

## Why is the air cooler at higher altitudes?

### Short answer

This vertical temperature trend is a consequence of 1) lower atmospheric pressure at higher altitude and 2) heating that takes place at the bottom of the troposphere rather than at the top. The rate of change of temperature with height, is called the **lapse rate** by meteorologists. In the **troposphere**, the lowest layer of the Earth's atmosphere, temperature decreases with altitude. This trend does not continue into the layer above.

### Explanation

#### 1. The Pressure Effect

**Air at higher elevations is cooler because the pressure is lower.** Gases expand at lower pressures. As a gas expands, the molecules (and atoms) within it move more slowly. Since air temperature is just a measure of how fast the molecules in air are moving, the rate of motion of molecules and the temperature are both lower at higher elevations.

**Gases are compressible.** The air that makes up the atmosphere is a mix of gases – mostly nitrogen, oxygen, argon and carbon dioxide. Because of its transparency, air looks like nothing, but its weight reveals the mass within it. A stack of air above the ground weighs about 14.7 pounds per square inch (~1013 millibars) at sea level.

The molecules in air are spaced very far apart and its density is extremely low compared to liquid and solid materials. Because of the available space between molecules, and the ability of individual molecules to move independently, air has a much greater capacity to compress or expand than solids or liquids. [For more information, check this topic - **ideal gas law**.]

**Atmospheric pressure.** The Earth's gravity keeps most of the molecules of air piled close to the ground. Even though most diagrams of the atmosphere extend upward to 100 km above sea level, half of the Earth's mass of air occurs within just 6 km of the ground surface. The density of the atmosphere thins rapidly up to ~35 km and then continues to gradually grade from very low levels until it eventually matches the near emptiness of outer space.

In a still column of air, the weight or pressure at the bottom of the stack of air is greatest. The further up you go, pressure is less because there are fewer molecules above.

**Why is air at elevation cooler as the pressure becomes less?** The temperature of air is cooler at elevation in response to the vertical pressure changes that happen to occur because of the Earth's gravity.

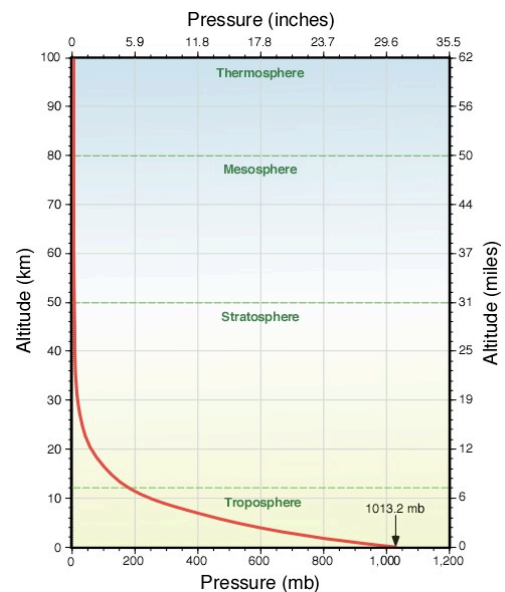


Figure 1.

Change in average atmospheric pressure with altitude.

Diagram from Fundamentals of Physical Geography.

<http://www.physicalgeography.net/fundamentals/7d.html>

Take two identical volumes (parcels) of air, taken from somewhere at a midlevel in the troposphere, **with each parcel containing an identical number of gas molecules and the same amount of heat energy to start.** Mentally place one parcel higher in the troposphere and one closer to the surface of the Earth, without allowing any molecules or heat energy to enter or leave each parcel of air. The parcel of air that you placed in the lower atmosphere is going to compress and warm because it finds itself in a place with higher pressure. The parcel of air that higher in the atmosphere is going to expand and cool because it finds itself under lower pressure. This kind of process, one which takes place without heat energy entering or leaving the parcel, is called an **adiabatic** process.

**Why does air warm at higher pressure?** Pressure has a large effect on gas. When a parcel of air is placed at higher pressure, the air outside of the parcel uses its energy to compress the parcel by pushing the gas molecules within it closer together. Is this energy gone and used up? No, the energy has just been transferred to the molecules in the air parcel and is now being used to move the molecules of air faster. Since temperature is just the measure of how fast the molecules of air move, the temperature of air is now higher.

