Lecture 13: Air-Sea Interactions Part 1

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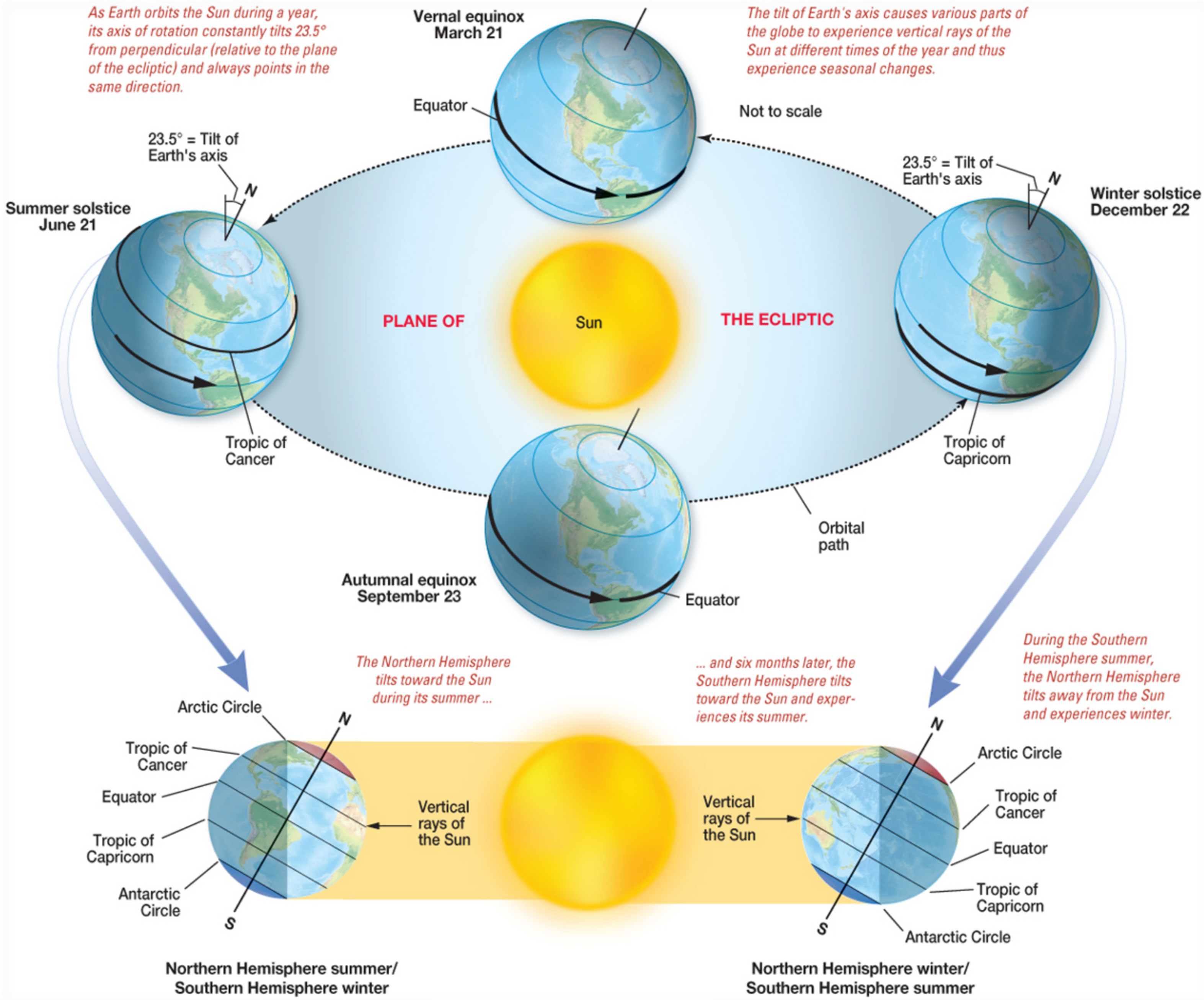
In this and the following lecture, we are going to discuss the interconnectedness of the ocean and the atmosphere. The two are are intimately connected through exchanges of water, gases, and energy. The connections between the ocean and atmosphere controls the temperature of the sea surface, moderates the weather and climate on Earth, and creates waves and currents. As an example, we have known for over a century, that El Niño (which is an ocean event) leads to catastrophic weather events around the world. And we already learned about how important the properties of water are in terms of heat capacity. Well, warm water at the surface of the ocean provides energy that fuels hurricanes (which are atmospheric phenomena).

Let's remind ourselves again about how the greenhouse effect works (we have discussed it in previous lectures). Solar radiation enters the atmosphere, and some of the energy is reflected back out as light, but other energy (infrared radiation) is released by surfaces on the Earth that are heated by solar radiation. That infrared energy is trapped in the atmosphere by greenhouse gases. These gases include water vapor, CO_2 (carbon dioxide), methane, and N_2O (nitrous oxide).

Why are different parts of Earth different temperatures? This largely has to do with variations in solar radiation around the globe. Consider the difference in temperature from day to night. During the day, the side of the Earth facing the sun gets exposed to solar radiation, while the side facing away from the sun get zero solar radiation. Exceptions to daily heating and cooling are found north of the arctic circle, and south of the Antarctic circle where during the summer and winter, these two regions experience complete daylight or complete darkness – [illegible] daily cycle. We will explore why in a minute. Over the course of a year, the temperature changes with seasons. The seasons change because the Earth rotates around the sun on a tilted axis. The angle of tilt is 23.5° away from being perpendicular to the plane of the elipse that the Earth follows as it travels around the sun. Many people think the seasons occur because of the Earth's path around the sun – they think that as the distance between the Earth and sun change, the seasons change. This isn't true – it is all about the tilt. Let's unpack that now.

