mb and 900 mb levels is about 900 m (2,950 ft), while the distance between 500 mb and 400 mb is about 1600 m (5,250 ft). Incidentally, meteorologist usually measure vertical distances in the atmosphere in meters or kilometers. If they're referring to a specific level then they give the vertical coordinate in terms of the pressure level (i.e. temperature at 500 mb, or winds at 900 mb). You are probably wondering what millibars are- they are a metric unit of pressure (force per unit area), similar to 'pounds per square inch'.

Let's return to our discussion on important forces that are at work in the atmosphere. Two additional forces that should be mentioned are the *Coriolis force* and the horizontal pressure gradient force (the word horizontal is usually dropped since we know by the context that it's not the vertical pressure gradient that's being referred to). The Coriolis force is named after G.G. de Coriolis, a 19th-century French mathematician who discovered it. The Coriolis force causes a horizontally moving parcel of air to change direction (deflection) without any change in it's speed. In the Northern Hemisphere this deflection causes air move to the right of its original course, but in the Southern Hemisphere deflection is to the left. For example, a wind that is blowing from west-to-east across the USA will be deflected to the south. Likewise a wind that travels from the Gulf of Mexico toward South Dakota will be deflected toward the Ohio Valley.

TABLE 2.1- Pressure and percent oxygen for selected mountain summits. Oxygen values based on sea-level being 100%.

Mountain	Height (m)	Pressure (mb)	% Oxygen
(sea-level)	0	1013	100
Mt. Washington- USA	1916	805	79
Mt. Lassen- USA	3187	685	68
Mt. Rainier- USA	4392	580	57
Mt. Blanc- Fr/Sw	4807	555	55
Mt Foraker- USA	5302	520	51
Mt. Logan- Canada	5951	475	47
Mt. McKinley-USA	6194	455	45
Aconcagua- Chile	6958	410	40
Muztagata- China	7433	385	38
Nanga Parbat- Pakistan	8126	350	35
Mt. Everest- Nepal/China	8848	310	31

The pressure gradient force is not hard to understand. In Figure 2.5 two columns of air are displayed. In column **A**, the average temperature is 10 degrees colder than the air in column **B** (the actual temperatures and heights are not important). Since both columns stretch from the surface to a height of 20 km (12.2 miles), column **A** will have a higher average density than the air in column **B**. As a result, the pressure at any given height in column A will higher then the pressure at the same height in column **B** (this example falls apart near the top of the columns). If pressure were the only force involved, air would want to move from high pressure (**A**) to lower pressure (**B**). In reality however, since there are always additional forces involved, air does not move (wind!)

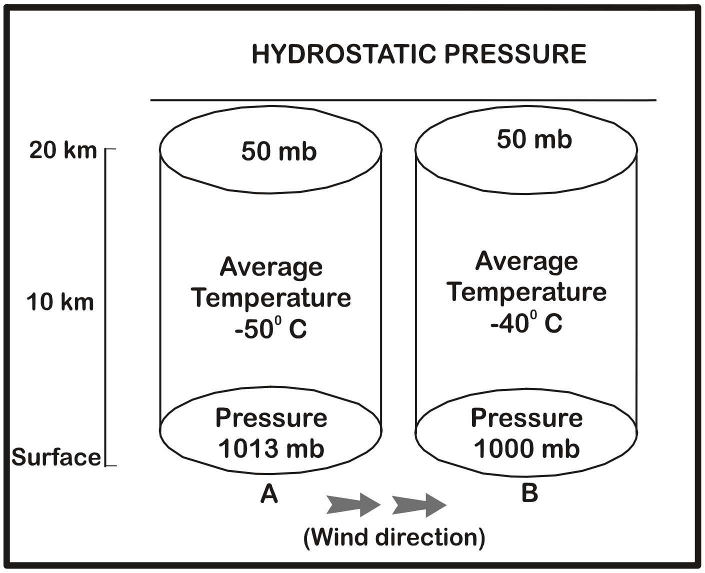
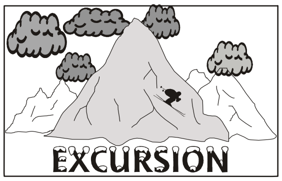


Figure 2.5- Pressure is a function of temperature.

directly from **A** to **B**, it almost always moves in a curved path.

