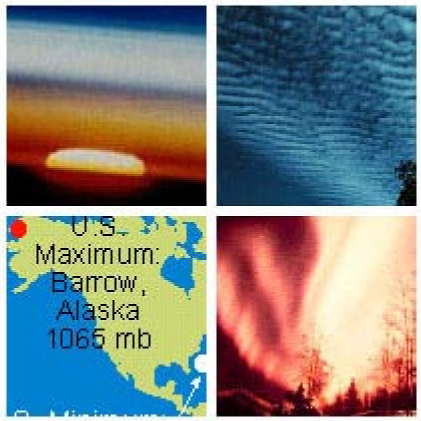
The Atmosphere



> . . . this most excellent canopy, the air, look you, this brave o'er hanging firmament, this majestical roof fretted with golden fire.
>
> William Shakespeare

> For the first time in my life, I saw the horizon as a curved line. It was accentuated by a thin seam of dark blue light - our atmosphere. Obviously, this was not the "ocean" of air I had been told it was so many times in my life. I was terrified by its fragile appearance.
>
> Ulf Merbold

Introduction

- The atmosphere is thin relative to the size of Earth.
- Two common gases make up 99% of dry air.
- Trace amounts of other gases play a critical role in the atmosphere.

Ironically, it is the view of Earth from the airless vacuum of space that provides us with a view of just how thin is the veil of atmosphere around the planet (Fig. 1). Earth has a radius of over 6,370 km (3,981 miles) but the narrow skin of atmosphere stretches upward to a maximum thickness of approximately 500 km (321 miles). Ninety-nine percent of the gases that compose the atmosphere are located below a height of 32 km (20 miles). The thin air of the atmosphere's outermost fringes contains a few stray gas molecules before it passes into the emptiness of space.

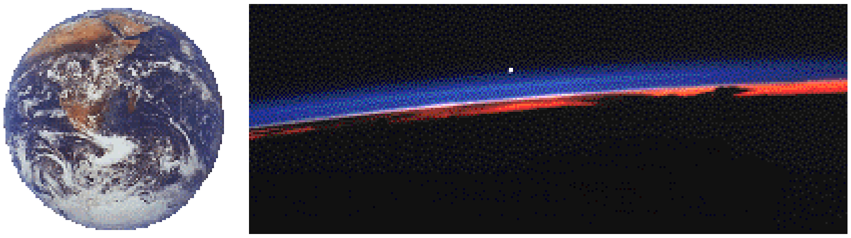


Figure 1. Left: view of the Earth with heavy cloud cover in the Southern Hemisphere as seen by the Apollo 17 crew. Right: Venus (center) shines clearly through the atmosphere above the Earth's horizon in this photo taken at night in May 1989. Images courtesy of NASA.

Earth's atmosphere protects us from incoming space projectiles (comets, asteroids) that burn up before reaching the planet's surface, and blocks harmful short wavelength radiation from the Sun. The lower boundary of the atmosphere is considered to lie on Earth's surface, the upper boundary is the gradational transition into space. The atmosphere can be divided into four layers on the basis of their thermal characteristics. The **structure of the atmosphere** is described in the next section.

The weather we experience at the land surface is largely determined by the interaction of different wavelengths of incoming **solar radiation** with the atmosphere. Solar radiation supplies the energy necessary for cloud formation, precipitation, and local weather conditions. The relatively pleasant average global temperature of 15°C is a direct result of two factors. First, visible light is converted to heat when solar radiation strikes Earth's surface. Second, the heat is trapped close to the planet's surface by **greenhouse gases** (carbon dioxide, methane, nitrous oxide, water vapor) that make up just a fraction of the atmosphere (Fig. 2).

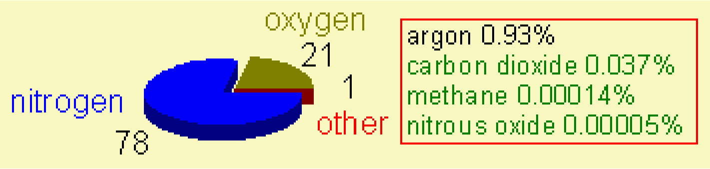


Figure 2. Concentrations of gases in dry air in Earth's atmosphere. Gases in green are greenhouse gases.

All planets have atmospheres but the specific mix of gases in Earth's atmosphere is termed **air**. Two common gases, nitrogen and oxygen, make up ~99% of dry air (Fig. 2). Moist air may contain up to 7% water vapor and/or aerosols (microscopic particles). In addition, trace amounts of other gases (carbon dioxide, methane, ozone) have proved crucial in recent discussions of global climate issues.

Water is the only naturally occurring compound that exists in **three states** (liquid, gas, solid) on Earth's surface. Heat energy is transferred through the atmosphere as water changes from one state to another. Heat is absorbed in processes such as melting, sublimation, and evaporation. In contrast, heat is lost to the atmosphere during freezing, condensation, and precipitation. The presence of moisture in the atmosphere is measured by the **humidity** of the air. Humidity and condensation are closely related as condensation inevitably occurs when the air is saturated with moisture (100% humidity). Air pressure decreases with altitude and results in temperature changes as descending air is compressed or rising air expands. The section on **air pressure and condensation** explains how such pressure changes can lead to condensation and cloud formation.

There are a variety of mechanisms that cause air to rise, thus leading to condensation and cloud formation. The form of clouds provides us with clues to approaching weather systems. The section on **clouds and cloud formation** discusses the lifting mechanisms that lead to cloud development and describes how we can read the sky to learn what the clouds can tell us about regional weather patterns. Weather systems are carried cross-country by prevailing winds that are tied directly to regional low- and high-pressure systems characterized by warm, ascending and cool, descending air, respectively. **Pressure and wind** details the relationship between air pressure and wind strength and direction and explores how other factors (friction, rotation of Earth) result in the flow of air into low-pressure systems and out of high-pressure systems.

The natural laws that govern the interaction between temperature, pressure, and moisture in the atmosphere make it possible for meteorologists to predict short-term changes in local weather conditions (weather forecasts). The fact that these forecasts are sometimes wrong illustrates the dynamic changes that such systems undergo during a single day and underscores the complexity of the atmospheric system.

The Structure of the Atmosphere

- Heat and temperature are different methods of measuring kinetic energy.
- The atmosphere can be divided into four thermal layers: troposphere, stratosphere, mesosphere, and thermosphere.
- The boundary with space is at an altitude of approximately 500 km.
- Air temperatures decrease upward in the troposphere which contains our weather systems.
- Temperatures increase with altitude in the stratosphere as ozone absorbs incoming solar radiation.
- Temperatures decline again in the mesosphere but increase in the thermosphere.

Heat vs. Temperature

Atoms in air are in constant motion, the energy of their motion is known as **kinetic energy**. Kinetic energy increases as the speed of atomic motion increases.

- **Heat** (energy) is the total kinetic energy of all the atoms in a substance. The more atoms present, the greater the heat.
- **Temperature** represents the average kinetic energy of the atoms in a substance. A few atoms with rapid motion will have a higher temperature than many atoms with slow motion.

The thermal characteristics of the atmosphere are determined by contrasts in heat and temperature within four atmospheric layers (Fig. 3). The composition of the air remains constant through the lower three layers up to altitudes of approximately 80 km (50 miles). The lower boundary of the atmosphere lies on Earth's surface, the upper boundary is the gradational transition into the vacuum of space. A few stray gas molecules exist more than 100 km (62 miles) above the planet's surface and spacecraft exiting Earth's atmosphere still feel the effects of frictional drag until they reach the **exosphere**, space beyond our atmosphere, at altitudes above 500 to 600 km (312-375 miles).

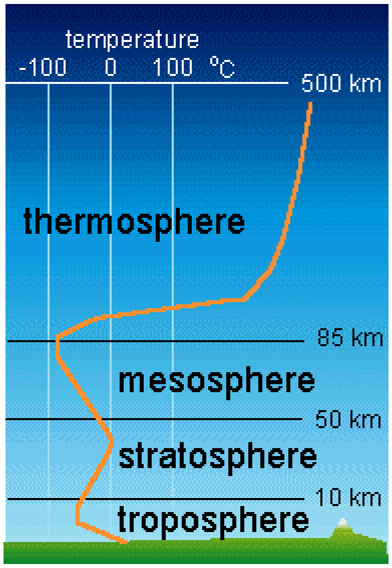


Figure 3. Four layers of the atmosphere are separated on the basis of their thermal characteristics. The orange line plots temperature variations with altitude. There are three areas of higher temperatures (the ground surface, upper stratosphere, thermosphere) and two of low temperatures (upper troposphere, upper mesosphere).

The Four Layers of the Atmosphere

Evidence collected using high-altitude balloons, rockets, and satellites reveals alternating warm and colder horizons within the atmosphere. The bulk of atmospheric gases (over 75%) lie within the lowermost atmospheric layer, the **troposphere**.