Every day the Earth rotates around its north-south axis. Every year the Earth orbits around the sun following a slightly elliptical (just off being circular) path. Think of the Earth spinning and travelling that orbit around the sun. The tilt of the Earth remains the same as it travels that path around the sun. That means that different parts of the Earth are tilted towards the sun at different times of the year. See the figure below for a diagram showing this. At the vernal equinox (March 21st, also known as the spring equinox in the northern hemisphere), the sun is directly over the equator and all locations on Earth experience the same day length. At the summer solstice (around June 21st) the sun is at its furthest north point above the Tropic of Cancer. At the summer solstice, the Earth's tilt faces the northern hemisphere towards the sun, making it warmer and longer day length in the north. At the autumnal equinox (September 23rd) the sun is again directly over the equator, and everywhere on the Earth again has the same day length. At the winter solstice (December 22nd), the sun is overhead of the Tropic of Capricorn in the southern hemisphere. The southern hemisphere at this time is tilted towards the sun and the southern hemisphere is warmest with longer days than the north.



Watch
[this video (https://www.youtube.com/watch?v=e9MU4TouzlI)](https://www.youtube.com/watch?v=e9MU4TouzlI)

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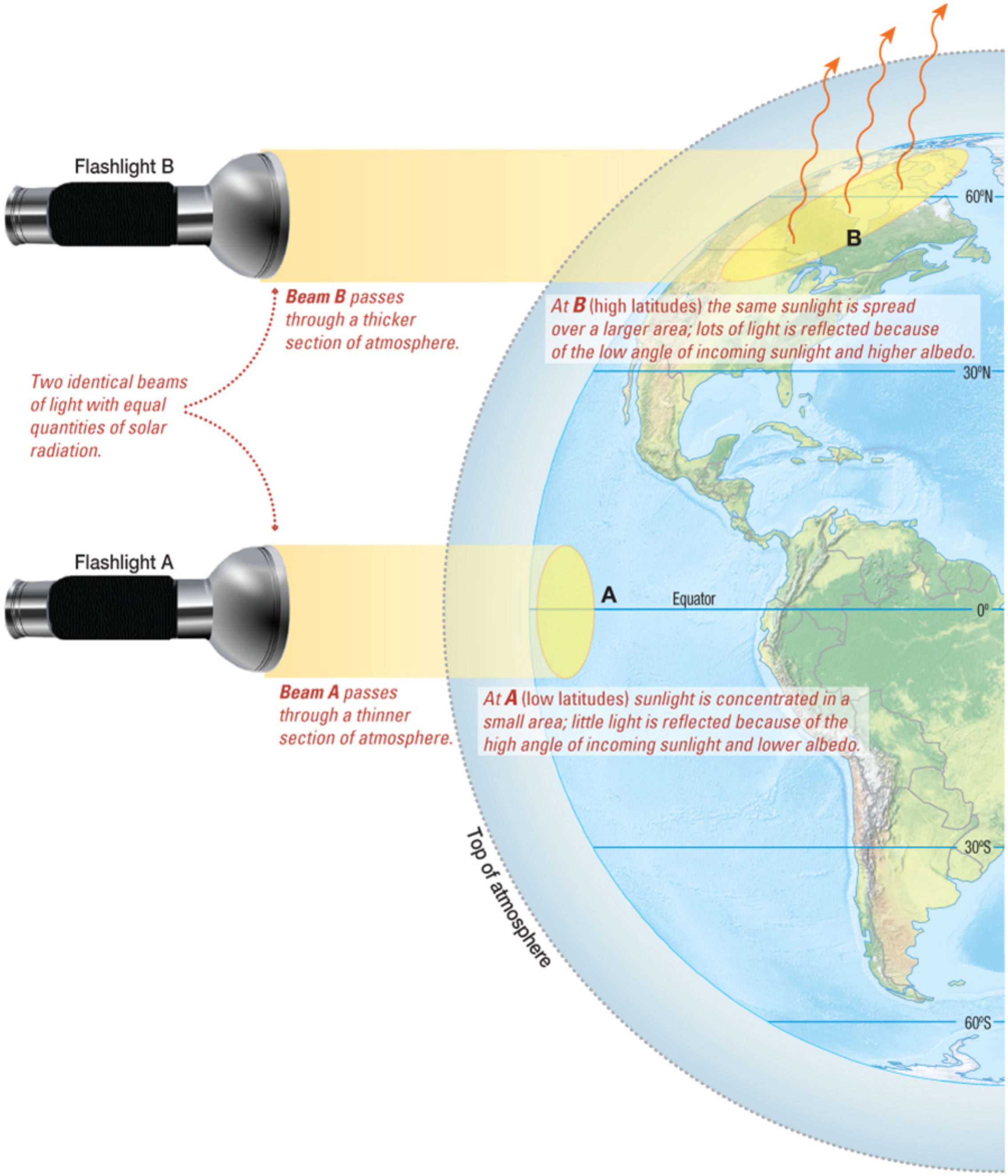
to see a demonstration of how the tilt of the Earth makes it warmer in summer here in NJ, and colder in winter (ignore the details of day length – the UK is a lot further north than we are in NJ).

As the seasons change, the location on the Earth of where the sun's rays hit the Earth directly (perpendicularly) ranges between the Tropics of Cancer and Capricorn from solstice to solstice. This is illustrated above. Because of this, the region between the Tropics (located at 23.5° N or S respectively) are called the tropics, and get much greater solar radiation throughout the year. These seasonal changes in solar radiation have big implications to the Earth's climate. On the summer solstice, the northern hemisphere experiences its longest day of the year (and the southern hemisphere has the shortest). On the autumnal solstice, the reverse is true – the northern hemisphere has its shortest day of the year.

