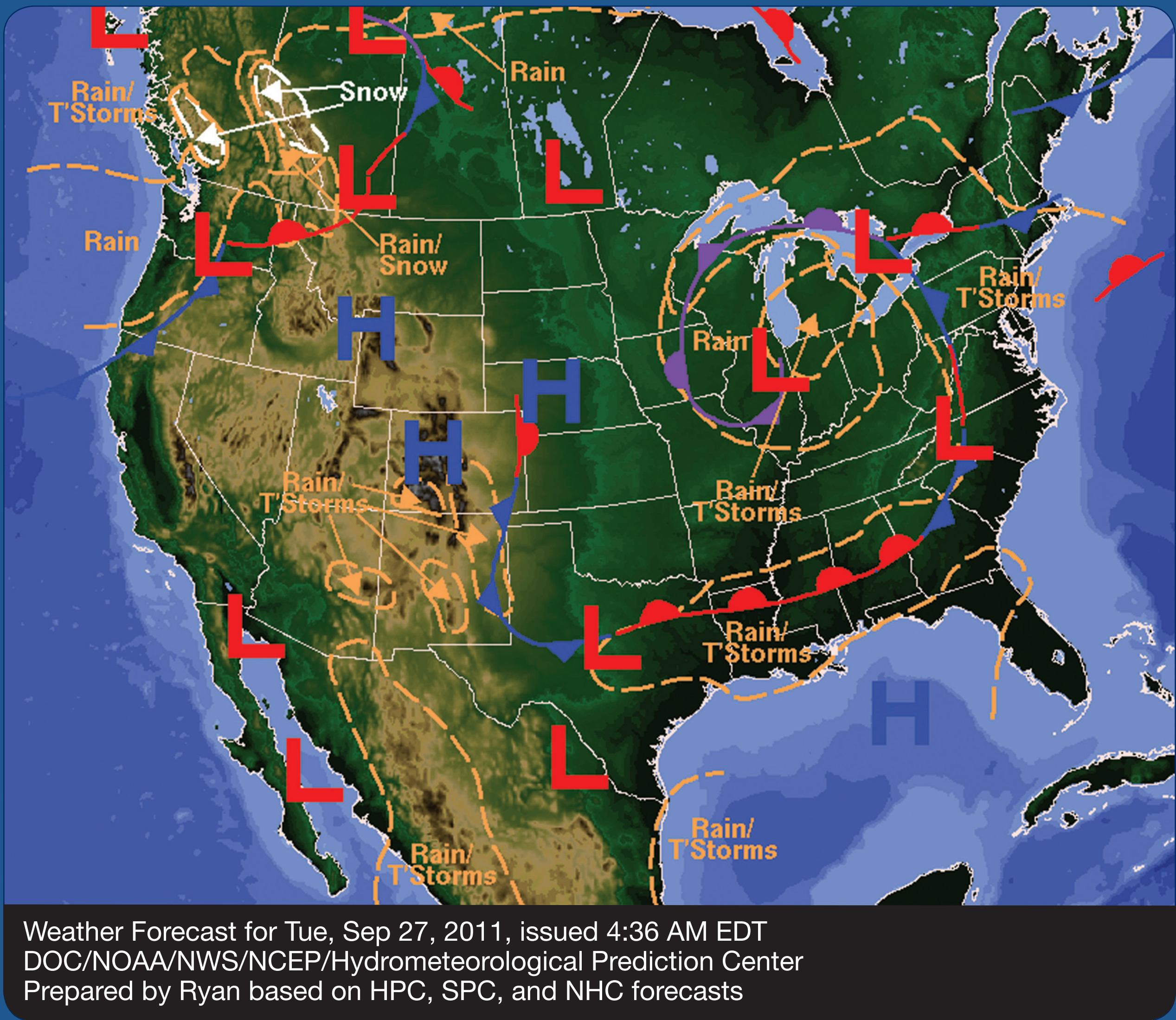
# CHAPTER 2

# Working




This NOAA map shows the weather forecast for the continental United States on 27 September 2011. Note the large low-pressure system spinning over the Great Lakes and the extensive areas where thunderstorms are possible.
*Courtesy of NOAA*

# Through Flight CONDITIONS

## Chapter Outline


LESSON 1
The Atmosphere

LESSON 2
Weather Elements

LESSON 3
Aviation Weather

LESSON 4
Weather Forecasting

LESSON 5
The Effects of Weather on Aircraft


"With all the knowledge and skill acquired in thousands of flights in the last ten years, I would hardly think today of making my first flight on a strange machine in a twenty-seven mile wind, even if I knew that the machine had already been flown and was safe."

*Orville Wright, 1919*

# LESSON 1

# The Atmosphere

## Quick Write

What are some of the advantages to using low-tech equipment? What are some of the disadvantages?

## Learn About

- the atmosphere's regions
- the roles of water and particulate matter in the atmosphere
- the primary causes of atmospheric motion
- the types of clouds
- how the atmospheric layers impact flight

Even in the twenty-first century some science tools remain low-tech. Weather offices have been using balloons since 1918 to measure different atmospheric qualities. These measurements ultimately help pilots fly more safely through the atmosphere because forecasters use the data to identify severe weather.

The balloons are filled with lighter-than-air gases, such as hydrogen, helium, or natural gas. Latex balloons form nice round spheres and rise fast and uniformly into the sky. Neoprene rubber balloons flatten out the more they rise. They also climb more slowly and less uniformly than latex balloons.

The National Weather Service, a part of the US government's National Oceanic and Atmospheric Administration (NOAA), releases balloons twice each day from about 100 locations across the United States. This adds up to nearly 75,000 balloons per year. The balloons ascend more than 100,000 feet (20 miles) into the atmosphere. Over the course of their two-hour flight, they can drift up to 200 miles from their launch site. These balloons provide a **meteorologist** (*a person who forecasts the weather*) data to predict everything from thunderstorms and hurricanes to aircraft icing, jet stream positions, and temperatures.

Attached to each balloon with a string is a small, battery-powered instrument called a *radiosonde*. The radiosonde is barely larger than a can of soda. It contains sensors that measure humidity, temperature, air pressure, wind speed, and wind direction. Ground-based radar tracks the radiosonde and collects and processes the weather data.

Not only do local weather offices use this information to forecast the weather, but *all* of the data also goes to a supercomputer in Washington, DC, which generates a computer model of the atmosphere.