The troposphere contains our **weather systems**, air pollution, and the bulk of volcanic gases. The layer is characterized by air **temperatures that decrease upward** as distance increases from the warm Earth's surface. Anyone who has ever found him- or herself at high elevations, knows that temperature decreases with altitude (that's why we go to the mountains to ski). Air temperature declines at a rate of 6.5°C/km (known as the normal lapse rate) through the troposphere, beginning at an average of 15°C at sea level. As the layer is defined by its thermal character, we would expect it to be **thicker above warm regions** and thinner over cold areas. Consequently, it comes as little surprise that the thickness of the troposphere increases from 8 km (5 miles) over the poles to as much as 16 km (10 miles) at the equator. The boundary between the

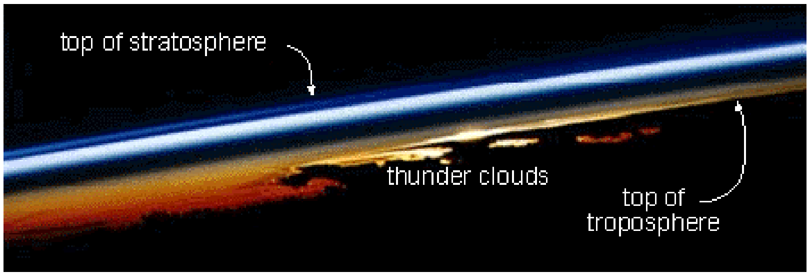


Figure 4. A slice through Earth's atmosphere is termed the limb of Earth, viewed here from the Space shuttle. Large thunderclouds rise into the troposphere, their flattened tops mark the location of the tropopause. Image courtesy of NASA's Johnson Space Center Image Services.

troposphere and the overlying stratosphere is known as the **tropopause** and temperatures at this altitude typically approach -50°C. This is the first of two temperature minima in the atmosphere (Fig. 4).

The **stratosphere** is over 40 km (25 miles) thick and contains the infamous **ozone** layer. Temperature increases upward in the stratosphere as ozone molecules concentrated in the upper two-thirds of the layer absorb ultraviolet solar radiation and decreasing air density results in greater agitation (more kinetic energy) of atoms. Maximum temperatures approach 0°C at the **stratopause** that separates the stratosphere and the overlying mesosphere (Fig. 3). The warm cap of the stratosphere overlying the relatively cool troposphere results in a stable atmospheric configuration as the cool air cannot rise into the warm layer.

Air temperatures in the **mesosphere** decrease upward to a minimum of -90°C at the **mesopause**, the boundary with the overlying thermosphere (Fig. 3). The upper mesosphere is the second temperature minima in the atmosphere.

The outermost layer of the atmosphere, the **thermosphere** (Fig. 3), blocks a variety of harmful cosmic radiation including X rays, gamma rays, and some ultraviolet radiation. Temperatures in the upper thermosphere may reach 1,500°C but the number of atoms is so small at this altitude that heat energy is actually very low. Isolated gas molecules in the thermosphere are broken into ions as solar radiation strips electrons from oxygen and nitrogen molecules. These ionized gases make up the **ionosphere**, from 80 to 400 km (50-250 miles). Spectacular visual effects called **auroras** occur when electrons and protons from the sun interact in the ionosphere (Fig. 5).

Figure 5. Left: Aurora borealis viewed near Anchorage, Alaska. Image from NOAA image collection.

Think about it . . .
Make a concept map of the characteristics of the atmosphere.

Solar Radiation and the Atmosphere

- Solar radiation occurs in a range of wavelengths represented by the electromagnetic spectrum.
- Incoming short- and intermediate-wavelength radiation may be absorbed by gases in the atmosphere, reflected back into space from the atmosphere or Earth's surface, or absorbed by Earth's surface.
- Incoming and outgoing long-wavelength radiation is absorbed by water vapor, carbon dioxide, and other gases in the atmosphere.
- The greenhouse effect occurs when long wavelength radiation is absorbed in the troposphere.

The interaction of solar radiation and the atmosphere provides the habitable planet we live on and contributes to the future potential for global warming. In addition, solar radiation supplies the energy necessary for cloud formation, precipitation, and local weather conditions.

Solar Radiation and the Electromagnetic Spectrum

Electromagnetic radiation may be measured by wavelength or frequency. Wavelength is the distance between two adjacent

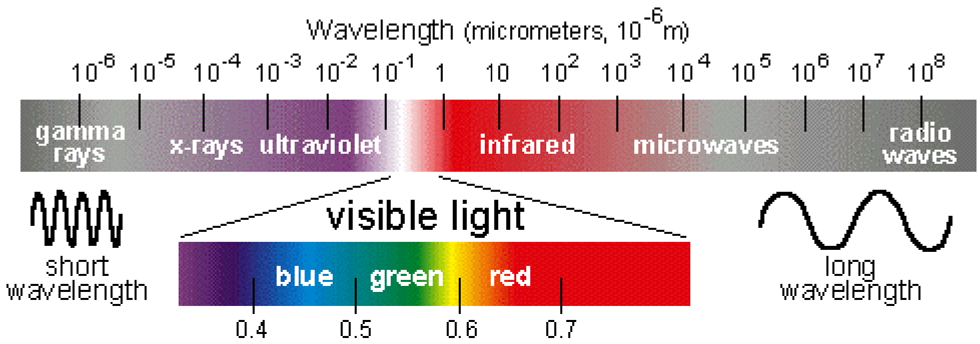


Figure 6. The electromagnetic spectrum. Radio waves can have wavelengths measured in hundreds of meters. In contrast, wavelengths for visible light are less than 1/1,000 mm across but are a million times larger than the wavelength of gamma rays. One million micrometers = one meter.

wave crests. Frequency represents the number of waves that pass a point in a second. Forms of energy with short wavelengths such as X rays have high frequencies. Long-wavelength radiation, for example, radio waves, have a relatively low frequency. The **electromagnetic spectrum** (Fig. 6) represents the range of wavelengths for electromagnetic radiation, from long-wavelength radio waves (100s of meters) to short-wavelength gamma rays (0.000001 micrometer).

All objects emit heat, and the hotter an object, the shorter the wavelength of radiation it emits. The relationship between the heat of a body and wavelength is expressed in **Wien's Law** which states that the wavelength of electromagnetic radiation can be determined by dividing 2,897 by the absolute temperature (T, expressed in degrees Kelvin, °K) of a body. (Sun, T = 6,000°K; Earth, T = 288°K)

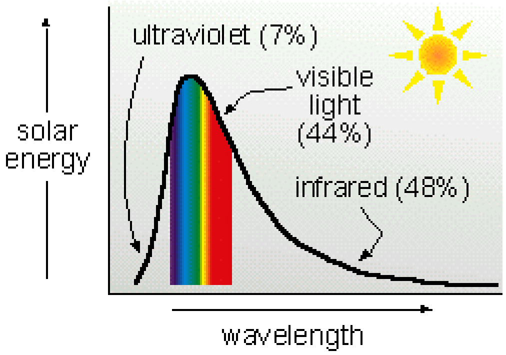
Maximum wavelength = (2897/T°K) micrometers

The supply of energy used daily by natural systems is derived almost completely from solar radiation. Substituting the temperature of the Sun into the above equation illustrates that incoming solar radiation should have a wavelength of approximately 0.5 micrometer which lies within the range of visible light.

Visible light and **near-infrared** radiation (wavelength 0.7-1.5 micrometers) make up over 90% of all solar radiation reaching Earth's atmosphere (Fig. 7). Less than 10% of solar radiation is short-wavelength **ultraviolet** (UV) radiation (0.01-0.4 micrometer).

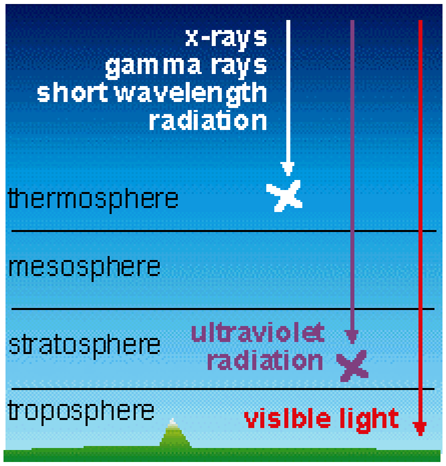
The relative proportion of wavelengths is important as atmospheric gases absorb specific wavelengths of radiation

Figure 7. The relative proportions of solar radiation reaching Earth.



(Fig. 8). Forms of radiation with the shortest wavelengths (X rays, gamma rays) are absorbed by the thermosphere. **Ozone** in the stratosphere absorbs ultraviolet radiation between 0.2 to 0.35 micrometer, effectively blocking the majority of incoming UV rays (Fig. 8). In contrast, **water vapor** and **carbon dioxide** in the troposphere absorb longer wavelength infrared radiation in the range of approximately 1 to 2 micrometers.

Figure 8. Most short-wavelength solar radiation, including x-rays, gamma rays, and ultraviolet radiation is intercepted before it reaches the troposphere. Visible light and infrared radiation are the most common wavelengths to reach Earth's surface.



Earth's Energy Budget

There are three possible fates for incoming solar radiation in Earth's atmosphere (Fig. 9):

1. The **albedo** is a measure of the magnitude of radiation that is **reflected back into space** from clouds, particles in the atmosphere, or from the land or ocean surface. The average albedo of Earth is ~30% but varies with region. Light-colored, reflective surfaces and thick cloud cover have high albedos (80-90%) because these features prevent the passage of sunlight. In contrast, dark surfaces (e.g., forests,

water) or the absence of cloud cover result in low albedo values (<25%).