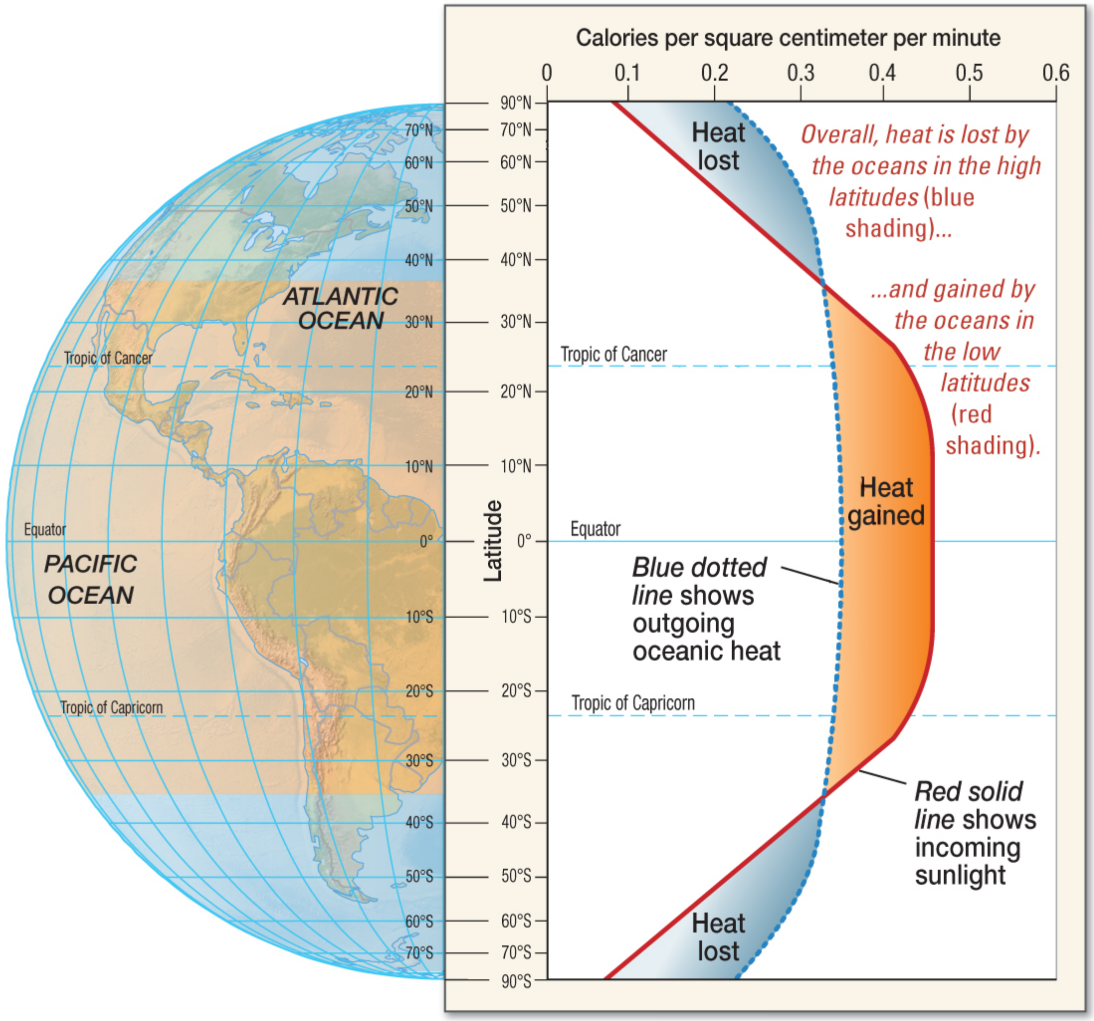
If Earth a flat pancake and the big flat part faced the sun, all parts of the side facing the sun would get the same solar radiation. But we all know that the Earth is a sphere, so that means that the solar radiation varies across the surface. Higher latitudes experience less radiation than lower latitudes. This variation in solar radiation is caused by a number of things:

- Solar footprint, or the area over which the sun's rays are concentrate, varies by latitude. Solar footpring is determined by the angle of incidence, or the angle that the sun rays hit the Earth. Think of a flashlight shining on a ball (see below). When the angle of incidence is high (when the sun is directly overhead) the area that the rays spread over is smaller, and the solar radiation is more concentrated.
- The atmosphere also absorbs some radiation. In higher latitudes the angle of incidence means that on an angle there is more of the atmosphere for the solar radiation to pass through (see the image below) which allows more solar radiation to be intercepted by the atmosphere at high latitudes.
- Albedo, which is the percentage of solar radiation that is reflected back to space, also varies the the heating of the Earth's surface. Materials like snow and ice have a very high albedo, meaning that those high latitude regions of the Earth tend to reflect more solar radiation than most places with lower albedo. Think about two cars sitting in the hot sun, one is black, the other is white. Which one gets hotter in the sun? The white one has a higher albedo. Albedo is the reason that painting roofs white helps keep cities cooler. Fun fact – the average albedo of the Earth's surface is 30%.
- Finally, the angle of incidence on the ocean surface determines how much solar radiation is reflected off the ocean. When the sun shines directly down onto a calm ocean surface, only 2% is reflected. However, when there is a steeper angle – say when the sun is low in the sky at 5 degrees above the horizon, then 40% of the sun's rays are reflected. This process of reflection off the ocean also means that more solar radiation is reflected at high latitudes.

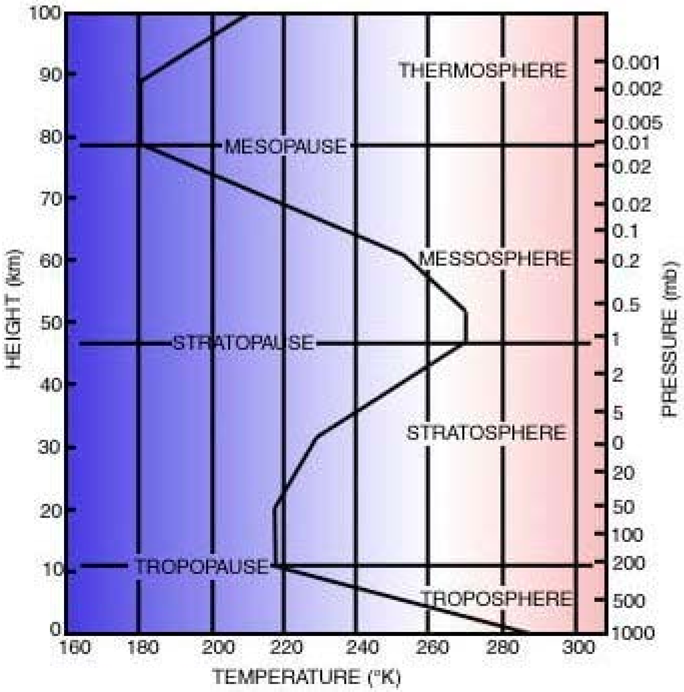


All of these things help to decrease the intensity of solar radiation at high latitudes, compared to those in low latitude nearer the equator.