When a balloon has risen as far as it can tolerate, it pops. A small parachute opens, which gently floats the radiosonde back to Earth. If you ever find one of these instruments tethered to a deflated balloon, it should have the message "Harmless Weather Instrument" printed on it. It may also smell like a rotten egg and make some strange noises, but don't be alarmed! That's just the nature of this equipment. Each instrument has an addressed, postage-paid return mailbag attached to it, so you can mail it back to the National Weather Service. Currently, the weather service only gets back 20 percent of the radiosondes it sends into the upper-air atmosphere each year. It has to replace the other 80 percent.

NOAA weather balloon launch
*Courtesy of NOAA*

## Vocabulary

- meteorologist
- atmosphere
- jet stream
- evaporation
- sublimation
- condensation
- deposition
- humidity
- relative humidity
- dew point
- saturated
- precipitation
- particulate matter
- nucleus
- atmospheric pressure
- latitude
- ceiling
- cumulonimbus clouds
- wind shear
- cabin altitude

## The Atmosphere's Regions

The atmosphere is *a blanket of air that surrounds Earth and consists of a mixture of gases*. It extends more than 350 miles from Earth's surface, but the air grows thinner the farther away you get from the planet. This mixture is in constant motion, like an ocean with its waves, swirls, and eddies.

> **Wing TIPS**
>
> Earth's magnetic field protects the planet from fast-moving particles streaming from the sun, but so does the atmosphere.

Life on Earth is supported by the atmosphere as well as by solar energy and the planet's magnetic fields. The atmosphere absorbs energy from the sun, recycles water and other chemicals, and works with electrical and magnetic forces to provide a moderate climate that can support organic life. It also protects Earth from high-energy radiation and the frigid vacuum of space.

Nitrogen accounts for 78 percent of the atmosphere's gases; oxygen represents about 21 percent; and argon, carbon dioxide, and traces of other gases account for the remaining 1 percent (Figure 1.1). The atmosphere also contains some water vapor, which varies from 0 percent to about 5 percent by volume. This small amount of water vapor is responsible for major changes in the weather.

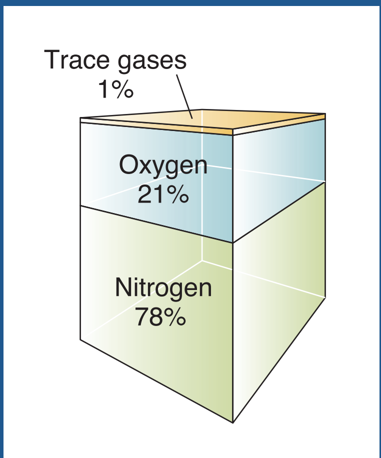



**Figure 1.1** Composition of Earth's atmosphere
*Reproduced from US Department of Transportation/Federal Aviation Administration*

### Five Distinct Layers

Five distinct layers compose Earth's atmosphere. Scientists identify each one by differences in temperature, chemical composition, movement, and density.

The lowest layer of the atmosphere, the *troposphere*, reaches from sea level up to anywhere from about four miles (eight km or 20,000 feet) at the poles to about nine miles (14.5 km or 48,000 feet) at the equator. This is a dense stretch of atmosphere where most weather takes place, along with clouds, storms, and temperature changes. The temperature drops at a rate of about 3.5 degrees F (2 degrees C) for every 1,000 feet gained in altitude. The pressure decreases as well at a rate of about one inch per 1,000 feet altitude gain. A boundary called the *tropopause* caps the troposphere and traps moisture and weather in the troposphere.

## The Jet Stream

The jet stream is *a strong current of air that generally sits atop the troposphere and flows from west to east*. Scientists often refer to it as a "river" of air because of its shape—up to thousands of miles long, a few hundred miles wide, and only a few miles deep. This stream can move along at more than 275 miles per hour.

The jet stream signals the boundary between hot and cold air in the atmosphere. The Northern and Southern Hemispheres sometimes have two jet streams each, the *subtropical jet* around 30 degrees North and South and the *polar jet* at 50 degrees to 60 degrees N/S (Figure 1.2). These are the latitudes where the temperature changes are often greatest. In the United States, the subtropical jet flows along the country's southern border, while the polar jet flows overhead somewhat following its northern border. Depending on the season and conditions, though, the jet streams can change latitudes and altitudes, split into narrower streams, or even disappear for a time.

Pilots of big commercial and military aircraft that fly at high altitudes keep track of the jet streams. If a plane is traveling from west to east, the jet stream provides a tailwind that can help the airplane make good time. But if the plane is traveling from east to west, the jet stream becomes a headwind that increases flying time and cuts fuel efficiency, so pilots try to avoid it when they can.

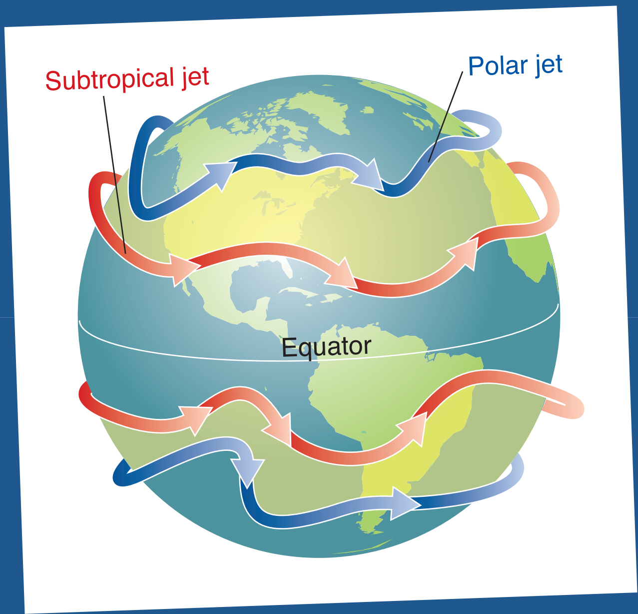



**Figure 1.2** The subtropical jet stream and the polar jet stream
*Reproduced from NOAA*

**Wing TIPS**

Ninety-nine percent of air is in the troposphere and stratosphere.