Altimeters and Changing Pressure



Everyone knows that an altimeter measures changes in elevation. But what you may not know is that altimeters actually measure atmospheric pressure, which is then converted into a elevation for display. Because of this property, an barometric altimeter can be used to monitor changes in atmospheric pressure. For example, a 10 m (33 ft) change in elevation corresponds to a pressure change of about 1 mb. But make sure that you understand that pressure change is inversely related to changes in elevation. When the reading on the altimeter decreases (when your descending for example) the pressure is rising, and when you ascend, the pressure is decreasing. If you want to use an altimeter as a barometer, make sure that the altimeter is not physically changing altitude; in other words, this only works when you have stopped hiking or climbing for the day and the instrument remains at one elevation for period of time.

Here are some simple steps to follow if you want to use your altimeter as a barometer. **Step One:** Read your altimeter when you first stop and set-up camp, you may want to write the value down. **Step Two:** In the morning, compare the current reading with the value from the previous evening. If, for instance, the altimeter rises 60 m (197 ft) during the night, you simply divide 60 by 10 (remember its 10 m or 33 ft per 1 mb). The result would indicate a pressure drop of about 6 mb. So what does this tell you about the weather? Well, during a typical 12-hour period atmospheric pressure will rise or fall 2 or 3 mb (20-30 m or 65-100 ft) on its own. A pressure change of 3 mb or more is required before any real significance can be attributed to it. A pressure drop of 6 mb in 12 hours is respectable, a 10 mb drop over the same period is pretty large. Since most major storm systems develop in association with low-pressure systems, this may indicate the approach of a storm and it's associated fronts. Keep in mind however, that a change in pressure is only one piece of the puzzle. **Step Three:** Observe additional meteorological elements such as changes in wind speed and wind direction, as well as the current and past cloud types. If the 6 mb decrease in pressure occurs at the same time that clouds are on the increase and the winds are either changing direction or increasing in speed, then you have enough information to deduce that a front is approaching your location. Armed with this information you can make an intelligent decision about whether to continue your climb/hike, remain where you are, or retreat.

How Winds are Generated

In order to help you understand how winds are generated consider the following scenarios. The first scenario takes place near earth's surface, where winds are a product of three interacting forces: the pressure gradient force, surface friction, and the Coriolis force. The net result of these forces is a surface wind that blows into a region of low pressure and out of an area of high pressure. As Figure 2.6 illustrates, these winds tend to move across isobars (lines of equal pressure that are drawn on a surface weather map), at an angle of about 30 degrees. Recall that the winds do not directly move from an area of low pressure to high pressure, friction and the Coriolis force cause the wind to have a curved path. Surface friction is a result of air moving over and through obstacles such as trees, mountains, buildings, etc.

The movement of air into an area of low pressure and out of high pressure has important implications for the development and dissipation of a storm. Air that moves into a region of low pressure has to continue in motion, otherwise air in the low would pile up and the pressure would increase. What actually occurs is that air moving into the center of a low is forced to ascend, which in turn produces clouds and precipitation.

Contrast this with regions of high pressure (a high), where air descends from higher levels within the atmosphere. This results in air moving out from the center of a high. Descending air tends to be dry, so few clouds are produced in regions of high pressure. By the way, <u>it's important for you to understand that surface winds are frequently weaker and do not necessarily blow in the same direction as the winds in the middle and upper troposphere.</u>