2. Some forms of radiation are **absorbed by the atmosphere** (Fig. 8).
3. Visible light and some ultraviolet and infrared radiation may **reach Earth's surface**. Sunlight absorbed by the land and oceans warms the planet's surface. Heat energy from Earth's warmed surface is radiated upward into the atmosphere. Earth is much cooler than the Sun (average temperatures 15°C vs. ~5,700°C) therefore **terrestrial radiation** has a longer average wavelength (~10 micrometers) than solar radiation.

The **infrared radiation** emitted from Earth's surface is intercepted by water vapor, carbon dioxide, and other trace gases (methane, nitrous oxide) in the troposphere creating a situation that has come to be known as the greenhouse effect. The **greenhouse effect** increases temperatures at Earth's surface by 33°C, ensuring that we have a livable planet. Earth would have an average surface temperature of –18°C rather than the present average of +15°C without the heat-trapping property of water vapor and other gases in our atmosphere. Venus, with a carbon dioxide atmosphere, has a runaway greenhouse effect with surface temperatures of over 200°C.

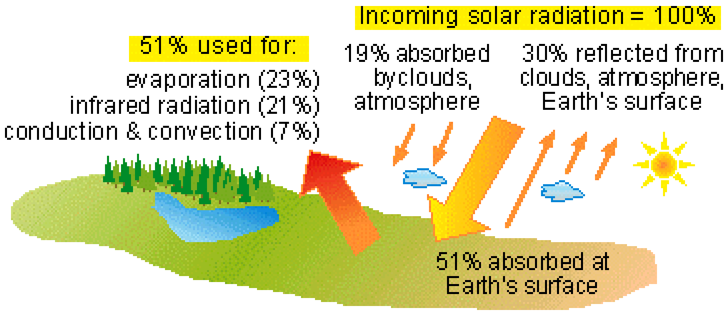


Figure 9. The solar energy budget. Approximately half of the incoming solar radiation heats Earth's surface.

Think about it . . .
Explain how the temperature of Earth would vary from present if the atmosphere was: (a) thicker, (b) thinner, (c) cloudier, or (d) mainly composed of carbon dioxide.

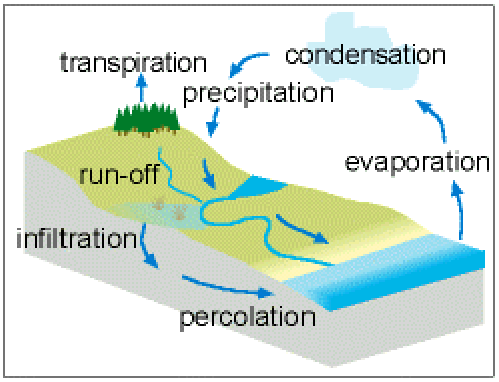
States of Water

- The bulk (>97%) of Earth’s moisture is in the oceans.
- Water can occur in three states (solid, liquid, gas) on or near Earth’s surface.
- The speed of motion of water molecules determines which phase of water exists at a given time and place.
- Water molecules exhibit the slowest motion and most ordered structure in ice and the most rapid motion and least ordered structure in water vapor.
- Heat is lost or gained as water changes state by freezing, melting, condensation, evaporation, precipitation, or sublimation.

The Hydrologic Cycle

The distribution of water on Earth is dependent upon the complex interaction between the planet's surface and the atmosphere that we call climate. The circular path of the **hydrologic cycle** links evaporation, condensation, runoff, infiltration, percolation, and transpiration (Fig. 10). These processes cause water to change state (vapor, liquid, or solid) as it moves between different elements of Earth system. (See the chapter, Groundwater & Wetlands, for more on the hydrologic cycle.)

Figure 10. The hydrologic cycle.



At any given moment, over 97% of Earth’s water is present in the oceans, most of the rest is on the continents in the form of ice, groundwater, streams, and lakes (Fig. 11). Less than 0.001% of all the water on the planet is in the atmosphere. Water is continually added to the atmosphere by evaporation from the oceans and is lost by precipitation. The volume of water falling as precipitation is approximately 0.42 $\times 10^{15}$ m^3

per year, many times greater than the moisture stored in the atmosphere. Water must be constantly cycled through the atmosphere to maintain such high precipitation volumes.

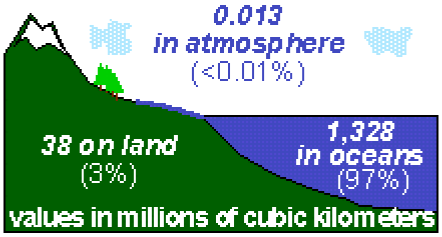


Figure 11. Water balance on earth. The majority of Earth's water is in the oceans.

Three States of Water

Water is the only natural compound that can exist in **three states** on Earth's surface; as **liquid water**, a gas (**water vapor**), and a solid (**ice**). Water molecules are in motion in all three states and the speed of the moving molecules determines the state of water for a given location.

Covalent atomic bonds between hydrogen and oxygen atoms create a characteristic bipolar atomic structure that has a negative charge adjacent to the oxygen atom and positive charge between the hydrogen atoms. The bipolar nature of the water molecules results in the formation of a bond (**hydrogen bond**) between the negative and positive poles of adjoining molecules (Fig. 12). In solid form the molecules join together in a well-ordered hexagonal structure. Groups of molecules remain attached in the liquid phase of water but have sufficiently rapid motion to generate less-ordered structures. Water molecules move too rapidly in the gas phase to allow bonding between molecules (Fig. 13).

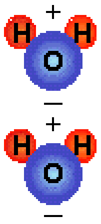


Figure 12. Hydrogen bond forms between water molecules

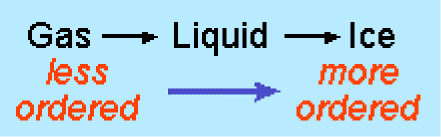


Figure 13. Water can occur in three states (forms) on Earth. The organization of atoms becomes more structured passing from gas to liquid to solid.

Heat energy is released or absorbed as water changes state. The heat capacity of a material is the amount of heat required (in calories) to raise the temperature of 1 gram of the substance by 1°C. Water has a high heat capacity because it can absorb or release substantial quantities of heat without any significant change in temperature.

We can measure the loss or gain of **sensible heat** by measuring temperature changes. Thus, if a pan of cold water (temperature of 0°C) was heated on a stove we could record the increase in water temperature with a thermometer. However, if the pan initially contained a mixture of water and ice, the temperature would not increase until the ice had melted. Heat is absorbed by the water during the change from ice to water but there would be no corresponding change in temperature until all the

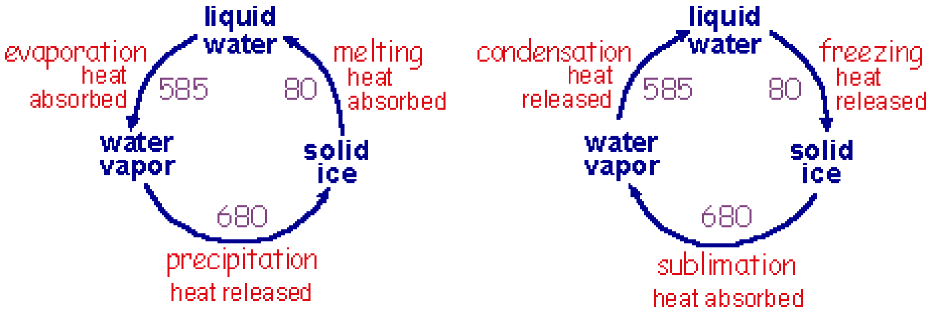


Figure 14. Release or absorbtion of latent heat occurs during changes of state in water. The calories per gram of water (heat) that are lost or gained during each change are least for freezing/melting (80) and are greatest for changes between solid and vapor forms (680). The calories lost/gained during condensation and/or evaporation are estimated for water at 20°C.

ice has melted. The amount of heat gained (or lost) as water changes state is termed **latent heat**.

Latent heat is released into the environment as water changes from a less-ordered state to a more-ordered state (Fig. 14; order = systematic organization of atoms). Heat is absorbed as water changes to a less-ordered state (Fig. 14). The amount of heat lost or gained per gram of water is expressed in calories of latent heat. The **latent heat of fusion**, the heat released as water is converted from liquid to solid, is 80 calories per gram of water. The reverse reaction, the conversion of ice to water described above, absorbs 80 calories of heat for each gram of water converted from a solid to a liquid state.

There are six potential changes in state where latent heat is either released (**freezing, condensation, precipitation**) or absorbed (**melting, evaporation, sublimation**). Two of these processes, evaporation and condensation, occur over large areas of Earth's surface and contribute significantly to the generation of weather phenomena and the redistribution of heat on Earth’s surface. Liquid water is converted to water vapor during **evaporation**. Heat is absorbed to convert the liquid to a less-ordered form. You may have noticed this change of state occurring on your skin after you step out of a hot shower or while you perspire during exercise; your body supplies the heat needed for evaporation, as heat is lost you feel cooler.

Much more latent heat is lost/gained during changes between liquid and gas states than during changes between solid and liquid states (Fig. 14). This is a function of the number of bonds that must be broken or modified between water molecules. During freezing/melting these bonds are altered but generally do not break as the atomic structure changes slightly. In contrast, during evaporation/condensation all the bonds between the molecules must be broken or formed, requiring much more energy.