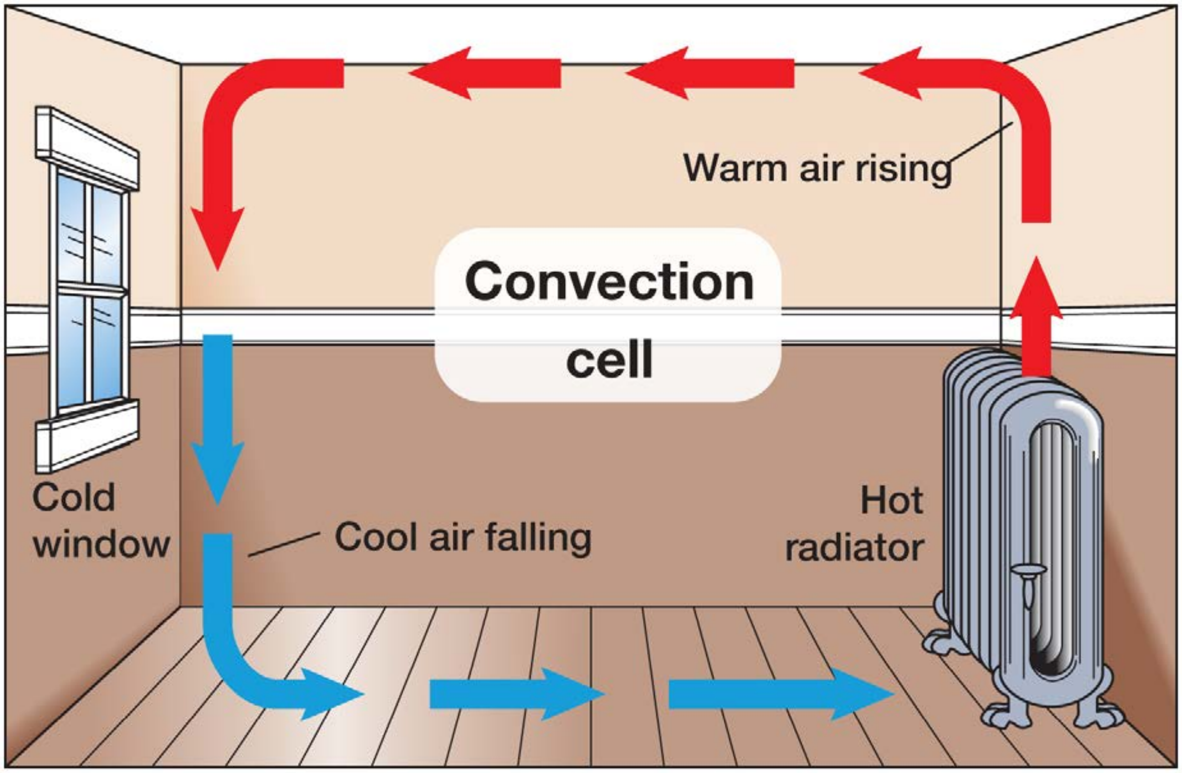
We have talked about a number of reasons that the solar radiation close to the poles (high latitudes) is low. In the polar regions, more solar energy is reflected back to the atmosphere than is absorbed. The opposite is true for the region of Earth between 35N and 40S (note that this extends further south in the southern hemisphere because there is more ocean surface in the south). Take a look at the figure below as an illustration. The graph shows solar radiation with the red line, and heat loss in the ocean with the blue line. You can see that for those regions between 35N latitude and 40S latitude, the heat gained from the sun is greater than that lost by the ocean, and vice versa for latitudes to the north or south. When you look at this graph, you might say, wait a minute – wouldn't this mean that the equatorial areas just keep getting hotter and hotter, while the poles just keep getting colder over time? Good point! The poles are colder than the equatorial region, but that difference in temperature tends to remain about the same because extra heat from the equatorial region is transferred around the Earth to the poles by ocean and atmospheric transfers.



Ok, so we have variations in heating and cooling of the Earth daily, seasonally, and latitudinally. Now let's talk about how the heat is circulated around by the atmosphere and oceans. First, the atmosphere. One might assume that as you go higher in the atmosphere and get closer to the sun things warm up. That is not the case. Most of the heat in the atmosphere comes from below from the warm surface of the Earth. Look at the temperature profile below that shows how the temperature of the atmosphere changes as you move away from Earth. The lower region of the atmosphere is called the troposphere – this is where weather is produced. As you move up into the troposphere the temperature cools, so much so that the upper troposphere is well below freezing. The troposphere is important because it is where a lot of mixing occurs.