**Why does air cool at lower pressure?** The lower pressure at elevation is not enough to maintain the original compression in your air parcel. Instead, your air parcel expands and uses its own energy to push the surrounding air aside. Where does your parcel get the energy to push surrounding air? It takes it away from the motion of the molecules of air, resulting in slower moving molecules. As air expands, temperature drops.

**But doesn't that contradict observations that warmed air expands and cooled air contracts?** No, because the situations aren't analogous. Remember, in this case you didn't allow any mass or heat energy to leave your parcel of air, even when air was placed at different heights in the atmosphere. In this next case, heat energy is added from outside the parcel.

## 2. The "Heating from Below" Effect

**The troposphere is warmest at sea level and cools upward because the Earth's atmosphere is heated from below.** The atmosphere is mostly heated by the surface of the earth below and not directly by the Sun from above, even though the upper atmosphere is closer to the Sun.

**The ground emits infrared radiation that heats the air.** Have you ever stood on an asphalt parking lot on a scorching summer day? You can feel the heat radiating from the asphalt. The asphalt is hotter than air. The thermal radiation from the asphalt heats the air near the ground as well as you. But the heat in the asphalt ultimately comes from the Sun. When the Sun goes down in the evening, both the ground and air lose energy and begin to cool.

Most of the sunlight that reaches Earth arrives in the form of visible light radiation. Visible light passes through the atmosphere without being absorbed very much. On the other hand, when visible light hits asphalt, its energy is absorbed. Eventually it is released (emitted) by the asphalt in a new form, as infrared radiation that you sense as heat. Air didn't absorb visible light, but now that the energy in sunlight has been converted to infrared radiation, it's a different story. Air absorbs infrared radiation and uses its energy to increase the speed of molecules within air.

When air absorbs heat from the ground, it expands a little. The atoms and molecules in air move faster, and the faster moving molecules push against surrounding air with greater force, causing air to expand. Using the energy supplied from outside the parcel of air, the parcel becomes less dense than air around it so that it rises. As it moves upward, the parcel is cut off from energy input from the ground. The parcel rises, expands and cools mostly adiabatically until it meets up with air that is of equal density and can rise no further.

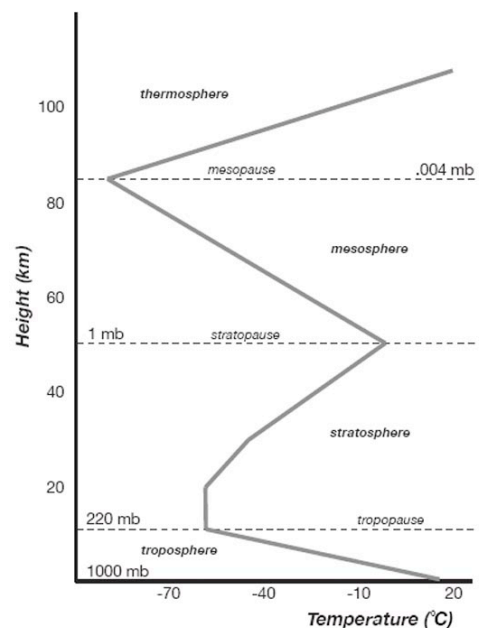


Figure 2.

Typical vertical temperatures in the Earth's atmosphere.

Diagram from Robert Fovell, UCLA. [http://www.atmos.ucla.edu/~fovell/AS3downloads/standard\\_atmo.pdf](http://www.atmos.ucla.edu/~fovell/AS3downloads/standard_atmo.pdf)

### Note:

The condensation of water vapor in the atmosphere adds an additional twist to the lapse rate.

## How would I explain to my class how and why it snows?

### Short answer

It snows when pieces of ice that form in the atmosphere fall to the ground. Ice forms when there is enough water in the air to form snowflakes and it becomes cold enough for ice to form. Solid snowflakes form directly from water vapor in gas form. It may not be cold enough for snowflakes to make the journey to the ground.

### Explanation

Water exists in three physical states (phases) – as gas (water vapor), liquid (water) or solid (ice) near the surface of the earth.