Think about it . . .
Two identical pans sit on a stove. Pan A contains a water and ice mixture. Pan B contains an equal volume of water that is chilled to the same temperature. The stove is turned on to high and both pans are heated until boiling occurs. Plot separate curves on the graph at the end of the chapter to illustrate how temperature changes with time for both pans.

Humidity

- Absolute humidity measures the amount of water in air.
- Relative humidity measures the amount of water in air relative to the maximum amount of water the air could hold.
- Relative humidity increases with increasing water vapor or decreasing temperature.
- The dew point is the temperature at which air becomes saturated with moisture.

Humidity is a measure of the moisture contained in air. **Absolute humidity** measures the mass of water (grams) in a volume of air (cubic meters), essentially the **density of water vapor** (mass per volume). The absolute humidity of air varies with temperature; warm air contains more moisture than cold air, or to put it another way, warm air has higher water vapor density than an equivalent volume of cold air (Fig. 15).

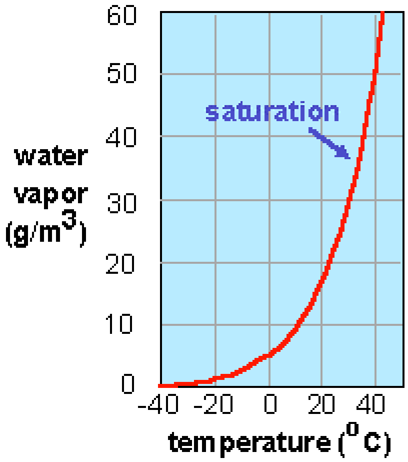


Figure 15. Increase in volume of water vapor in a volume of air (absolute humidity) with increasing temperature.

Evaporation and **condensation** are occurring concurrently in any air mass but one typically dominates. This is a function of phase relations between the liquid and vapor forms of water. Condensation occurs if more molecules are converted from vapor to liquid; evaporation occurs if more are transformed from liquid to vapor. Warm air overlying cooler water will warm the water. The bonds between the water molecules break as the velocity of the molecules increases and the liquid is converted to a gas phase. The addition of water molecules to the air increases the vapor density, and thus the absolute humidity, of the air mass.

Absolute humidity is expressed as g/m^3 (grams per cubic meter); in contrast, **relative humidity** is expressed as a percentage. Relative humidity measures the amount of moisture in air in comparison to the maximum volume of moisture the air would contain when saturated. **Saturation** represents the point where increasing vapor density results in condensation.

$$\text{Relative Humidity} = \frac{\text{actual vapor density}}{\text{saturated vapor density}} \times 100\%$$

Relative humidity increases if:

- Water is added to the air. Adding water vapor increases the actual water vapor density.
- The air temperature decreases. Reducing temperature decreases the saturated vapor density as colder air holds less moisture than warm air.

Warm air that contains as much water as cold air has a lower relative humidity. For example, air with a temperature of $25^{o}C$ and an absolute humidity of $11.5\ g/m^3$ has a relative humidity of 50% because water at that temperature can hold up to 23 g/m^3. In contrast, the relative humidity of the air would be 100% if the air was cooled to $12^{o}C$ and the moisture content remains constant ($11.5\ g/m^3$).

Condensation occurs when the air becomes saturated with moisture (relative humidity = 100%). As temperature falls the relative humidity of the air rises. The temperature at which condensation begins is termed the **dew point**.

Think about it . . .
Measurements reveal that a cubic meter of air at 12 ^{o}C holds 6 grams of water. What happens if the temperature of the air increases but no water vapor is added? Explain your choice of answer.

a) Both absolute & relative humidity increase
b) Absolute humidity increases, relative humidity remains constant
c) Both absolute & relative humidity decrease
d) Absolute humidity remains constant, relative humidity decreases

Pressure and Condensation

- Air pressure decreases with increasing altitude and decreasing air density.
- Half of all the air in the atmosphere lies below an altitude of 5.5 km.
- Adiabatic temperature changes occur because of the compression or expansion of air: Dry adiabatic lapse rate = 10^{o}C per 1,000 m (1 km); wet adiabatic lapse rate = 6^{o}C per 1,000 m (1 km).
- Rain drops begin to form as cloud droplets that nucleate on dust particles and aerosols.

Air Pressure and Altitude

Air (atmospheric) pressure is the pressure exerted by the weight of the overlying column of air (Fig. 16). For example, the air pressure on the earth's surface is determined by the weight of a 500 km (312 mile) tall air column. Pressure at the top of the stratosphere would be less as it includes a shorter column (415 km) of atmosphere.

Air pressure at any point is also influenced by **air density**. Air density represents the number of atoms of nitrogen, oxygen, etc., per volume of air. Air pressure would decrease uniformly with altitude if gases were evenly distributed throughout the atmosphere. However, gravity pulls most gases close to Earth's surface where they are compressed by the weight of the overlying column of air:

- 50% of all air lies below 5.5 km (3 mile) altitude therefore air pressure at this altitude is half of the air pressure at sea level.
- 99% of air lies below 32 km (20 mile) altitude.

Weather maps typically measure air pressure in **millibars** (mb; or hectopascals hPa); air pressure at sea level is approximately 1,000 mb and will vary locally with changing weather conditions. The National Weather Service reports air pressure at the surface at sites throughout the U.S. in **inches of mercury** (in. Hg). One millibar is equivalent to 0.02953 inches of mercury. Moving upward through the atmosphere, air pressure decreases rapidly at lower altitudes and decreases slowly at higher (>10 km) altitudes. Close to Earth's surface, air pressure declines at a rate of 1 mb per 8-meter (26 foot) increase in altitude (Fig. 16).

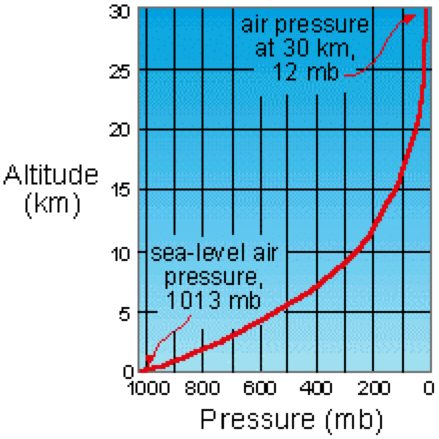


Figure 16. Air pressure declines with increasing altitude as the bulk of air molecules lie close to Earth's surface.

Air pressure varies with elevation but also with weather systems. Meteorologists must correct for changes in altitude to understand the pressure characteristics of air masses in order to forecast future weather patterns. Pressure data on weather maps are therefore recalculated to reflect pressure measurements for hypothetical **sea level** elevation.

Condensation

The condensation of moisture in the atmosphere forms **clouds**. Air cools as it rises, eventually becoming saturated with moisture when the temperature passes below the **dew point**. This section describes the factors that cause air to rise and that affect condensation.

Adiabatic temperature changes occur as a result of the compression or expansion of air. These temperature changes represent the conversion of mechanical energy into heat energy and are not associated with the addition or loss of heat from outside sources. **Compressed air becomes warmer, expanding air becomes cooler**. Some of the mechanical energy needed to force air into a confined space is converted to heat when air is compressed. Consequently, the air in a car tire warms up as tire pressure is increased or the barrel of a bicycle pump becomes warm as a tire is pumped up. When air expands it converts heat to mechanical energy so the air escaping from a punctured tire feels cooler than the surrounding air.

Air pressure decreases with altitude, therefore, air expands as it rises in the atmosphere. The expansion results in an adiabatic temperature decrease of 10^{o}C per 1,000 m for dry (unsaturated) air, termed the **dry adiabatic lapse rate**. The relative humidity of the air increases as cooling occurs until the air becomes saturated. At that point condensation occurs. Latent heat is released in the conversion of water from a vapor to a liquid state that occurs with condensation. The addition of the latent heat partially counteracts the cooling effect of the adiabatic temperature changes. This results in a reduction of the cooling rate to 4 to 9^{o}C per kilometer, known as the wet adiabatic lapse rate. An average value for the **wet adiabatic lapse rate** is 6^{o}C/km (Fig. 17).

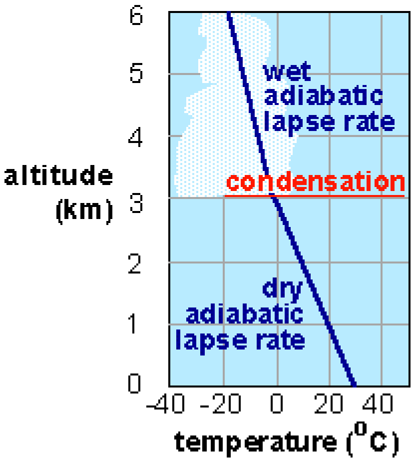


Figure 17. Decrease in the adiabatic lapse rate because of the addition of the latent heat of condensation for a hypothetical air mass following condensation at 3 km altitude.

Condensation typically occurs on **preexisting surfaces**. Condensation occurs on surfaces such as dust particles and aerosols to form tiny cloud droplets. The droplets are readily kept airborne by air turbulence until they become so common that they collide and coalesce. The larger droplets fall, colliding with other droplets to eventually form a rain-drop (containing approximately one million cloud droplets). With decreasing temperatures (less than -10^{o}C) ice crystals replace water droplets.