The *stratosphere* is the next layer of the atmosphere. It starts above the troposphere and extends to about 30 miles (50 km or 160,000 feet) high. This second layer is drier and less dense than the troposphere. The temperature actually begins to rise again in this region to about 26.6 degrees F (−3 degrees C) as you gain altitude because the stratosphere absorbs ultraviolet radiation from the sun. The ozone layer, which absorbs and scatters solar ultraviolet radiation, resides here. The stratosphere has a boundary layer called the *stratopause* that separates it from the next layer.

**Wing TIPS**

Why is the thermosphere so hot? Well, it's where solar radiation makes first contact with Earth. The thermosphere intercepts extreme ultraviolet (EUV) photons from the sun before they can reach the ground. When solar activity is high, solar EUV warms the thermosphere, causing it to puff up like a marshmallow held over a campfire. When solar activity is low, the opposite happens.

The *mesosphere* runs from above the stratosphere to about 53 miles (85 km or 280,000 feet) high. Temperatures dip once more, as low as −135.4 degrees F (−93 degrees C), with increases in altitude. The chemicals in this layer exist in an excited state because they absorb energy from the sun. The boundary layer at the top of the mesosphere is the *mesopause*.

The *thermosphere* starts above the mesosphere and extends to more than 350 miles (560 km). The temperature takes yet another swing, going as high as 3,140.6 degrees F (1,727 degrees C), due to the sun's energy. Chemical reactions occur much faster here than on Earth's surface. The thermosphere's boundary layer is the *thermopause* (Figure 1.3).

Beyond the thermosphere is the *exosphere*, which stretches to the edges of space at around 6,200 miles (10,000 km).

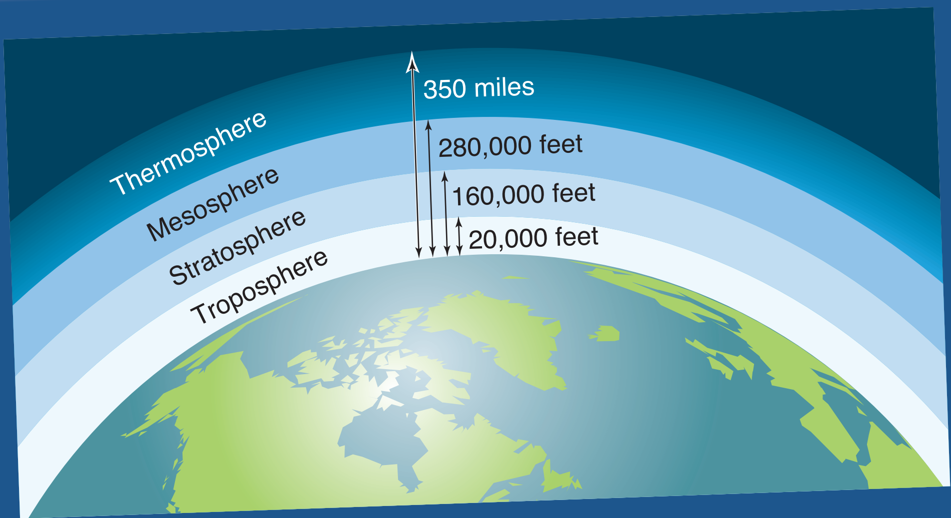



**Figure 1.3** The layers of the atmosphere. This drawing does not show the exosphere, which is above the troposphere.
*Reproduced from US Department of Transportation/Federal Aviation Administration*

## The Roles of Water and Particulate Matter in the Atmosphere

As you read earlier, the atmosphere contains water in the form of water vapor. Temperature determines how much moisture the atmosphere holds. A rise in temperature increases the amount of moisture the air can hold, just as a drop in temperature decreases that amount.

Water in the atmosphere takes three forms: liquid, solid, and gas. Each form can change into another form. When they do change, a heat exchange occurs. These changes come about through the processes of:

- Evaporation—*The transformation of a liquid to a gaseous state, such as the change of water to water vapor*
- Sublimation—*The process by which a solid changes to a gas without going through the liquid state*
- Condensation—*A change of state of water from a gas—water vapor—to a liquid*
- Deposition—*The process by which a gas changes to a solid without going through the liquid state*
- Melting
- Freezing.

However, water vapor enters the atmosphere only through evaporation and sublimation.

### Evaporation and Sublimation

Oceans hold 97 percent of the world's water, and they are the source of 86 percent of the evaporation taking place around the planet. Besides moisture, however, evaporation requires heat. This heat destroys the bonds between water molecules and allows them to evaporate. When water evaporates from the oceans, the air loses heat when the liquid water changes into vapor. This is known as the *latent heat* of evaporation. It cools ocean surfaces (just as sweat cools your skin).

The warm water vapor enters the atmosphere and generally condenses onto tiny particles of dirt, dust, or pollution in the atmosphere because of the colder temperatures aloft. The condensing water then forms clouds. The water in these clouds can fall as rain, snow, or in some other form over the oceans or land. Moisture falling over the land seeps into the soil or groundwater through *infiltration*. Evaporation takes place at other sources, too: lakes, rivers, trees, and even soil (in the case of plants and soil, the process is called *transpiration*—Figure 1.4).