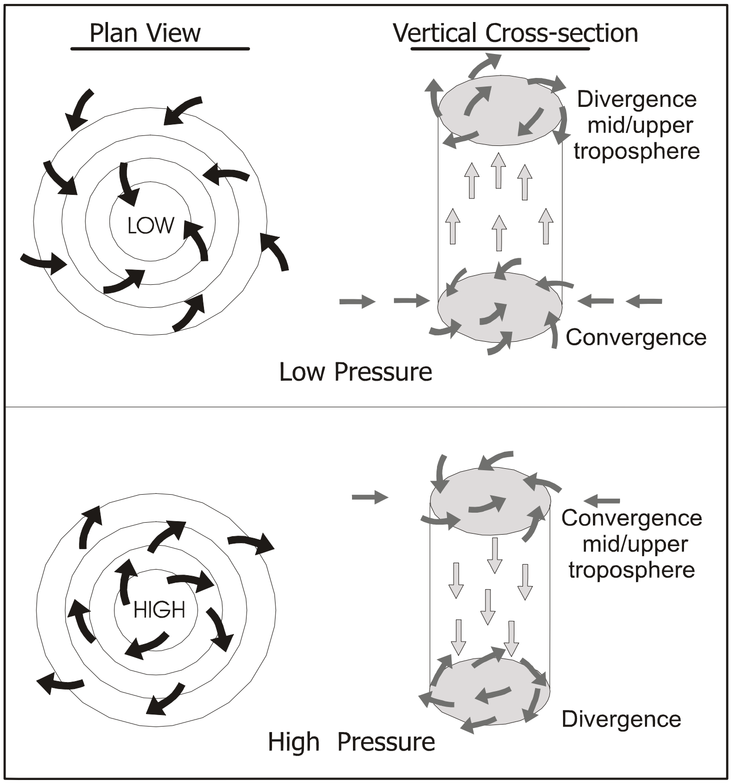


Figure 2.6- Air spirals into a LOW in a counterclockwise direction, while air spirals out of a HIGH in a clockwise direction. In the Southern Hemisphere the direction of rotation is the opposite.

In our second scenario, lets move above the influence of surface friction and into the middle and upper troposphere, where the two most important forces that generate wind are the pressure gradient force and our new friend, the Coriolis force (technically one has to also consider centrifugal forces but we will ignore them for now). Since the pressure gradient is balance by the Coriolis force, the wind moves parallel to the isobars (this is called the geostrophic wind). Above the earth's surface however, we no longer use isobars; we measure the height of a given pressure level above mean sea-level. This sounds ominous, however it is quite easy to use. Since the units are in meters, the term 'heights' is used when we refer to a pressure level.

A three-dimensional example is illustrated in Figure 2.7. You'll notice in this figure that the top of the box represents a constant elevation above sea-level, while the thin solid lines represent the height of the 500 mb pressure level above sea-level. Large heights (5480 m in this example) represent higher pressure, while lower heights (5120 m) represent lower pressure. In other words, the 500 mb pressure level in this example is not parallel with the earth's surface; it's higher in the south, and lower in the northwest. The spacing of the height lines gives an indication of wind speeds. Closely spaced height lines mean that the pressure gradient is large and the resulting wind speeds are high, while height lines that are widely spaced indicate lower speeds. We have added the arrows to indicate which way the winds are blowing. But you already know that wind travels counterclockwise around low pressure systems, and clockwise around highs, hence you won't need the help of arrows in the future. Keep in mind, however, that Figures 2.6 and 2.7 show highly idealized wind systems, although they're pretty accurate approximations in most cases. As you can see from the examples illustrated in this chapter, most large-scale winds follow a wavy (sinusoidal) course as they move around the globe. This turns out to be important because these waves help to transport warm air from the tropics and cold air from the polar regions.

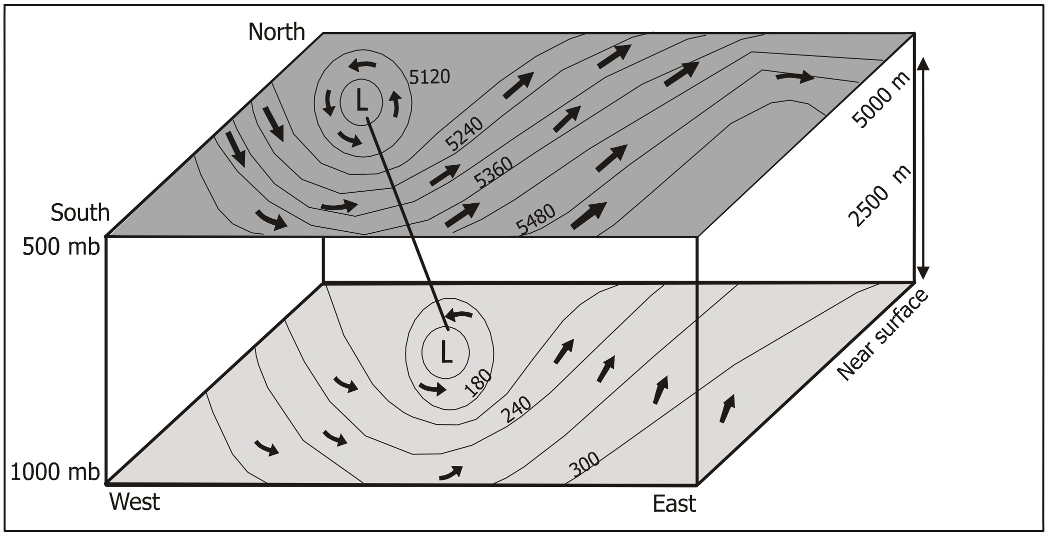


Figure 2.7- Wind vectors (arrows) and geopotential heights (solid lines in meters), for a typical low positioned in the mid/high latitudes. Note that the top pane represents the winds on the 500 mb pressure level, the bottom pane the winds at 1000 mb. The dot-dashed line indicates the western tilt of the low.