Think about it . . .
Fog is a form of cloud at ground level. Review the conceptest questions about fog at the end of the chapter and determine which conditions would result in fog formation.

Clouds and Cloud Formation

- The normal lapse rate for stable (non-moving) air is 6^{o}C per 1,000 m.
- Density lifting occurs when a warm air mass rises surrounded by cooler air.
- Frontal lifting occurs when warm air rises over cold air along a warm or cold front.
- Orographic lifting takes place when air is forced to rise over a mountain range.
- Convergence lifting occurs when air masses collide, forcing air upward.
- Clouds are classified by shape and altitude.

Clouds form as a result of condensation driven by adiabatic cooling processes. A parcel of air may rise naturally if it is warmer than the surrounding air masses (density lifting) otherwise it may be forced upward by a variety of processes (frontal lifting, orographic lifting, convergence lifting).

Density Lifting

The temperature of **stable air** (air that is neither rising nor falling) decreases with altitude at a rate of 6^{o}C per 1,000 m (1.8oC per 1,000 feet); this is termed the **normal lapse rate**. A mass of warm air will rise through the stable air as long as the temperature of the warm air mass remains above that of the surrounding air. The warm air mass will cool according to the dry adiabatic lapse rate. The air mass cools more rapidly than the surrounding air because the adiabatic lapse rate is greater than the normal lapse rate. The air mass continues to rise until it cools to a temperature that is equal to that of the surrounding stable air (Fig. 18).

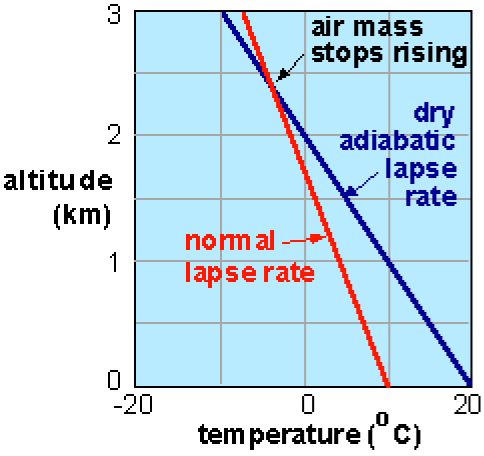


Figure 18. Assume that a warm air mass begins to rise with a temperature of 20°C and that the surrounding (stable) air has a temperature of 10°C. The temperature of the air mass and the stable air will be equalized at –5°C at an altitude of 2.5 km.

Altitude (km)	Temperature (°C)	
	Warm Air Mass	Stable Air Mass
0	20	10
0.5	15	7
1.0	10	4
1.5	5	1
2.0	0	-2
2.5	-5	-5

Frontal Lifting

Frontal lifting occurs when two large air masses of contrasting density (temperature, moisture content) meet (Fig. 19). The boundary between the air masses is termed a front and may be 10 to 150 km (6-94 miles) across and hundreds of kilometers in length. A **warm front** forms when a warm air mass advances over a cold air mass. The warm air rises above the colder air. Warm air is also forced upward when cold air approaches a

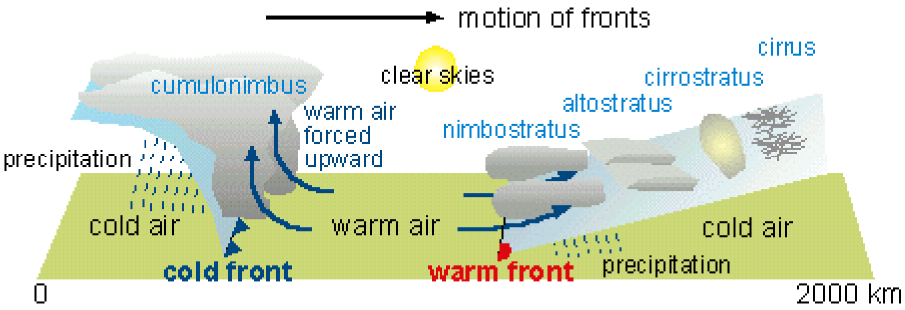


Figure 19. Weather conditions and air temperatures associated with advancing warm and cold fronts.

warm air mass along a **cold front**. Cold fronts are steeper than warm fronts and cause cloud formation and precipitation to occur across a narrower area.

Figure 20. Clouds forming over the Bighorn Mountains, Wyoming. View from west.

Orographic (Topographic) Lifting

Orographic lifting occurs when air is forced to rise over an obstruction in the landscape, typically a mountain range (Fig. 20). Condensation occurs as the air cools with increasing altitude along the windward flank of the range and precipitation may occur at high elevations. The air warms up and can absorb moisture as it descends the lee side of the mountains creating a **rain shadow** effect where precipitation is relatively rare.

Convergence Lifting

Convergence lifting occurs when two air masses collide, forcing some air upward as both air masses cannot occupy the same space (Fig. 21). This happens regularly over Florida where air moves westward from the Atlantic Ocean and eastward from the Gulf of Mexico to collide over the Florida peninsula.

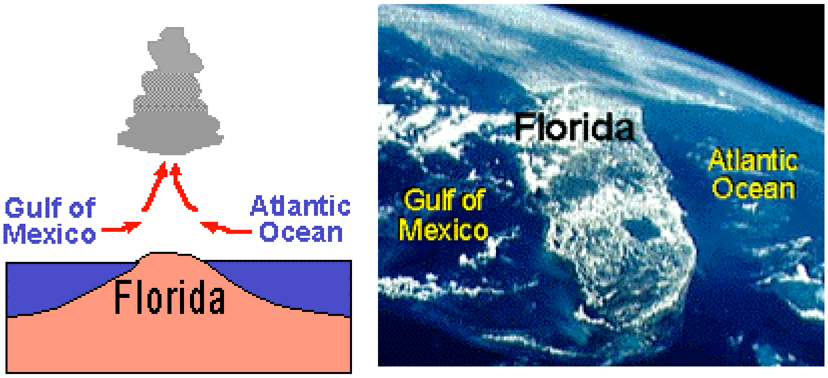


Figure 21. Convergence lifting occurs over the Florida peninsula. Condensation above Florida may be assisted by density lifting because air overlying the land mass will be warmer than air above the adjacent ocean. Image on right courtesy of JSC Image Services.

Condensation Processes

There are two processes that allow moisture to condense to form clouds. Clouds are composed of billions of tiny water droplets that eventually combine to form rain, snow, or other forms of precipitation. These tiny **water droplets** form when water vapor condenses on surfaces in the atmosphere or on the land (e.g., dew or frost on vegetation). **Microscopic particles** in the air (dust, smoke, salt, pollutants) range in size from 0.001 to 10 micrometers (0.00001-0.01 mm) and serve as nucleation surfaces for water droplets that are approximately 20 micrometers in diameter. There are literally billions of these droplets in a single cubic meter of air. It takes about a million water droplets to form a single raindrop.

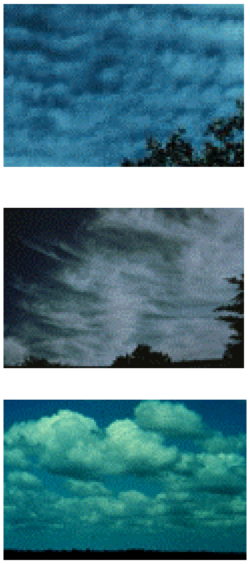
Cloud Classification

Clouds are classified on the basis of their altitude and appearance. Most clouds occur at a specific range of altitudes but some, such as cumulonimbus clouds associated with thunderstorms, may span several levels. The prefix **cirr-** indicates a high-level cloud; **alto-** indicates midlevel clouds.

Altitude	Cloud Types
High (>6 km)	Cirrus, cirrostratus, cirrocumulus
Middle (2-6 km)	Altostratus, altocumulus
Low (< 2 km)	Cumulus, stratocumulus, nimbostratus

The most commonly recognized clouds are the puffy, cauliflower-shaped cumulus clouds. If a sufficient number of these clouds are formed they may create an irregular low layer of stratocumulus clouds. **Cumulus** clouds at higher altitudes are termed altocumulus or cirrocumulus clouds.

Stratus clouds form sheets that cover the whole sky and may form at all levels. They are typically associated with frontal lifting. Especially thick stratus clouds are termed nimbostratus. Cirrus clouds are composed of ice crystals and have a wispy form and occur at high altitudes.



Altocumulus, cirrus, and cumulus clouds (top to bottom).

Precipitation follows one of two processes:

- **Collision-coalesence** occurs when water droplets collide and combine together to form larger droplets as larger droplets are pulled earthward by gravity. Updrafts can recycle the droplets through the cloud, increasing droplet size.
- **Bergeron processes** occur where temperatures fall below freezing. Pure water droplets remain liquid until supercooled to temperatures of more than -20^{o}C (below freezing). Miniature ice crystals or **supercooled** water droplets may act as condensation surfaces. However, the **density of water vapor** in the air prior to saturation is slightly less adjacent to ice surfaces than water surfaces. Consequently, water vapor is added to the growing ice crystals (by **deposition**) rather than the water droplets. Eventually, precipitation of ice or snow occurs unless the frozen water is warmed as it falls through the atmosphere, resulting in rain.