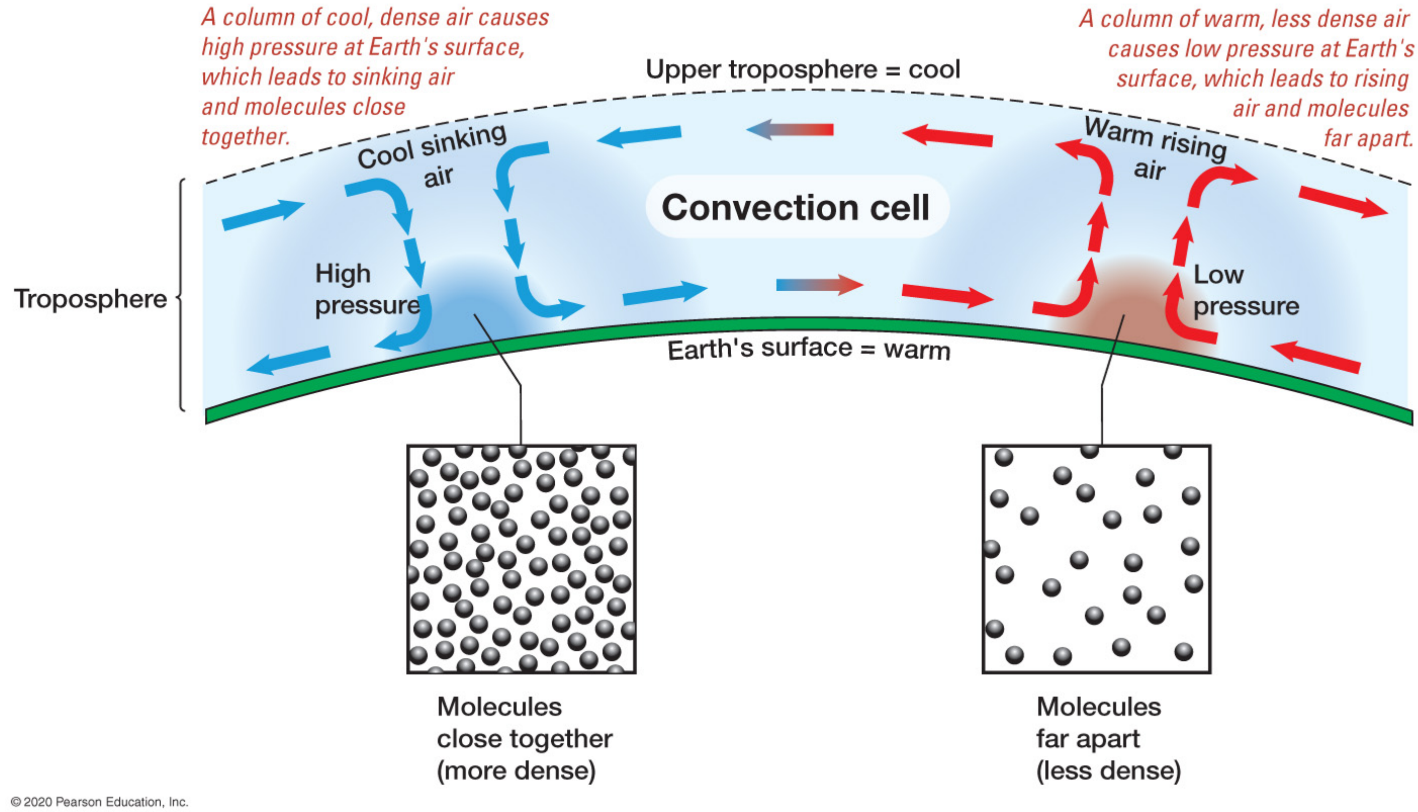


The air in the atmosphere is composed of molecules, and even though it is 'thin', it still has varying density like water does. Just like with water, as temperature of the air increases, the molecules tend to move faster and have more space between them, and thus lower density. And by now, I am sure you have this density thing down, so you already know that less dense warm air tends to rise, and more dense cool air tends to sink. We talked about convection when we discussed the Earth's mantle – the same process applies to heating and cooling air. Consider your dorm room with a heater on one side and a cool window on the other. The heater warms the air around it, which becomes less dense and rises. The warm air cools and becomes more dense in front of the window and sinks. Voila – you have a convection cell in your dorm room. The amount of water vapor in air is related to the temperature of the air. Warm air can hold more water vapor than cold air. Water vapor also alters the density of air because water vapor is less dense than air. Air with more water vapor is therefore less dense.

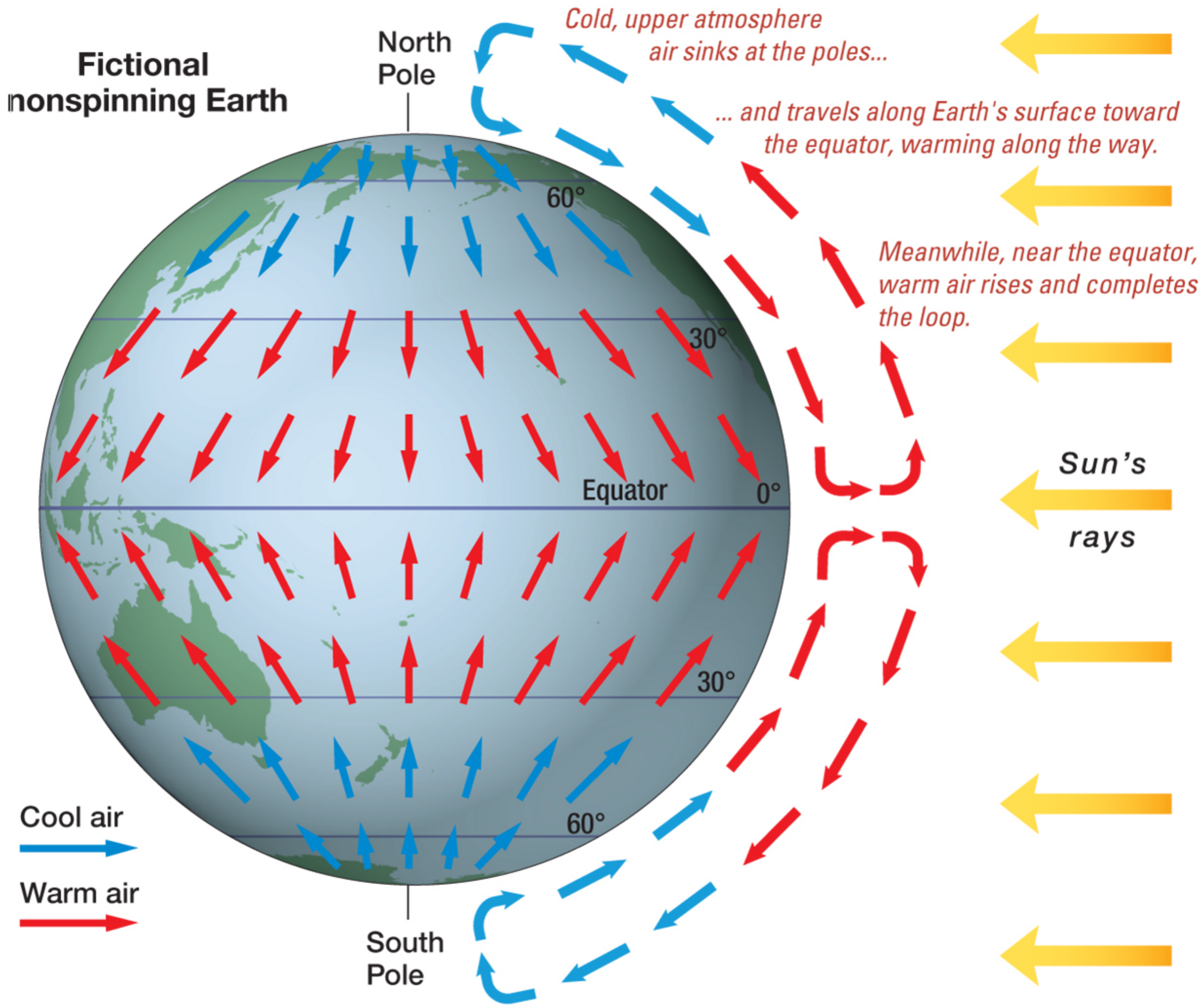


*A circular-moving loop of air (a **convection cell**) is created in this room by warm air rising and cool air sinking.*