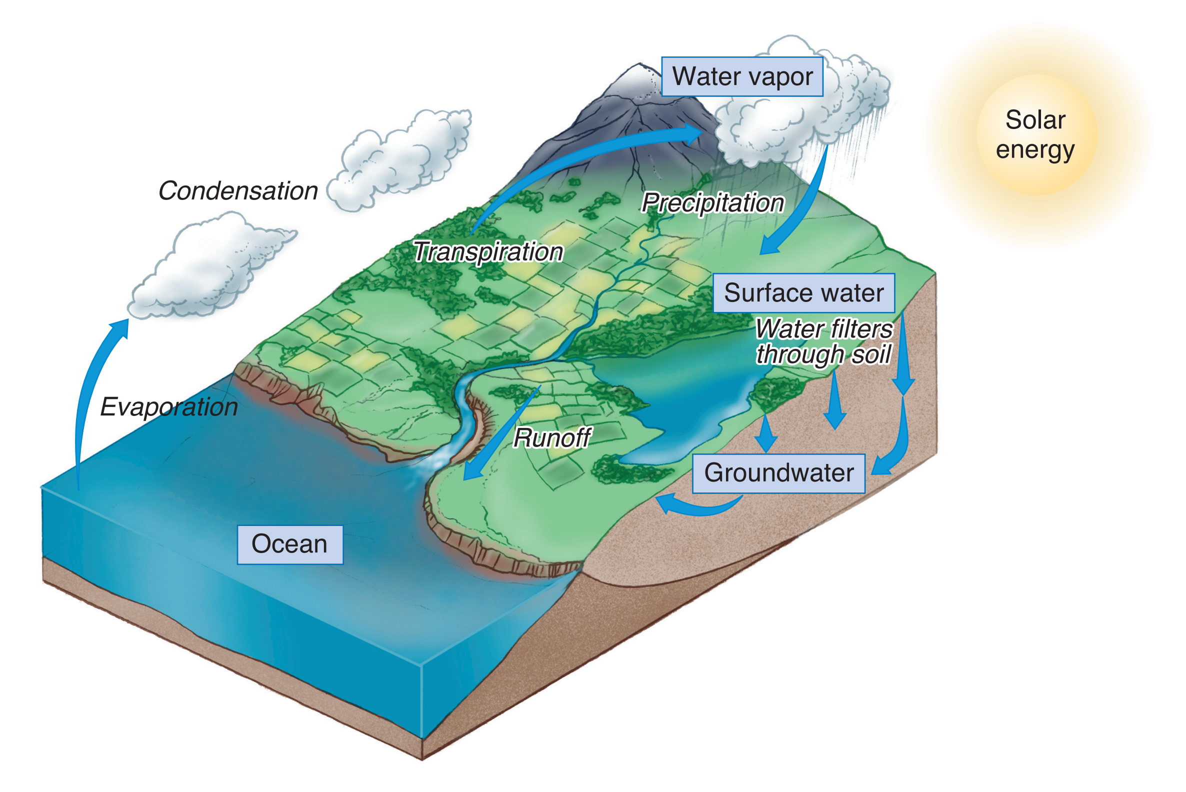



**Figure 1.4** The water cycle

Sublimation contributes far less water vapor overall to the atmosphere than the evaporation process does. It generally takes place in colder climates than evaporation, as well. For instance, the temperatures will often be too cold on a mountaintop to melt snow and ice to liquid water, but intense sunlight sometimes coupled with strong winds can transform that snow and ice into water vapor. In the American West, scientists have a name for a wind so strong and so dry in the region that it turns water solids straight into gas with no melting in between: Chinook, after an Indian tribe that lives along the Pacific Northwest coast.

## Humidity

Humidity is *the amount of water in the atmosphere at a given time*. Relative humidity is *the actual amount of moisture in the air compared with the total amount of moisture the air could hold at that temperature*. For example, if the current relative humidity is 65 percent, the air is holding 65 percent of the total amount of moisture that it is capable of holding at that temperature and pressure. While much of the western United States rarely sees days of high humidity, relative humidity readings of 75 percent to 90 percent are common in the southeastern United States during the warmer months.

## Dew Point

The relationship of dew point and temperature further explains relative humidity. Dew point is *the temperature at which air can hold no more moisture*. When temperatures fall to the dew point, the air becomes saturated—or *as full of moisture as something can get*—and the water in the atmosphere condenses as fog, dew, frost, clouds, rain, hail, or snow. However, rain is the most common form of precipitation—*any or all forms of water particles that fall from the atmosphere and reach Earth's surface*.

Air can reach its complete saturation point by four methods. First, when warm air moves over a cold surface, the air temperature drops and reaches the saturation point. Second, when cold air mixes with warm air. Third, when air cools at night through contact with the cooler ground. And fourth, when air rises upward in the atmosphere, it uses heat energy to expand. As a result, the rising air loses heat rapidly, and so arrives at its saturation point.

## Particulate Matter

Water vapor goes through a complex process before it can fall as rain. Water vapor and cloud droplets make up a cloud. Both are very, very small. However, when you look at a cloud, what you see is not the invisible water vapor but the cloud droplets. Even so, these droplets aren't big enough or heavy enough to fall as rain. In fact, it takes millions of cloud droplets to form one raindrop.

A shelf cloud rolls over Oklahoma in 2008.
*Courtesy of Sean Waugh NOAA/NSSL*

To create a single raindrop, water vapor must first cling to particulate matter (*material suspended in the air in the form of minute solid particles, such as dust, salt, or smoke particles*) to condense into cloud droplets. The bits of particulate matter are smaller than the water vapors, yet they are necessary to the formation of raindrops because they act as the nucleus—*or core*—of the raindrop. The cloud droplets collide with other droplets and continue to grow until they are heavy enough to fall to Earth.

## The Primary Causes of Atmospheric Motion

In addition to affecting moisture levels, heat also causes air to circulate around Earth's surface. Scientists refer to this as *atmospheric circulation*. While other factors play a role in moving the air about, a main factor is energy radiation from the sun.

When the sun heats the atmosphere, air molecules spread apart and the warm air rises. As the air expands, it becomes less dense and lighter than the surrounding air. Cooler air, with tightly packed air molecules, sinks and replaces the warmed air. This process of rising warm air and heavy, sinking cool air results in the atmosphere's circular motion.

Furthermore, because Earth rotates on a tilted axis while orbiting the sun, some regions of the planet receive more heat at any given time than others. This also affects atmospheric circulation. For instance, because more heat from the sun reaches the equator, the air there is less dense and rises. This warm air flows toward the poles where it cools and sinks.

### Atmospheric Pressure

The unequal heating of Earth's surface also affects air pressure. The invisible gas particles that make up the atmosphere create atmospheric pressure. These gas particles—or air molecules—have weight and take up space. Therefore, atmospheric pressure is *the weight of air molecules*. Altitude—along with temperature and air density—determines how much pressure these particles apply.

Pressure is greatest at sea level where the gas particles are close together. The weight of the air above compresses the molecules below and so increases the pressure. As altitudes increase, the molecules begin to spread apart so that there's more space between them, causing the pressure to drop.

The actual pressure at a given place and time changes depending on altitude, temperature, and air density. These conditions are important for flight, particularly during takeoff, climb, and landing. Scientists measure atmospheric pressure with instruments called *barometers*. When the pressure is high, the weather should be good. But when the barometer shows a drop in pressure, weather conditions will deteriorate. You'll read more about air pressure's effect on weather in the next lesson.