H<sub>2</sub>O in gas form is called “water vapor.” All air contains at least some water vapor in gas form. Water vapor is transparent and invisible in air.

When H<sub>2</sub>O in the gas phase gets cold enough, it transforms into either H<sub>2</sub>O in the liquid phase, or H<sub>2</sub>O in the solid phase. The terms condensation and deposition are both used to describe the process by which a gas transforms into a solid. Ice forms rather than the liquid when the temperature is low enough. [Clarify terms that refer to phases of water such as ice and water vapor, vs. processes of transformation from phase-to-phase such as melting, solidifying, condensing, sublimating, etc.]

Solid ice can crystallize directly from water vapor in the air. Snowflakes form this way. The term snowflake is used to describe individual six-sided flakes or a bunch of flakes that have become stuck together. If you have ever seen frost grow on the inside of a freezer, you have seen solid ice form directly from a gas.

Snow isn't the only kind of solid H<sub>2</sub>O that forms in the atmosphere. Larger pieces of ice such as hail and sleet can also form, but they solidify from liquids rather than gas. Hail and sleet form when raindrops freeze or melted ice refreezes.

Since it's colder at high altitude, you can often see clouds of ice in the sky. The thin, wispy clouds called cirrus clouds are made up of ice rather than liquid water droplets.

To find snow after a storm has passed, it's best to look after a particularly cold storm and to look on the tops of the highest mountains. That's where the greatest amount of snow falls and where snow is best preserved for at least for a day or two in San Diego County.

Snow is very important to our water supply in California because it keeps water in cold storage on the highest mountaintops, such as in the Sierra Nevada, over the hot summer months. Since it melts and flows into streams gradually, people can capture and use melting ice water in months with little or no rain. Winter and spring rains run off too quickly to be captured in the summer.

Why doesn't snow form all the time at high altitude? At high altitudes in the troposphere, air is always cold enough to form ice. But not all air has enough moisture within it to form rain or snow, and moist air doesn't always rise to places where it is cold enough for ice to form. Unless air rises, it does not cool. To be called snow, snowflakes need to fall all the way to the ground. In San Diego, it is rarely cold enough to keep snowflakes from melting before they hit the ground.

### Other resources:

#### Great photos and content about snowflakes.

SnowCrystals.com

Kenneth Libbrecht at CalTech

<http://www.its.caltech.edu/~atomic/snowcrystals/>

#### Phase diagram of water at:

Same website as above.

<http://www.its.caltech.edu/~atomic/snowcrystals/ice/ice.htm>

## Can you please describe rain/precipitation and all of its functions in terms that a fourth grader would understand?

### Short answer

What is rain or precipitation? It's water (H<sub>2</sub>O) that falls from the sky as drops of water or pieces of ice. When the National Weather Service uses the terms **rain** and **precipitation**, they mean very specific things. Rain or drizzle refers to drops of liquid water, depending on the size of the drops. The term precipitation includes all the forms of water that fall to the ground – rain, drizzle, snow, sleet, hail, etc.

### Explanation

Even though it's invisible, there's usually at least a little bit of water (H<sub>2</sub>O) in the air everywhere. Water that exists as a gas is called **water vapor**. Water vapor exists in the air along with other gases such as nitrogen, oxygen, argon, and carbon dioxide.

The water vapor in air transforms into liquid water at specific temperatures depending on atmospheric pressure. The process of transformation, from a gas into the liquid, is called **condensation**.

Raindrops condense around microscopic pieces of solid dust in the atmosphere. On a microscopic scale, molecules of water sticks to the surfaces of dust and small water droplets all the time. At the same time, water evaporates off of these surfaces too. Raindrops do not grow when water molecules leave the surfaces of liquid water droplets as fast as they land.

The molecules of water in microscopic water droplets are actually moving very rapidly. The warmer the liquid in the droplet, the faster the molecules move. Temperature is just a measure of the average speed of the molecules. When they are moving fast enough, some of the water molecules have enough energy to leave the surface of the water droplet and join the other gas molecules.

As temperature drops, the water molecules in the water droplet move more slowly. At low temperatures, fewer water molecules are moving fast enough to escape the surface of the water droplet. Water molecules still land, but fewer escape and the raindrop grows by adding water molecules to its surface.