The atmosphere has density, so with all of that dense air above us, it must be exerting pressure downward. Yes, the atmosphere creates pressure. We assign a value of 1.0 atmospheres of pressure at sea level (1.0 atmospheres = 760 mmHg = 101,300 Pascals = 1013 millibars: all of these are equivalent measures using different scales). The amount of pressure is related to the amount of air above – bigger column of air means greater pressure. As you go up in the atmosphere there is less air above and the pressure decreases. If you have ever felt your ears pop when you go up in an airplane or elevator – that is because the pressure around your head decreased and your ears need to adjust the amount of air in the middle ear. Changes in air pressure causes air to move around. Cool dense air creates high pressure and that air mass will sink. The opposite is true for warm less dense air which will move upward. We mentioned the troposphere earlier – well this air movement happens in the troposphere and convection cells can occur there with air moving upward or downward with heating or cooling, and then moving from areas of high pressure to low pressure, as illustrated below.



Let's imagine for a minute, an Earth that doesn't spin, and has a sun that rotates around the equator. This fake earth will receive more solar radiation at the equator and the air above those warmer areas will heat up from the heat released from the warmer land. You already know that this warmer air will be less dense and rise and create an atmospheric low pressure zone. The rising air will cool and the water vapor it contains will condense to liquid water and form rain. The rising air at the equator will eventually reach the top of the troposphere where you will recall temperatures are very cold. This air will cool and become more dense and sink at the poles creating a zone of high pressure. Recall that cold air doesn't hold much water vapor, so the cold air sinking at the poles is also very dry. Air movement (or wind) is always from areas of high pressure to low pressure, so on this imaginary non-spinning Earth, which way will surface winds blow? From the high pressure regions at the poles, toward the low pressure region at the equator. See the diagram below of our non-spinning Earth. In the northern hemisphere, the surface winds are Northerly winds (note that wind direction is named for the cardinal direction that the wind comes from).



This fictional Earth doesn't quite represent how the atmosphere works on our real spinning planet, but those principles of how air heats/cools/condenses etc are all real. Now let's talk about the spinning Earth. The Earth's rotation towards the East causes a super interesting phenomenon called the Coriolis effect, in which any object that is moving over the Earth surface will change path. On Earth, it causes the path of moving objects to curve. In the northern hemisphere, an object in motion will deviate (curve) to the right, while in the southern hemisphere it will curve to the left (note that these are to the right or left from the direction it comes from). These 'curving' paths are due to the Earth rotating below the moving object at different rates by latitude. The reason that latitude matters is that rotational velocity changes by latitude – the further you are from the poles, the faster you are spinning round on the Earth. This fact is used by NASA and other space agencies to help launch rockets. Launches that are made at locations with high rotational velocity don't need as much fuel to leave the atmosphere because the rocket is already getting a velocity jump start.

[This video (https://youtu.be/aeY9tY9vKgs)](https://youtu.be/aeY9tY9vKgs)

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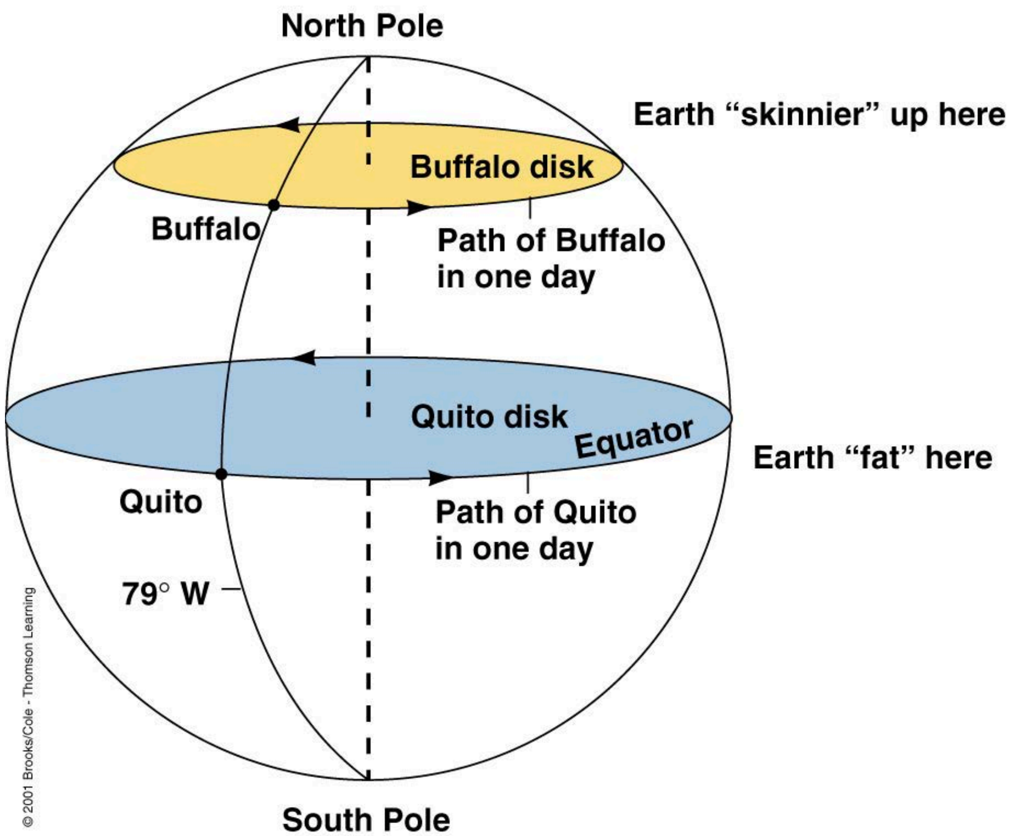
does a great job of illustrating the Coriolis effect (and the contents are course material). Watch it, the merry-go-round demo gives a fantastic example of how it happens and why hurricanes spin the way they do.