Getting the names right- time for a quick word about nomenclature:

Low-pressure systems (i.e. storms) are called *lows* or *cut-off lows* if the isobars completely encircle the area of lowest pressure, as depicted in the lower panel of Figure 2.7. Sometimes a region of low pressure forms, but the isobars are not closed; these features are called *troughs*. Areas of high pressure are called *highs* or *anticyclones* if the isobars are closed, or *ridges* if not closed. In your reading you may encounter the term cyclonic, which in the Northern Hemisphere refers to the counterclockwise motion around a low or trough, while anticyclonic refers to clockwise motion around highs and ridges. Frequently, a cut-off low will form in the lower troposphere but has the structure of a trough in the middle and upper troposphere. Note that 'tropical cyclone' is another name for a hurricane or typhoon. These storms are deep low-pressure systems that are generally only found in the tropics and sub-tropics.

Pressure Systems: the Highs and the Lows

In the tropics and polar regions, winds predominately blow from east-to-west, these types of winds are called *easterlies*. In the mid-latitudes (30° - 70°), winds blow from west-to-east and are commonly called *westerlies*. In meteorology the wind direction indicates the direction which wind is blowing out-of. Since most highs and lows form in the mid-latitudes, these features tend to move along with the westerly winds. However, there are certain regions on earth that favor the formation of highs and lows, at least during certain times of the year. In winter in the Northern Hemisphere, for example, there are two dominate lows and three dominate highs. The lows are the Aleutian low, which is centered near the Aleutian Islands, and the Icelandic low, which usually southwest of Iceland. These lows won't necessarily show up on the surface weather map every day in winter, but over the course of the whole season they are frequently found near these two areas.

Two of the highs are located over the sub-tropical oceans, centered near latitude 30^o N, therefore they are called sub-tropical highs. One of these lies off the coast of California, while the other is located in the central Atlantic, west of the Azores. The third high is located in central Siberia at about 50^o N, and is therefore called the Siberian High. It, unlike the sub-tropical highs, is produced by very cold air that is trapped in the lower troposphere, hence it forms during the winter months.

The sub-tropical highs are directly linked to the Hadley Cell circulation. In fact these highs are produced by sinking air that originated near the equator. These large regions of subsiding air tend to be very dry and hence relatively cloud free.

During the summer, the Aleutian and Icelandic lows weaken, while the sub-tropical highs strengthen and move slightly north and west of their winter positions. These semi-permanent lows and highs play a very important role in the overall climate of many regions. Areas to the west of lows tend to be cold and dry during the winter, while areas to the east are typically wet and cool. Regions to the west of the sub-tropical highs are dry and warm while areas to the east are very dry and hot. Its no coincidence that the largest deserts on earth are located to the east of sub-tropical highs.

In later chapters you will read about the weather and climate in various mountain ranges; note how the local weather is, in large part, controlled by its location with respect to one of these features. In the Southern Hemisphere, there are semi-permanent highs and lows as well. For example, the sub-tropical high located off the west coast of South America, is the main reason that most of the central Andes are quite dry.

The Size of Weather

This chapter is going to conclude with what many of you will think is a very dull subject-the scale at which weather occurs. Meteorologists typically use four scale sizes to help classify weather features: planetary, synoptic, mesoscale, and local-scale. First, note that these scales are used as approximate delineations. In other words, scale is relative, not exact. Second, the scale size is usually inversely proportional to the resolution. When you look at weather on the planetary and synoptic scales, your looking at the gross features over a large area. When you deal with the mesoscale and local-scale, your looking at finer details over a limited area.

A good way to understand these scales is to imagine a camera orbiting the earth, which takes photographs with four different lenses (Figure 2.8). The planetary scale would be equivalent to a picture of the earth's atmosphere taken from space with a wide-angle lens. It would capture the largest weather features, but it's not going to resolve thunderstorms developing over the Wasatch Mountains of Utah.

If the wide angle lense is replaced with one with a medium focal-length, the new image would be equivalent to the synoptic scale. This scale has a horizontal dimension of several thousand kilometers. It by the way is the scale used for most weather analysis. Additionally, a map of the continental USA that depicts surface pressure is another example of weather analysis on the synoptic scale.