## Coriolis Force

In 1835 a French scientist named Gustave-Gaspard Coriolis came up with a theory to further explain atmospheric circulation. His discovery—called the *Coriolis force*—describes how Earth's rotation affects the motion of air.

**Wing TIPS**

Actually, the Coriolis force affects everything, even humans walking on Earth's surface, but the effects of the force are only noticeable over long distances and on objects of great size, such as air masses and oceans.

Low-pressure areas lie at Earth's warm equator regions. High-pressure areas sit over the cold polar regions. If Earth were stationary, these high-pressure areas would flow along Earth's surface straight toward the equator. But Earth isn't still. Its rotation about its axis creates the Coriolis force, which affects large bodies such as air masses.

This force deflects air to the right in the Northern Hemisphere. The air takes a curved path rather than flowing in a straight line. In the Southern Hemisphere, the Coriolis force pushes the air left. The air once again curves rather than flowing in a straight line.

The size of the curve depends on latitude (*a line north or south from Earth's equator and parallel to it*) and the moving body's speed. The deflection is greatest at the poles and decreases to zero by the time you reach the equator. And the greater the air's speed, the more the curve increases.

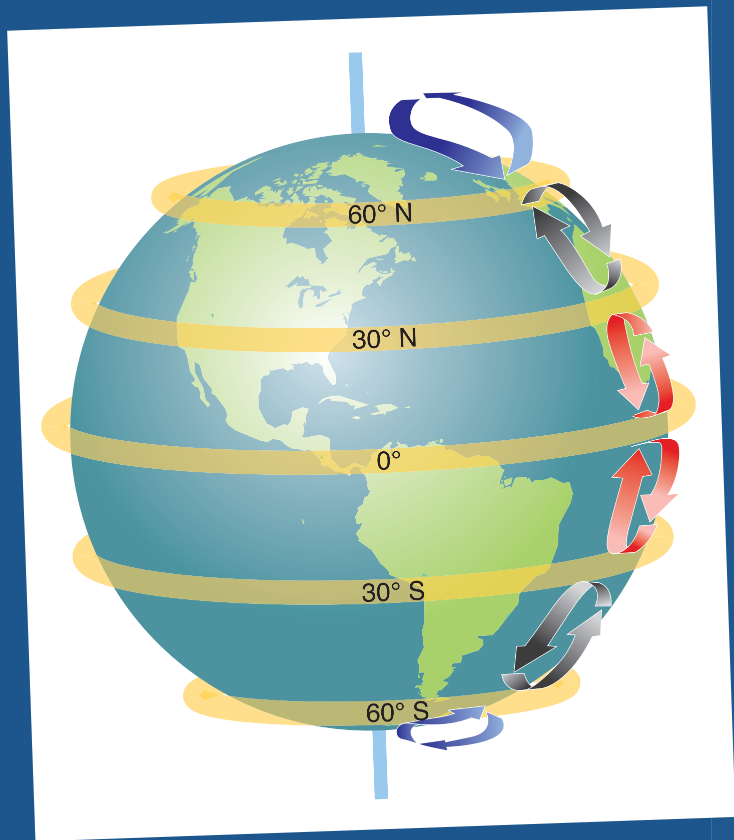



**Figure 1.5** Circulation cells in the Northern and Southern Hemispheres due to Earth's rotation
*Reproduced from US Department of Transportation/Federal Aviation Administration*

The speed of Earth's rotation breaks up the flow of air into three cells at different latitudes in each hemisphere (Figure 1.5). In the Northern Hemisphere, these cells are from the equator to 30 degrees N, from 30 degrees N to 60 degrees N, and from 60 degrees N to the North Pole. From the equator to 30 degrees N, warm air rises from the equator, moves north, and curves east due to Earth's rotation. The air cools as it moves, sinks at around 30 degrees N to form a high-pressure area, flows south along Earth's surface, and bends right due to the Coriolis force. This creates northeasterly trade winds from the equator to 30 degrees N. The other latitudes also experience circulation cells. The continental United States, for instance, sees westerly winds.

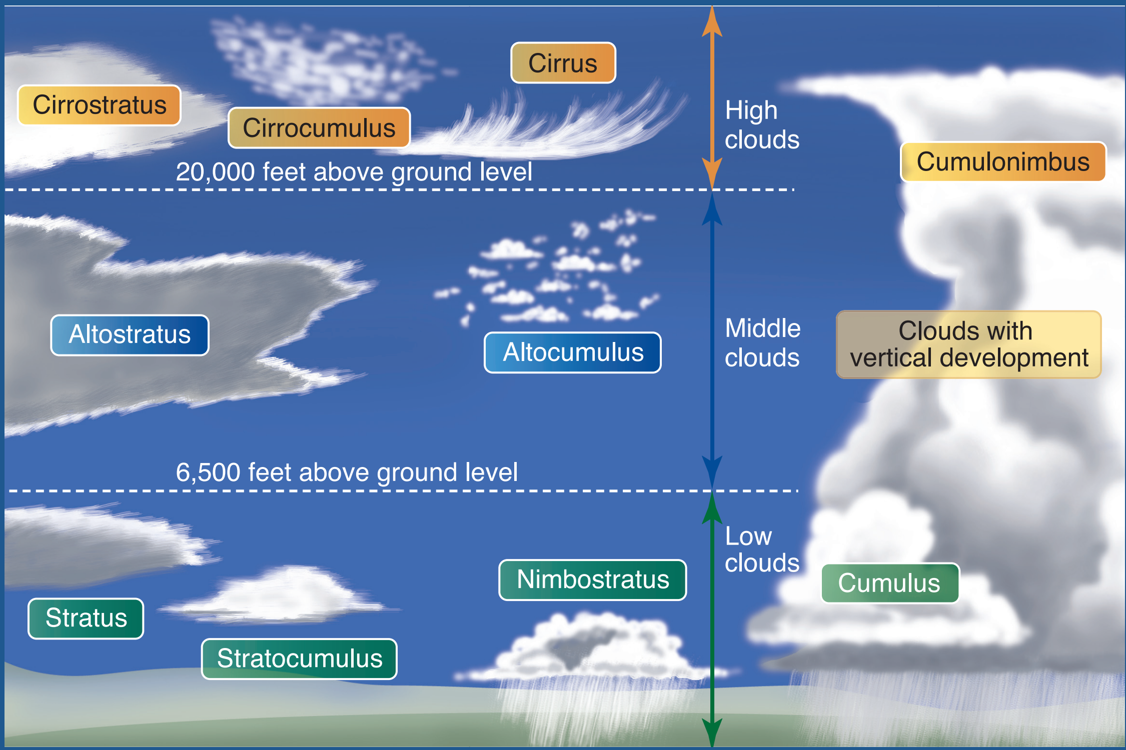



**Figure 1.6** Types of clouds
*Reproduced from US Department of Transportation/Federal Aviation Administration*

## The Types of Clouds

Like the motion of the atmosphere, clouds are an important weather factor. They can tell you about current weather conditions as well as what to expect in the future.