Let's make sure this whole latitude differences in rotational velocity is clear. If we were to track the distance that the city of Buffalo travels in 1 hour (Buffalo is approximately 42 degrees North latitude), and compare that to a city on the equator – let's use Quito because it is very close to the equator and a super cool city in the Andes. Buffalo rotates 1,260 km in 1 hour (which is 15 degrees of longitude, FYI), whereas Quito rotates 1,668 km in the same time. So Quito is rotating ~400 km/hr faster than Buffalo! The image below should help make this point clear.



Now that we know all about Coriolis – think back to air circulation on our hypothetical non-spinning Earth. Recall the way that convection cells set up surface winds. Now if we spin the Earth beneath that those moving air masses will appear to deflect from Coriolis which sets up 3 sets of convection cells in each hemisphere. At the equator, solar radiation heats the Earth which warms the air and warm humid air rises. As it does, it cools in the atmosphere and the water vapor condenses to form liquid water (rain). At the top of the troposphere, that air moves towards low pressure (around 30 degrees latitude). This equatorial circulation cell, the largest of the cells, is called a Hadley Cell for the scientist who first discovered it. Two additional cells set up in atmospheric circulation that work like rotating air masses that cycle through warm and cold temperature, and high and low pressure. These are Ferrel cells (again named for a scientist) between 30 and 60 degrees latitude which act like a gear spinning between the two other cells, and Polar cells between 60 degrees latitude and the poles that are the smallest cells of the three. The diagram below shows these cells around the globe, and [this video demonstrates (https://youtu.be/xqM83_og1Fc)](https://youtu.be/xqM83_og1Fc)

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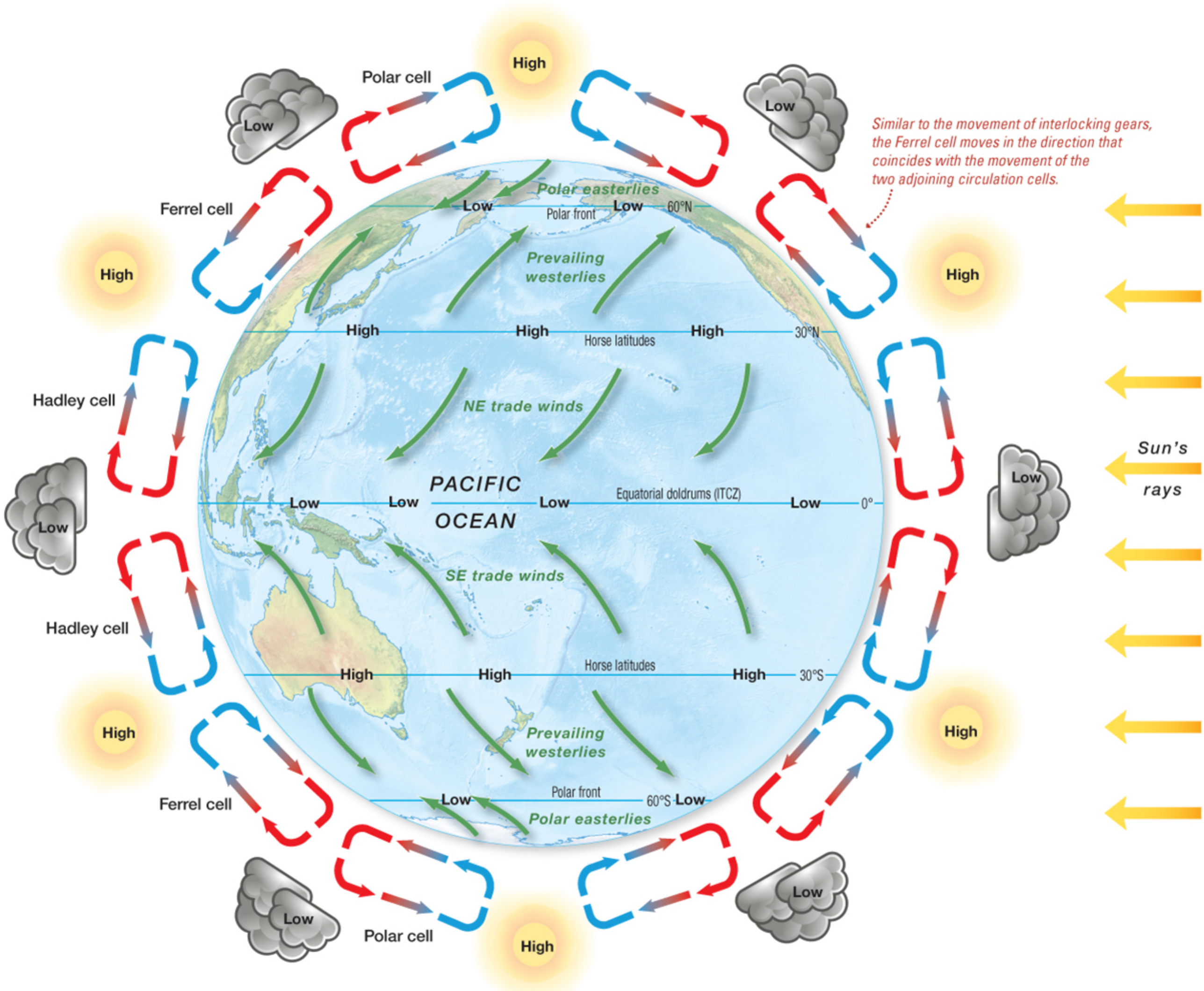
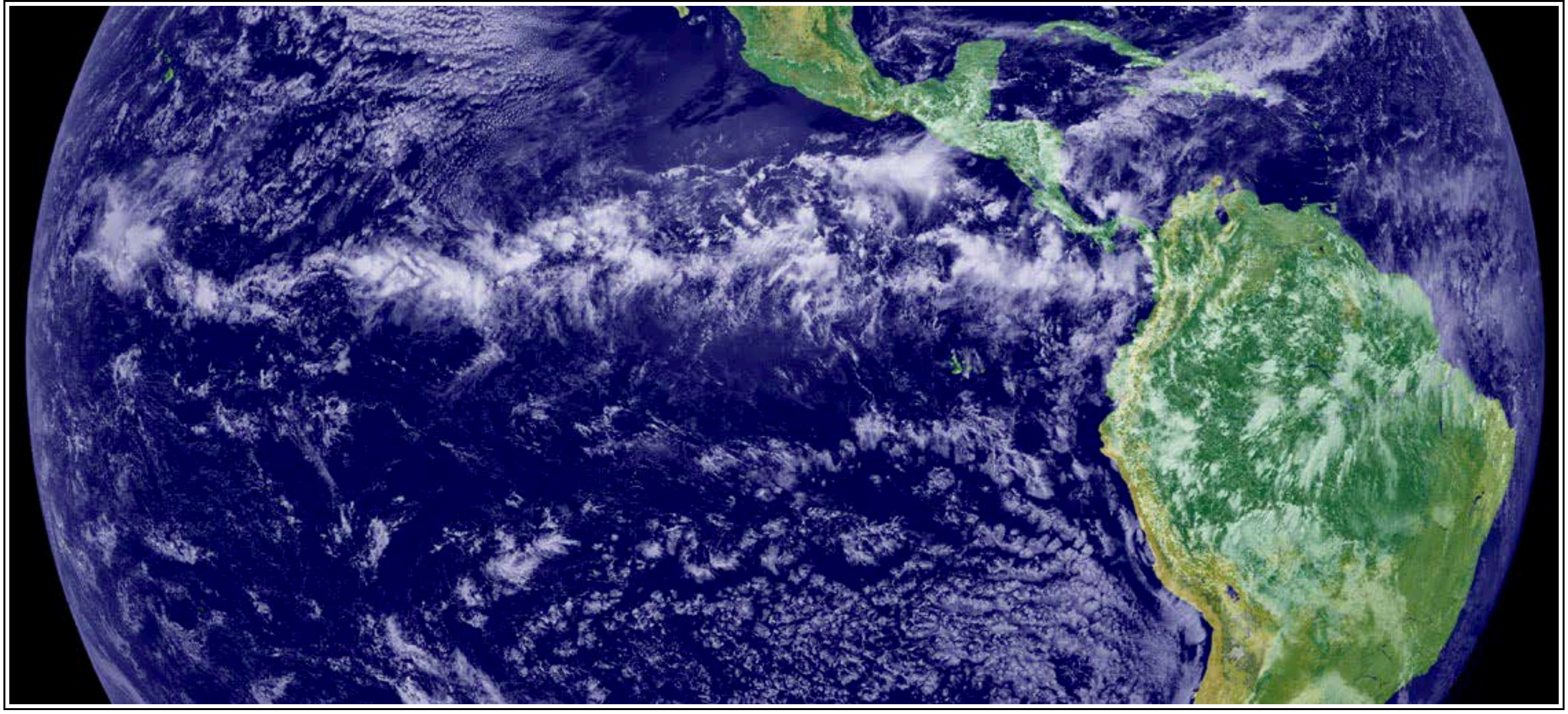
how they operate – watch it (and note that the tropopause is another word for troposphere). Make note of where areas of high and low pressure are globally and remember that air always moves from high to low pressure.