Pressure and Wind

- Wind is the horizontal movement of air from areas of high- to low-pressure.
- High-pressure regions are dominated by cold, descending air.
- Low-pressure areas are associated with warm, rising air masses.
- Winds blow perpendicular to the pressure gradient.
- Winds are deflected from their course by the Coriolis effect.
- Winds converge on low-pressure cyclones and diverge from high-pressure anticyclones.
- Good weather is associated with high-pressure, poor weather with low-pressure.

Wind is the horizontal movement of air arising from differences in air pressure. Winds flow from areas of high pressure to areas of low pressure. Winds are characterized by wind speed and direction. Maximum wind speeds are associated with hurricanes and may reach velocities of over 320 km per hour (200 mph). Winds are named for the direction they blow from, for example, a westerly wind blows from the west.

We have described vertical variations in air pressure (air pressure decreases with increasing altitude) above. Horizontal variations in air pressure result from **differential heating** of air masses near Earth's surface.

An air mass will expand when warmed and contract when cooled. Contraction of an air mass results in greater compression of the atmosphere within the air mass and higher air pressures. In contrast, expansion results in the same air mass occupying a larger area and is accompanied by a decrease in pressure. **High-pressure** regions are dominated by cold descending air whereas **low-pressure** areas are characterized by warm, ascending air masses. It should come as no surprise that the highest pressures are recorded near polar regions and the lowest pressures are recorded in tropical regions (associated with hurricanes/ typhoons; Fig. 22).

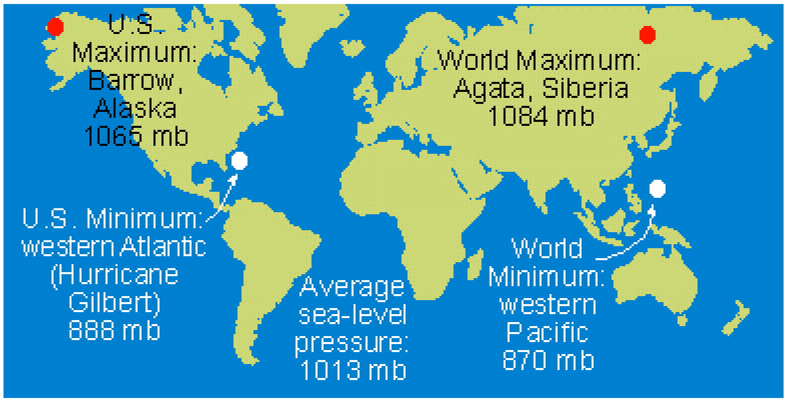


Figure 22. Maximum and minimum global pressure measurements. Highest pressures are found in colder regions, lowest values are associated with hurricanes (typhoons in Pacific Ocean) in tropical oceans.

At the time of writing, air pressure variations in the continental U.S. ranged from a low of 1,008 millibars (mb) over Michigan to a high of 1,028 mb over Utah. Check the Intellicast map of the U.S. to see the range of values for today.

Wind Speed and Direction

Winds will blow from areas of high pressure to areas of low pressure. Three factors influence wind speed and direction: the regional pressure gradient, the Coriolis force, and friction.

Pressure Gradient

The pressure gradient is the magnitude of the change in pressure between two points divided by the distance between those points. The greater the contrast in pressure and the shorter the distance, the steeper the gradient will be and the faster the wind will blow. **Isobars** (lines of constant pressure) join points of equal pressure plotted on a map (Fig. 23). If no other factors influenced wind direction, winds would blow down the pressure gradient, across the isobars (Fig. 23).

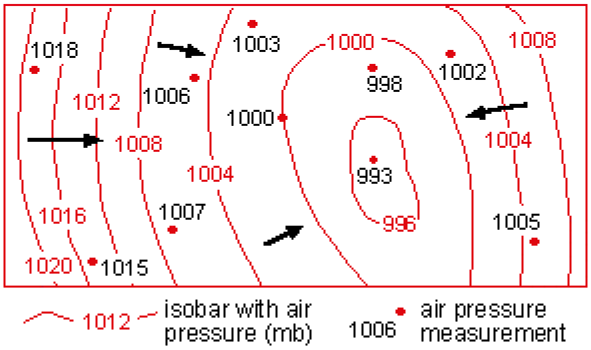


Figure 23. Isobars, lines of constant air pressure, connect points of equal pressure. Arrows indicate wind direction, from high- to low-pressure regions.

The closer the isobars are together, the faster the wind speed (greater pressure drop with distance). For example, on the map above, wind speed would be greatest between the 1,008 and 1,020 mb isobars and least from the 996 to 1,004 mb isobars.

Wind direction is initially controlled by the pressure gradient, flowing perpendicular to the isobars and parallel to the maximum pressure gradient. However, that initial wind direction will be modified by the influence of the Coriolis effect and friction close to the planet's surface.

Coriolis Effect

Currents are deflected to the right of their course in the Northern Hemisphere and to the left of their course in the

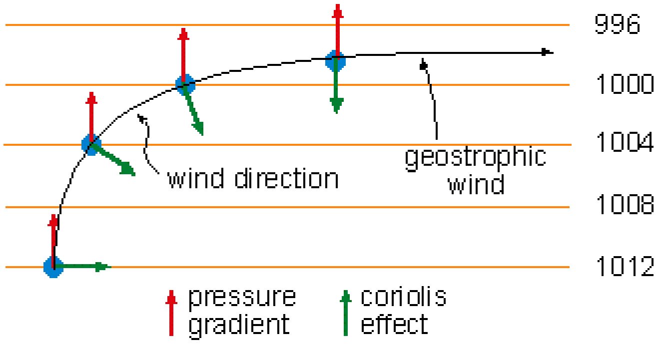


Figure 24. Interaction of pressure gradient and Coriolis effect on wind direction.

Southern Hemisphere: this pattern is termed the **Coriolis effect**. (See separate section on page 28 for more details on the Coriolis effect)

The Coriolis effect will deflect winds blowing from areas of high pressure. Rather than moving perpendicular to the trend of the isobars, winds will be deflected to the right of their course in the Northern Hemisphere (Fig. 24). The deflection of the Coriolis effect increases with increasing pressure gradient. Winds will continue to be deflected until the pressure gradient effect balances the Coriolis effect and the wind moves parallel to the isobars. Winds blowing parallel to isobars are termed **geostrophic winds**.

Geostrophic winds are disrupted by the influence of friction immediately above Earth's surface but are fully developed a few kilometers above the surface (Fig. 25).

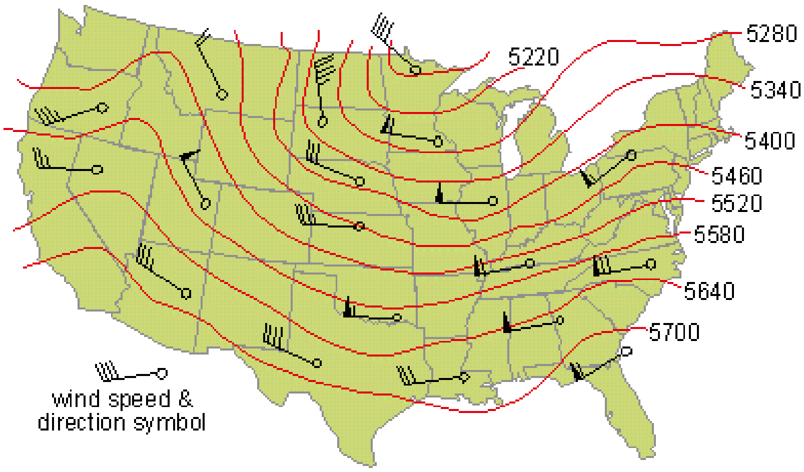


Figure 25. Wind direction and elevations (meters) of 500 mb pressure surface in the troposphere above the U.S., January 23, 2000. Contours represent elevation of surface and are essentially parallel to isobars. Note wind directions are parallel to contours.

Friction

Wind blowing near Earth's surface is slowed by frictional drag from surface features. Increasing friction reduces the Coriolis force that is proportional to wind speed. The diminished Coriolis effect cannot balance the influence of the pressure gradient and results in **non-geostrophic winds** close to Earth's surface (Fig. 26). Winds are **oblique to isobars**, the angle between wind direction and the pressure gradient is dependent upon the character of the underlying surface. Friction decreases with increasing elevation (Fig. 25). Frictional effects are most dramatic above rugged land surfaces (e.g., mountains), resulting in wind directions that are oriented 40 to 50 degrees

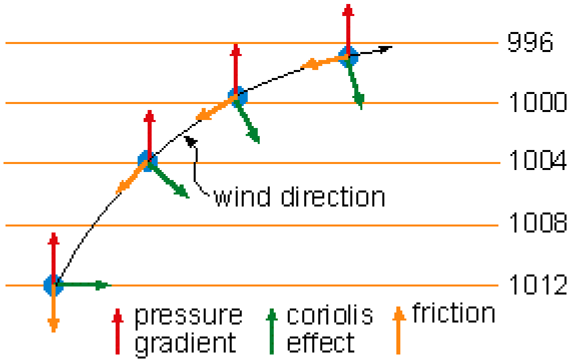


Figure 26. Influence of friction close to Earth's surface results in winds that are oriented at an angle to isobars.

from the surface isobars. Friction is less significant above flat terrain or the ocean surface but still results in winds that are oriented 10 to 20 degrees from the isobars.