You read earlier about particulate matter. Clouds form from water vapor clinging to particulate matter. When the air cools to its saturation point, the water vapor condenses on the particulate matter to form visible cloud droplets. While the development process is about the same for each, clouds come in many heights, shapes, and behaviors. Classifications depend on the height of a cloud's base—low, middle, or high—as well as its vertical development (Figure 1.6).

*Low clouds* form near Earth's surface up to about 6,500 feet. Water droplets are their main ingredient. Sometimes they include *supercooled water droplets* (water droplets that have cooled to below freezing but are still in a liquid state), which can produce hazardous aircraft icing. Typical low clouds are *stratus*, *stratocumulus*, and *nimbostratus*. Fog is also a type of low cloud. All have a low ceiling (*the height above Earth's surface of the lowest layer of clouds*) and can change quickly. They can also make visibility difficult, so pilots must rely on instruments to fly through them.

*Middle clouds* start around 6,500 feet and reach up to about 20,000 feet. They are made up of water, ice crystals, and supercooled water droplets. Typical middle clouds are *altostratus* and *altocumulus*. You might spot these if you sit in a window seat when flying at a higher altitude while traveling cross-country. Altostratus clouds pose a moderate icing hazard and can create turbulence. Altocumulus clouds, which can form when altostratus clouds break up, may offer light turbulence and icing.

*High clouds* start above 20,000 feet. They usually form only in stable air, that is, air where the ride is smooth and little weather is present. High clouds contain ice crystals, yet pose no real risk of turbulence or icing. Typical high clouds are *cirrus*, *cirrostratus*, and *cirrocumulus*.

Clouds with lots of vertical development are *cumulus* clouds. This type of cloud has a flat base that forms in the low or middle cloud regions. Its plump, billowing vertical development stretches up into the high cloud zone. Cumulus clouds, particularly cumulonimbus clouds—*thunderstorms*—can mean turbulent weather ahead. Cumulonimbus clouds contain large amounts of moisture and unstable air, which can produce hazardous weather such as lightning, hail, tornadoes, gusty winds, and wind shear (*a sudden, drastic shift in wind speed, direction, or both that may take place in the horizontal or vertical plane*). These can be the most dangerous type of cloud to encounter in flight.

Cumulus clouds as seen from a NOAA Research Aircraft DC-6 40C
*Courtesy of NOAA/AOML/Hurricane Research Division*

## Fog

Fog is a cloud that begins within 50 feet of Earth's surface. It typically forms in a stable air mass when the air's temperature near the ground has cooled to the air's dew point. At this point, water vapor in the air condenses and appears as fog.

Fog comes in several varieties, depending on how it forms. These include:

- ***Radiation fog***—This type of fog develops on clear nights when little or no wind is present. It forms in low-lying areas such as mountain valleys. This type of fog occurs when the ground cools rapidly and the surrounding air temperature reaches its dew point. As the sun rises and temperature increases, radiation fog lifts and eventually burns off. Wind quickens the dissipation process.
- ***Advection fog***—This fog occurs when a layer of warm, moist air moves over a cold surface. It requires wind up to 15 knots to form. Above 15 knots, the fog lifts and forms low stratus clouds. Advection fog is common along the coast where sea breezes blow air over cooler landmasses.
- ***Upslope fog***—This variety of fog forms when moist, stable air moves up sloping land features such as mountain ranges. Like advection fog, it needs wind to form and survive. Upslope and advection fog can last for days (unlike radiation fog, which burns off with the morning sun). It also reaches greater heights than radiation fog.
- ***Steam fog***—Also called *sea smoke*, this fog develops when cold, dry air moves over warm water. As water evaporates from the water surface, it rises and looks like smoke. This type of fog is common over water during the coldest times of year. Steam fog produces low-level turbulence and icing.
- ***Ice fog***—This is also a cold weather fog. It occurs when the temperature is a good deal below freezing (usually −25 degrees F or more). The water vapor forms directly into ice crystals. Otherwise, it requires the same conditions as radiation fog. It generally forms in the arctic regions, although sometimes the middle regions get ice fog.

Radiation fog
*© iStockphoto/Thinkstock*

Advection fog rolls over the Golden Gate Bridge in San Francisco. This type of fog occurs when a layer of warm, moist air moves over a cold surface.
*Courtesy of NOAA/National Weather Service*

Some very faint sea smoke, or steam fog, over the Bering Sea west of Alaska, as taken from onboard the NOAA ship *Surveyor.*
*Courtesy of NOAA*

## Cloud Classifications

Clouds come in many shapes, sizes, and functions. If a pilot knows how to read them, they can help him or her fly more safely. The cloud types are:

- ***Cumulus***—Heaped or piled clouds
- ***Stratus***—Formed in layers
- ***Cirrus***—Ringlets, fibrous clouds, also high-level clouds above 20,000 feet
- ***Castellanus***—Common base with separate vertical development, castlelike
- ***Lenticularus***—Lens-shaped, formed over mountains in strong winds
- ***Nimbus***—Rain-bearing clouds
- ***Fracto***—Ragged or broken
- ***Alto***—Meaning high, also middle-level clouds existing at 5,000 feet to 20,000 feet.

### Wing TIPS

Some aircraft fly in the stratosphere for the advantages it offers, such as safety from the effects of stormy weather and increased fuel efficiency.

## How the Atmospheric Layers Impact Flight

The different layers of the atmosphere present their own set of challenges in flight. The troposphere, however, is where most flight takes place. Three atmospheric factors to take into account are air density, pressure, and temperature. These characteristics change in part due to changes in altitude.