The mesoscale on the other hand, covers a much smaller region, roughly several hundred kilometers on edge. At this scale, terrain becomes a significant weather factor. A forecaster who is writing a forecast for the northern Cascades, would first analyze the weather on the synoptic scale, then adjust it for the terrain (more on the forecast process in a later chapter).

The smallest scale is the local-scale, or what can also be called the microscale, which covers a distance of 100 km (60 miles) or less on edge. Most forecast for urban areas, where it may affect millions of people are made at this scale. In rural areas, most forecasting is done on the mesoscale. This means that when you read a forecast for a mountainous region, it typically only gives general wind, temperature, and precipitation information. In other words, there is going to be considerable variations in weather across that zone, due to changes in elevation, and rain shadow effects to name a few, which are not typically covered in the forecast.

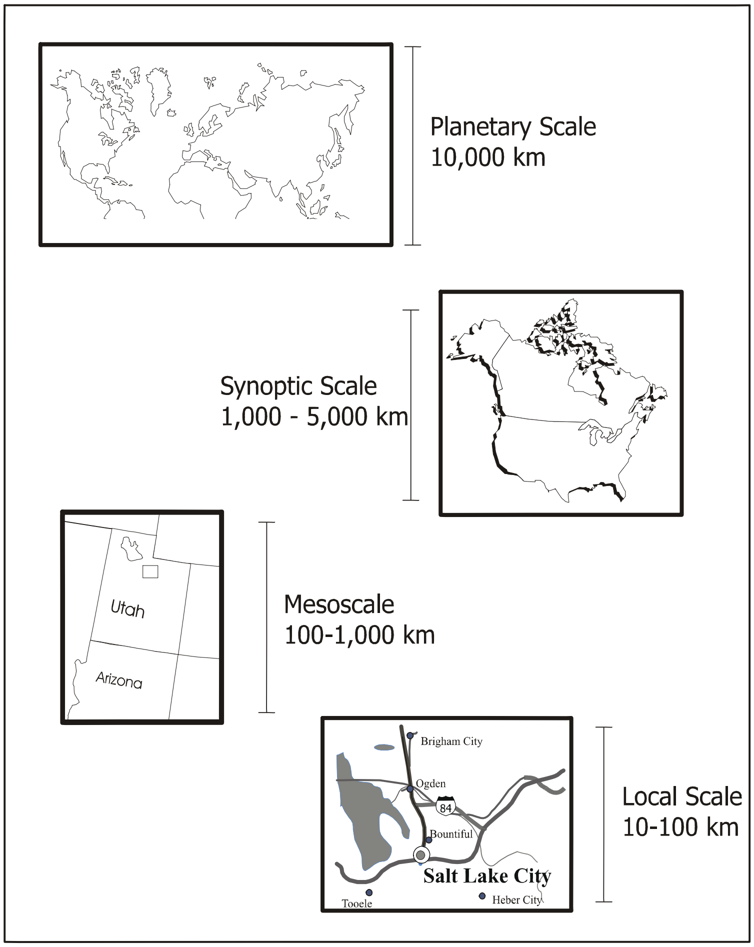
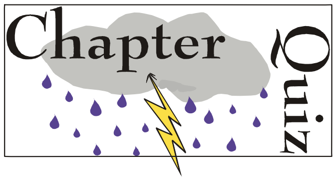


Figure 2.8- The four scales used in meteorology.

The main point of this section has been to point out that weather occurs on a variety of spatial scales. In general, it is easier to forecast on the larger scales then it is on the smaller scales. In addition, it is easier to forecast weather in the middle and upper troposphere then it is near the earth's surface. This is a result of the fact that friction and turbulence to name a few, add a lot of complexity to weather dynamics.



1. Name the four types of fronts: ______, ______, ______, ______.
2. True/False: The Coriolis force only changes wind speed, not wind direction.
3. Oxygen is the: 1st, 2nd, 3rd, 4th most abundant gas found in a sample of air.
4. A rising altimeter signifies what?
5. Air moves in a ________direction around an area of low pressure (Northern Hemisphere).
6. True/False: more oxygen is available to a climber on the summit of K2 than to a climber on the summit of Mt. McKinley.
7. A cold air mass moves: a) over b) through c) under, a warm air mass.
8. A westerly wind is moving in what direction?