Cyclones and Anticyclones

The combined effect of the controls on wind direction is that airflow spirals inward (converges) into areas of **low-pressure**, generating a feature known as a **cyclone** (Fig. 27). In contrast, winds diverge from **high-pressure** systems (**anticyclones**; Fig. 27). Circulation in low-pressure systems is therefore counterclockwise, whereas flow is clockwise in anticyclones.

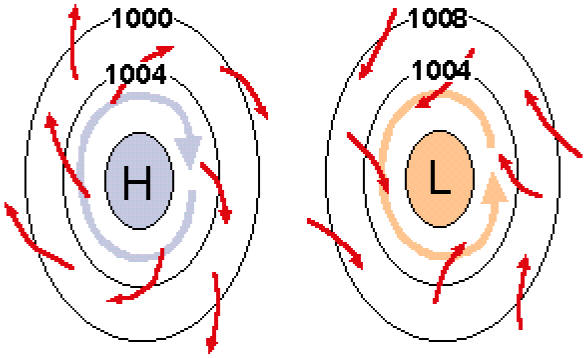


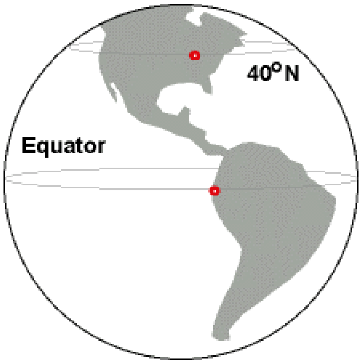
Figure 27. Winds converge in low-ressure systems (right) creating a counterclockwise airflow at the surface and diverge from high-pressure systems (left), generating a clockwise airflow.

Cyclones require divergent airflow at higher altitudes to balance the convergent flow at the surface whereas anticyclones must have convergent flow aloft to ensure their survival. Low-pressure systems would be rapidly dissipated by converging air unless the inrushing air was balanced by a rising air column. Rising air becomes cooler and may reach saturation, resulting in **clouds and rain**. In contrast, air descends in high-pressure zones, warming as it approaches Earth's surface. As the air becomes warmer its relative humidity decreases resulting in dryer air. Low-pressure systems are often associated with rainfall and cloud formation whereas high-pressure systems result in **clear skies** and dry weather.

Think about it . . .
Review the map of U.S. surface pressure conditions at the end of the chapter. Can you predict the wind directions associated with these conditions?

The Coriolis Effect

The earth makes one complete rotation on its axis every 24 hours. An object on the equator travels the circumference of the globe (approximately 40,000 km) each day. Objects at the poles simply rotate around a vertical axis but don't move in space. The distance traveled per day (and velocity of rotation) decreases with increasing latitude. The city of Columbus, Ohio, located at 40°N, travels at 1,284 km/hr (~360 meters per second) whereas U.S. cities located along the 30th parallel (e.g., New Orleans) rotate at 1,452 km/hr (~400 m/sec). Meanwhile, Seward, Alaska (60°N), pokes along at only 838 km/hr.



Every point on the earth's surface must make one complete rotation of the planet each day. Objects on the earth's equator travel further (and faster) than objects at higher latitudes. A site located along the equator travels at 1,675 km/hr, whereas a site along latitude 40°N (or 40°S) has a velocity of 1,284 km/hr. It is this contrast in velocity that results in the Coriolis effect.

The Coriolis effect can be a difficult concept to grasp because although we recognize that the earth rotates, it is difficult to accept that most of the population of the U.S. is hurtling along at over a thousand kilometers per hour. It is much like traveling in a car. Although we are sitting still in a car that is moving at 100 km/hr (62 mph), we recognize that we too are traveling at the same speed. If we were foolish enough to try to exit the vehicle we would have the same velocity as the car (until we hit something that wasn't moving, e.g., the ground).

So what has all this got to do with the Coriolis effect? This contrast in velocity with latitude causes travel paths (of winds, ocean currents, missiles, etc) to be deflected to the right of their course in the Northern Hemisphere. Here's why. Imagine yourself in Panama City, Florida, near 30°N and 1,100 km directly south of Columbus, Ohio. You fire a rocket directly north at noon. The rocket travels north at 1,100 km/hr. However, it also has the eastward velocity (1,452 km/hr) of the launch site (the earth is rotating to the east). The rocket would arrive in Columbus at 1 p.m if Columbus were rotating at the same velocity as Panama City. Luckily for Columbus the city moves eastward only 1,284 km between noon and 1 p.m. As the rocket moves eastward an additional 168 km it will land east of

Columbus in the rural Appalachian plateau near the border with West Virginia. Your dastardly plans are thwarted.

To the citizens of Columbus it would appear that the rocket was **deflected to the right of its course**. If they sought to retaliate by launching a similar missile toward Panama City they would find that they too would miss their target by 168 km. Because Panama City moves east more rapidly than Columbus, the rocket would land west of the city, again an apparent deflection to the right of its (southerly) course. The deflection is the Coriolis effect.

Summary

1. Is there air on other planets?
No. Other planets have atmospheres but the unique blend of gases that exclusively makes up Earth's atmosphere are known as air.

2. What is the composition of air?
Air is mainly composed of two gases (nitrogen, oxygen) but contains trace amounts of other gases (e.g., carbon dioxide) that play a significant role in Earth's climate despite their modest volumes.

3. When is high temperature not accompanied by heat?
Kinetic energy, the motion of atoms in a gas, can be represented by heat (the sum of all the atomic motions) or temperature (the average speed of the atomic motions). Any number of fast-moving atoms can generate high temperatures but only large numbers of atoms can result in heat. Here's an analogy. The temperature of the flame in a small fire may be the same as that of the flames in a big fire but the big fire can heat a larger room. Heat will be greater close to Earth's surface where the majority of atoms are found. A few isolated atoms in the high atmosphere may move quickly (high temperature) but they won't generate any significant heat.

4. Is Earth's atmosphere uniform everywhere?
Yes and no. The composition of the atmosphere remains relatively similar around the world but the atmosphere is differentiated into four structural layers on the basis of their thermal character. In order, from Earth's surface to the

boundary with space, the four layers are the troposphere, stratosphere, mesosphere, and thermosphere.

5. How do scientists tell the difference between the four layers of the atmosphere?

Temperatures decrease with increasing altitude in two layers (troposphere, mesosphere) and increase with altitude in the stratosphere and thermosphere. Generally, the atmosphere should get colder with increasing distance from the relatively warm Earth surface. Exceptions to this rule occur in the stratosphere and thermosphere because of the effects of variations in atmospheric composition and solar radiation, respectively. The stratosphere is enriched in ozone which absorbs ultraviolet radiation, exciting atoms and increasing their average kinetic energy. Cosmic radiation bombards atoms in the outer reaches of the thermosphere, increasing their speed of motion and hence the measured temperature.

6. How is the energy we receive from the Sun related to rainbows?

Rainbows are formed when sunlight is refracted through raindrops. The range of colors (violet to red) that we see in a rainbow represents the spectrum for visible light. The different colors of light may be defined by their wavelengths. However, solar radiation is made up of a range of wavelengths, most of which are invisible to us. Visible light lies between the short-wavelength (e.g., X rays, UV rays) and long-wavelength radiation (e.g., infrared, microwaves).

7. Are we in danger from the harmful forms of solar radiation?

Not really. The most harmful forms of solar radiation (gamma rays, X rays) are absorbed in the upper atmosphere and most of the potentially harmful ultraviolet rays are blocked by ozone in the stratosphere. Most of the radiation reaching Earth is visible light or near-infrared. Still, it never hurts to wear a sunblock with UV protection if you are outside on a sunny day.

8. What happens to incoming solar radiation?

Two things might happen to solar radiation when it reaches Earth if it is not absorbed by the atmosphere. It might be reflected back to space (especially from a light-colored surface) or it may be absorbed by land or ocean at the surface. The warmed surface of the planet radiates long-wavelength (infrared) radiation out to the atmosphere.

9. Is the greenhouse effect good or bad for Earth?

The original greenhouse effect is good for Earth. Temperatures would be below freezing (-18^{o}C) if carbon dioxide in the atmosphere did not absorb heat radiated from the planet's surface. The atmospheric concentration of carbon dioxide is steadily increasing. Scientists generally believe that more carbon dioxide will lead to higher temperatures but the exact consequence of such changes are still under investigation.

10. How is water distributed on Earth?

Water occurs in three forms on our planet, this is one of the unique features of Earth. Liquid water is most common and 97% of all water occurs in the oceans. About three-quarters of the remaining water is found in solid form (ice) near the poles or at high elevations. A small fraction (<0.01%) of the water budget is present as a gas (water vapor) in the atmosphere.

11. Why does water become less ordered as it passes from solid to liquid to gas forms?

Water molecules naturally bond together to form hexagonal chains of molecules. The chains are well ordered and complete if the molecules and their constituent atoms remain in place but break up (become less ordered) as the motion of the molecules increases. Atoms and molecules naturally move fastest in a gas phase and don't form chains. Liquid water is more ordered than gas but the chains are still incomplete because the molecules are still free to move. In solid form the molecules join together in a well-ordered hexagonal structure

12. What is latent heat?

The amount of heat gained or lost as water changes state is termed latent heat. Latent heat is released into the environment as water changes from a less-ordered state to a more-ordered state (e.g., gas to liquid). Heat is absorbed as water changes to a less-ordered state (e.g., solid to liquid). For example, ice absorbs heat as it is converted to water but the initial temperatures of the ice and water would be the same (0^{o}C).