### Density

Altitude, in fact, affects every aspect of flight from aircraft performance to human health. At lower altitudes, the density of the air increases, and at higher altitudes, air density decreases. As air becomes less dense:

- Engines and propellers are less efficient because they take in less air (although jet engines operate better with cold intake air)
- Engines and propellers generate less thrust
- Lift decreases because the thin air exerts less force on the airfoils
- Drag also decreases
- Takeoff and landing distances increase because it takes longer to create enough airflow over the airfoils for lift.

## Pressure

As you climb through the troposphere, the increasing altitude also affects atmospheric pressure. As you read earlier in this lesson, air pressure is greatest at sea level and decreases as you move higher. Because atmospheric pressure changes with time and location, scientists developed another means to measure pressure. They came up with *standard conditions*, a reference for the standard atmosphere at sea level, where the surface pressure is measured as 29.92 inches of mercury (″Hg), or 1,013.2 millibars (mb). A millibar is one-thousandth of a bar, a measure of pressure developed by a British meteorologist in 1909 (Figure 1.7).

Under what are called *standard conditions* at sea level, the weight of the atmosphere exerts an average pressure of 14.7 pounds per square inch (psi) of surface, or 1,013.2 millibars (mb). The higher the altitude, the less air you have above; therefore, the atmosphere's weight at 18,000 feet is half what it is at sea level (Figure 1.8).

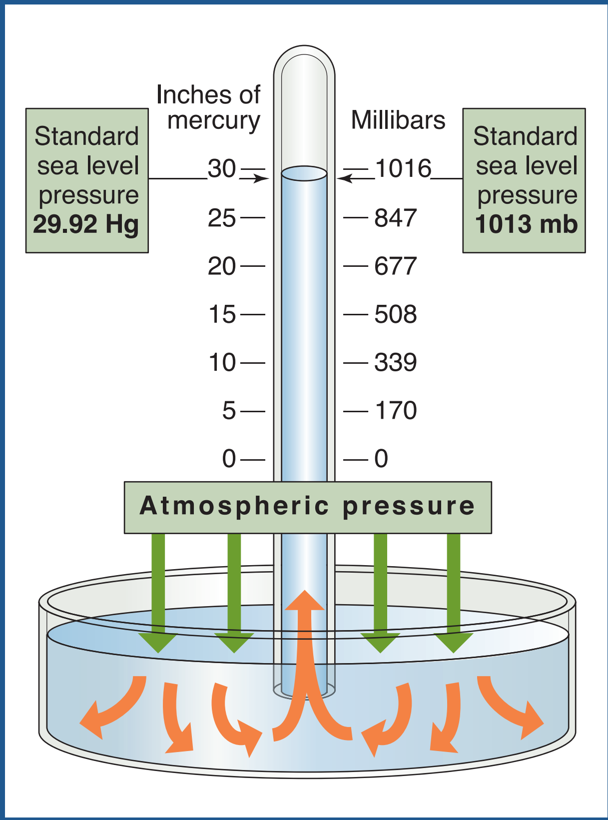



**Figure 1.7** Standard sea level pressure: inches of mercury versus millibars
*Reproduced from US Department of Transportation/Federal Aviation Administration*

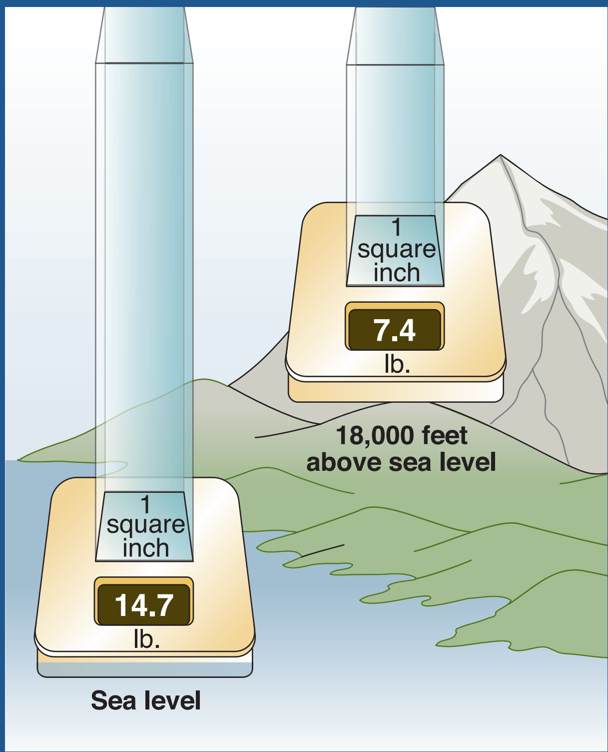



**Figure 1.8** Weight of atmosphere at different altitudes
*Reproduced from US Department of Transportation/Federal Aviation Administration*

At sea level, the atmospheric pressure is just right for people to lead healthy lives. But by 18,000 feet—where aircraft are better able to conserve fuel and avoid bad weather and a lot of turbulence—the atmospheric pressure drops to a level that can be fatal. This is because air molecules spread out more and more with greater altitudes. People can't get enough oxygen to survive. (You'll read more about flight and health in Chapter 3.)

To counter these ill effects, aircraft have pressurized cabins. The sealed fuselage holds air under a pressure that's higher than the atmospheric pressure outside the airplane. Government regulations require a cabin altitude—*cabin pressure equal to what it would be at the same altitude above sea level*—of 8,000 feet (Figure 1.9). It keeps the passengers and crew comfortable and safe. The system also releases air from the fuselage through an outflow valve and admits a fresh supply through an inflow valve.

The altitude at which the standard air pressure is equal to 10.9 psi can be found at 8,000 feet.

At an altitude of 28,000 feet, standard atmospheric pressure is 4.8 psi. By adding this pressure to the cabin pressure differential of 6.1 psi difference (psid), a total air pressure of 10.9 psi is obtained.

| Atmospheric Pressure | |
|---|---|
| Altitude (ft) | Pressure (psi) |
| Sea level | 14.7 |
| 2,000 | 13.7 |
| 4,000 | 12.7 |
| 6,000 | 11.8 |
| 8,000 | 10.9 |
| 10,000 | 10.1 |
| 12,000 | 9.4 |
| 14,000 | 8.6 |
| 16,000 | 8.0 |
| 18,000 | 7.3 |
| 20,000 | 6.8 |
| 22,000 | 6.2 |
| 24,000 | 5.7 |
| 26,000 | 5.2 |
| 28,000 | 4.8 |
| 30,000 | 4.4 |

**Figure 1.9** Standard atmospheric pressure chart
*Reproduced from US Department of Transportation/Federal Aviation Administration*

## No April Fool's Joke: Lost Cabin Pressure

On 1 April 2011 Southwest Airlines passengers on a flight from Phoenix to Sacramento heard a loud noise and then felt strong winds sweep through the cabin. A hole about five-feet long had ripped open in the aluminum roof of the Boeing 737-300, leaving a view of the sky above. At 36,000 feet, cabin pressure fell to dangerous levels.