Once a raindrop grows so large that it is too heavy to stay suspended in the air, it falls. If a raindrop is large enough to fall to the ground without vaporizing on the way down, it is called rain.

### What is the function of precipitation?

Precipitation does not have a function in the same way that the parts and behaviors of living things change and adapt in order to survive. Rainfall patterns can be different from place-to-place and from time-to-time, but it does so in a very fixed way in response to existing physical conditions. Patterns of precipitation can change in ways that are not ideal for the survival of living things.

### Then, what does rain happen to do on Earth?

- Precipitation supports all life on Earth. Where there is more precipitation on land, vegetation tends to be more lush and animals are more abundant.
- Precipitation is part of the global water cycle that recycles the same water around the planet, over and over again. The water cycle makes seawater fresh enough to drink and lifts water up and over land, making accessible to living things on land.
- Precipitation shapes the land by weathering and eroding its surface. As raindrops merge into growing streams of water, the water dissolves bits of earth and the force of running water carves out the land. Streams carry dissolved and solid particles of sediment to the sea.
- For people, precipitation provides water for drinking, bathing, cleaning, irrigation of food and ornamental plants, and production of electricity.
- When raindrops condense in the atmosphere, it releases energy that fuels the motion of weather phenomena such as storms and hurricanes.

## How much do clouds influence the current predictions of global warming?

### Short answer

A lot. So much that it causes significant uncertainty in the specifics of predictions of future climate although there is no doubt that the Earth is warming. While this offers the possibility that clouds counteract global warming to some degree, it raises awareness that the true extent of global warming due to greenhouse gases has been underestimated.

Your question “**how much**” is a difficult one. Scientists like Dr. Veerabhadran Ramanathan at Scripps Institution of Oceanography have spent a significant part of their careers investigating aspects of this question. For an overview, I recommend reading the following article by Drs. Ramanathan and Barnett at Scripps:

**Global Warming : Both Sides, 2003.**

<http://www-ramanathan.ucsd.edu/VRpdfFiles/WQspring2003.pdf>

### Notes on the key ways in which clouds affect climate

1. Clouds located low in the atmosphere tend to reflect sunlight and cause cooling at the surface of the Earth. For example, thick clouds obscure the Sun and make for a gray and chilly day.
2. The same clouds also trap heat energy radiated from the Earth's surface and warm the air near the surface. For example, it's usually warmer at night on a day with cloud cover rather than a clear sky.
3. When multiple processes like those in items 1 and 2 occur, the net effect is the sum of each of the changes. There seems to be a tendency for scientists to think that low level clouds will help to cool the surface overall.
4. Thin wispy cirrus clouds located high in the atmosphere act to warm the surface. They're too thin to reflect much sunlight, but they're effective at absorbing outgoing thermal energy radiated from the Earth's surface. Contrails from aircraft may have the same effect. The altitude and thickness of clouds determine the degree to which they reflect sunlight or trap radiation from the Earth's surface.
5. In a warmer world, the sea surface which is a primary source of water vapor in the air will be warmer. Warm water evaporates more than cool water. That should make the world more humid and supply clouds with more water. Warming could be offset by greater cloud cover that is more reflective. On the other hand, water that stays in vapor form acts as a greenhouse gas and increases warming. What will be the net effect?
6. Clouds not only depend on the availability of moisture in the air, but on surfaces around which water droplets grow. Combustion of the same carbon-based fuels that are the source of key greenhouse gases in the atmosphere also introduces small particles (aerosols) into the atmosphere. Aerosol particles reflect sunlight and can cause cooling. But aerosols can also increase cloudiness because they cause more water droplets to condense.

In some places, pollutant aerosols in the atmosphere are so concentrated that a “brown cloud” is visible on satellite photos. The shading caused by increased reflectivity of the atmosphere has been called “global dimming.”

### Other Resources

**NASA Facts: Clouds and the Energy Cycle**

[http://eosps0.gsfc.nasa.gov/ftp\\_docs/Clouds.pdf](http://eosps0.gsfc.nasa.gov/ftp_docs/Clouds.pdf)

**NOVA: Dimming the Sun**

<http://www.pbs.org/wgbh/nova/sun/dimming.html>