13. What is the difference between relative and absolute humidity?

Both give a measure of the amount of moisture contained in the air. Absolute humidity measures the actual amount of water vapor in a given volume of air and is expressed in units of grams per cubic meter. In contrast, relative humidity is a ratio of the amount of moisture in air in comparison to the maximum volume of moisture the air would contain when saturated. Relative humidity is expressed as a percentage. 0%, no water vapor; 100% air is saturated with water vapor and can't hold any more.

14. What factors result in an increase in humidity?
Both absolute and relative humidity increase with the addition of more water vapor (e.g., when an air mass moves over water). Relative humidity increases with decreasing temperature but absolute humidity doesn't change.

15. What does air pressure represent?
Air (atmospheric) pressure at any location is the pressure exerted by the weight of the air overlying that site. The more air over your head, the greater the air pressure. Air pressure is greater at low elevations and less at high altitudes.

16. Where is most air located?
Gravity pulls molecules of oxygen and nitrogen down toward Earth's surface and most of the air is therefore found within the troposphere (99% is below 32 km altitude). The air pressure at sea level averages 1,013 millibars and declines gradually with increasing elevation, dropping to just 12 mb at 30 km.

17. What are adiabatic temperature changes?
Adiabatic temperature changes occur as a result of the compression or expansion of air. These temperature changes represent the conversion of mechanical energy into heat energy. Compressed air becomes warmer, expanding air becomes cooler. Rising air is under decreasing pressure and therefore undergoes adiabatic cooling, typically at a rate of 10^{o}C/km.

18. Why is the wet adiabatic lapse rate less than the dry lapse rate?
Rising air undergoes adiabatic cooling, resulting in increasing relative humidity and eventual saturation. Following this point, continued cooling causes condensation, releasing latent heat as water becomes more ordered (gas to liquid state). The addition of heat to the atmosphere decreases the cooling rate to 6^{o}C/km.

19. Why do clouds form?
Clouds form as a result of condensation driven by adiabatic cooling. Air may rise naturally if is warmer than the surrounding air masses (density lifting), otherwise it may be forced upward by a variety of processes (frontal lifting, orographic lifting, convergence lifting).

20. Are clouds made up of raindrops?
Actually, no. Clouds form when condensation takes place but condensation forms tiny water droplets that condense on minute dust particles in the air. It takes a million or so droplets to form a single raindrop.

21. So how does rain (or other forms of precipitation) form?
Precipitation can occur by two processes. The little water droplets can collide with each other to form larger drops (the collision-coalescence process) that are eventually big enough to fall to the land surface. Tiny ice crystals grow (by the Bergeron process) by the addition of water vapor, eventually becoming large enough to fall to Earth as ice or snow.

22. How are clouds classified?
Clouds are classified on the basis of their altitude and appearance. The prefix cirr- indicates a high-level cloud (e.g., cirrus); alto- indicates mid-level clouds (e.g., altocumulus). Puffy, individual clouds are cumulus and are typically found at low levels (less than 2 km). Sheets of clouds are termed stratus clouds (e.g., altostratus).

23. What is wind?
Wind is the horizontal movement of air that flows from areas of high pressure to areas of low pressure. Winds are named for the direction they blow from, for example, a northeasterly wind (known as a nor'easter) blows cold maritime air onshore from the North Atlantic to New England.

24. What causes differences in air pressure at Earth's surface?
Horizontal variations in air pressure result from differential heating of air near Earth’s surface by solar radiation. Air expands when warmed and contracts when cooled. Contraction results in higher air pressures, expansion results in air occupying a larger area and is accompanied by a decrease in pressure. Highest pressures are associated with high latitudes and lower pressures are found near the tropics.

25. How do changes in pressure close to Earth's surface influence wind speed and direction?
The greater change in pressure between two points the greater the wind velocity. Points of equal pressure on weather maps are joined by isobars (lines of equal pressure). If pressure differences represented the only control over wind direction, wind would blow perpendicular to the isobars.

26. What is the Coriolis effect and why does it work?
Wind and ocean currents are deflected to the right of their "ideal" course in the Northern Hemisphere, this is the Coriolis effect. The Coriolis effect occurs because of the difference in the velocity of Earth's rotation with latitude.

27. What is a geostrophic wind?
Geostrophic winds occur when the Coriolis effect that deflects the wind balances the influence of the pressure gradient causing the wind to flow in a direction that is essentially parallel to the isobars (lines of equal pressure).

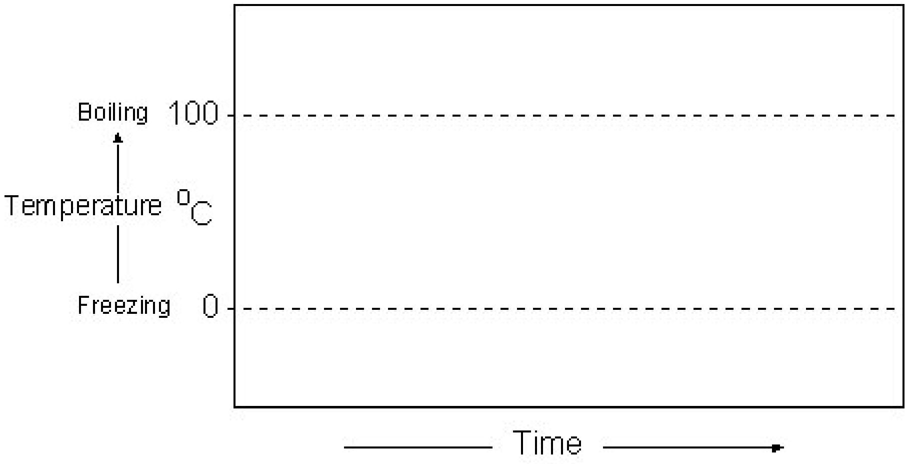
28. How does friction prevent purely geostrophic winds from forming above the land surface?
Increasing friction reduces the Coriolis force which is proportional to wind speed. The diminished Coriolis effect cannot balance the influence of the pressure gradient and results in non-geostrophic winds that are oblique to isobars.

29. What air circulation patterns are associated with low- or high-pressure systems?
The combined effect of the controls on wind direction (pressure gradient, Coriolis effect, friction) is that airflow spirals inward into areas of low pressure. In contrast, winds diverge from high-pressure systems. Circulation in low-pressure systems is therefore counterclockwise, whereas flow is clockwise in high-pressure systems. Low-pressure systems would be rapidly dissipated by converging air unless the inrushing air was balanced by a rising air column and divergence in the upper troposphere.

Changing States of Water

Two identical pans sit on a stove. Pan A contains a water and ice mixture. Pan B contains an equal volume of water that is chilled to the same temperature. Each pan contains a thermometer that records the temperature of the water/ice mixtures. The stove is turned on to high and both pans are heated until boiling occurs. Heat continues to be applied for several more minutes.

Plot separate curves on the graph below to illustrate how temperature changes with time for both pans. Label the curves.



Fog Formation

Fog is a form of cloud at ground level. Identify which of the following conditions would be most likely to result in fog formation?

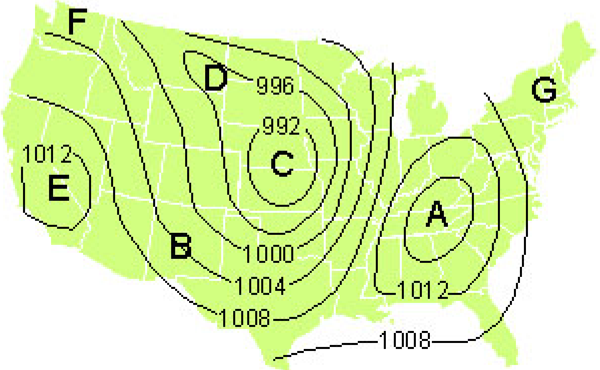
1. Under which of the following conditions is fog most likely to form?
   a) Moist air moves over cooler ocean.
   b) Moist air moves over warmer ocean.
   c) Moist air moves over cooler land.
   d) Moist air moves over warmer land.

2. Under which of the following conditions is fog most likely to form?
   a) Warm air lies over colder water of a lake.
   b) Cold air lies over warmer water of a lake.
   c) Warm air lies over a colder land surface.
   d) Cold air lies over a warmer land surface.

3. Under which of the following conditions is fog most likely to form?
   a) Moist air is forced to move downslope.
   b) Dry air is forced to move downslope.
   c) Moist air is forced to move upslope.
   d) Dry air is forced to move upslope.

Wind Directions and Air Pressure

Review the map of surface pressure conditions above the U.S. Can you predict the wind directions associated with these conditions?



1. Circle the area on the map above with the highest wind velocity based upon the isobars alone.
2. Identify the center of a low-pressure system on the map above.
   a) A b) B c) C d) D e) E
3. If Earth did not rotate, wind would blow directly from ________.
   a) A to C b) C to A c) C to B d) F to E e) B to E
4. Fully illustrate the circulation patterns of winds on the map above when corrected for the Coriolis effect.
5. Draw the wind directions associated with the low- and high-pressure systems for the map below that shows actual air pressure readings from January 2000