Oxygen masks immediately dropped from above the passenger seats. Some people passed out before they could get their masks on, however, and two people had minor injuries. To get the plane back to a safer altitude where passengers could breathe, the pilot quickly descended to 11,000 feet. The plane then made an emergency landing at Yuma Marine Corps Air Station. The Federal Aviation Administration ordered emergency inspections of about 80 737-300 airplanes operated in the United States.

## Temperature

Temperatures also drop dramatically in the troposphere with altitude (Figure 1.10). Earlier you read that they fall at a rate of about 3.5 degrees F (2 degrees C) for every 1,000 feet gained. This drop continues until somewhere around 36,000 feet, where the temperature sits at about −65 degrees F (−55 degrees C) up to 80,000 feet (by which point, you're in the stratosphere and temperatures begin to slowly rise).

Today's airplanes have systems that regulate temperature and heat cabins. Passengers and crew can travel in comfort. But back in World War II, bomber crews endured wretched conditions during missions. Air systems and pressurized cabins were not yet the norm.

"Breathing was possible only by wearing an oxygen mask—cold and clammy, smelling of rubber and sweat—above 10,000 feet in altitude," writes historian and author Stephen E. Ambrose in his book about World War II B-24 bomber crews, *The Wild Blue: The Men and Boys Who Flew the B-24s Over Germany*. "There was no heat, despite temperatures that at 20,000 feet and higher got as low as 40 or even 50 degrees [F] below zero.... The oxygen mask often froze to the wearer's face. If the men at the waist touched their machine guns with bare hands, the skin froze to the metal."

| Standard Atmosphere | | | |
|---|---|---|---|
| Altitude (ft) | Pressure (Hg) | Temperature °C | °F |
| 0 | 29.92 | 15.0 | 59.0 |
| 1,000 | 28.86 | 13.0 | 55.4 |
| 2,000 | 27.82 | 11.0 | 51.9 |
| 3,000 | 26.82 | 9.1 | 48.3 |
| 4,000 | 25.84 | 7.1 | 44.7 |
| 5,000 | 24.89 | 5.1 | 41.2 |
| 6,000 | 23.98 | 3.1 | 37.6 |
| 7,000 | 23.09 | 1.1 | 34.0 |
| 8,000 | 22.22 | –0.9 | 30.5 |
| 9,000 | 21.38 | –2.8 | 26.9 |
| 10,000 | 20.57 | –4.8 | 23.3 |
| 11,000 | 19.79 | –6.8 | 19.8 |
| 12,000 | 19.02 | –8.8 | 16.2 |
| 13,000 | 18.29 | –10.8 | 12.6 |
| 14,000 | 17.57 | –12.7 | 9.1 |
| 15,000 | 16.88 | –14.7 | 5.5 |
| 16,000 | 16.21 | –16.7 | 1.9 |
| 17,000 | 15.56 | –18.7 | –1.6 |
| 18,000 | 14.94 | –20.7 | –5.2 |
| 19,000 | 14.33 | –22.6 | –8.8 |
| 20,000 | 13.74 | –24.6 | –12.3 |

**Figure 1.10** Standard atmosphere properties
*Reproduced from US Department of Transportation/Federal Aviation Administration*

Ambrose also details how wind whipped through the cabin whenever the bombardiers opened the bomb bay doors to deliver their loads on targets below. Frigid air also got through windows that the waist gunners used to shoot at enemy planes. Further, the lack of pressurization meant that any food the crew ate could create excruciating "pockets of gas in a man's intestinal tract." This list of lack of comforts goes on.

By contrast, today's Airmen sit in cockpits and wear suits that protect them from the elements. For instance, the F-22, a mainstay of the US Air Force, can fly well into the stratosphere with the aircraft's ceiling at 50,000 feet. Its maximum speed is Mach 2. These two characteristics expose pilots to many dangers, such as below-freezing temperatures and pressure changes. But the F-22's life-support systems overcome these challenges.


An F-22A Raptor flies over Fort Monroe, Virginia.
*Courtesy of USAF/TSgt Ben Bloker*

The fighter's cockpit comes equipped with an onboard oxygen generation system (OBOGS) so pilots can breathe normally. If a pilot has to eject into water during a mission, he or she will be wearing a suit capable of maintaining body heat even when submerged in water that's only 32 degrees F (0 degrees C) for up to two hours. Ejecting from an aircraft like the F-22 can mean exposing a pilot to winds of 600 knots. So the fighter's escape system shields the pilots from the heat and ripping effects these winds could inflict. The F-22's life-support systems also address hazards such as high altitudes, high speeds and acceleration, and chemical and biological situations, among others.

This lesson has discussed the atmosphere's makeup. In the process, you've also gotten an idea of the hazards a pilot faces from the atmosphere at great altitudes. The more you understand the atmosphere and how to read its signs, the more safely you will be able to fly. In fact, the next lesson will delve further into the atmosphere's components and how they affect weather.

## CHECK POINTS

### Lesson 1 Review

Using complete sentences, answer the following questions on a sheet of paper.

1. Which is the lowest layer of the atmosphere?
2. How far does the stratosphere extend from Earth's surface?
3. Water vapors enter the atmosphere through only two processes. What are they?
4. How many cloud droplets does it take to form one raindrop?
5. What is the process that results in the atmosphere's circular motion?
6. In which direction does the Coriolis force deflect air in the Northern Hemisphere?
7. What can clouds tell you?
8. What do cumulonimbus clouds contain?
9. What are two things that happen when air becomes less dense?
10. What can't people get enough of to survive at higher altitudes?

## APPLYING YOUR LEARNING

11. What types of conditions and challenges would you expect when flying in the stratosphere?