These three circulation cells determine patterns of pressure, weather, and wind. What kind of weather would you expect in high pressure areas? The high presure air tends to be dry, and the skies tend to be more frequently clear. Weather in the areas of low pressure tends to be cloudy with frequent precipitation (recall that the air there tends to be warm and rising which cools it and turns vapor into liquid). Along the equator there is a low presure zone of convergence known as the Intertropical Convergence Zone (ITCZ). Here is a cool satellite image of the ITCZ and the clouds it creates.



The lower part of the belt systems closest to the surface are what creates the wind belts of the world. Again, recalling our hypothetical non-spinning Earth, these surface winds would blow north-south. But the Earth is spinning and you know how Coriolis works, so this next part should be easy. The Hadley cells set up what are called trade winds. In the northern hemisphere the trade winds blow Northeast because they are deflected to the right due to Coriolis (remember that the wind direction is named for where it comes from, not where it is blowing to). In the southern hemisphere where Coriolis deflects to the le, the trade winds blow from the southeast. Ferrel cells generate winds called the prevailing westerlies (note that these winds are westerly winds in both hemispheres even though the Coriolis deflection differs. Finally, the polar cells generate polar easterly winds – again, look at the diagram above and convince yourself of the Coriolis deflection in each hemisphere. Here is

[another video (https://youtu.be/PDEcAxfSYaI)](https://youtu.be/PDEcAxfSYaI)

[(https://youtu.be/PDEcAxfSYaI)](https://youtu.be/PDEcAxfSYaI)
that demonstrates these wind patterns.

The 'Horse Latitudes', found between 30 - 35 degrees north and south (a location of subtropical high pressure), is an area notoriously problematic for sailors and was avoided by early sailing ships. These locations were known to be calm (very little wind and rain - take a closer look at the image above and think about why). Often ships would find themselves stalled there without the wind needed to continue sailing (the Doldrums are a region with the same risk at the equatorial low pressure). When this happened, freshwater stores on the ship would continue dwindling even though they were getting no closer to their destination. Being out of freshwater is an even bigger concern than scurvy, so sailors would throw dehyrdated and dying horses overboard to save water. Jim Morrison (of The Doors) wrote a poem about this legendary sailing peril (well, he might have been using the legend as a metaphor for societal dismissal of lower classes, but we won't get into philosophy here).

Now I know you are all looking for a place to visualize global wind patterns – **here is a link (https://earth.nullschool.net/)** to an awesome data visualization tool you can play with.