# ANSWER KEY

# Real World Globes - Investigating Jet Streams and Planetary (Rossby) Waves

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## Purpose:

- To review and investigate Earth's global wind patterns.
- To investigate the geographic locations of the subtropical jet and polar jet.
- To understand the physical mechanism by which jet streams are produced.
- To investigate the latitudinal variation in jet streams with the seasons.
- To investigate changes in amplitude of planetary (Rossby) waves.
- To understand how changes in latitude, amplitude, and wind velocity of a jet stream influences synoptic weather patterns.

## Target Audience:

- High school students

## Materials:

- Mother Earth Globe™
- Mars Albedo Globe™ or Mars Topo Globe™ (optional)
- Clear 18" hemisphere
- Dry-erase markers, eraser
- Computer with internet access

## Related Lesson Activities:

- Investigating the Coriolis Effect - Globe Activity

## Introduction:

**Jet streams** are rapidly moving (80 - 140 mph), relatively narrow (a few hundred miles wide, and often less than three miles thick) streams of air found at the **tropopause** (the boundary between the **troposphere** and the overlying **stratosphere**). There are four major jet streams that encircle the planet - two in the northern hemisphere and two in the southern hemisphere. They are known as the **subtropical jet stream** and the **polar jet stream** (see figure 1). Both jet streams move in a west to east direction (the same direction as the Earth's rotation). These jet streams vary on a daily and seasonal basis - moving to higher latitudes (toward the poles) in the summer and lower latitudes (toward the equator) in winter. During the winter, the jet streams are often more powerful due to the greater air mass temperature differential between the air north of the jet stream and south of the jet stream. During the summer, when this temperature differential is less exaggerated, the jet streams often slow down. Jet streams have a major influence on the day-to-day weather and are the driving force behind the movement of weather systems from a west to east direction. Without jet streams, weather systems would barely move and there would be prolonged periods of the same weather at a given location. Jet streams often also provide upper-air support for surface low and high pressure weather systems, causing them to strengthen.

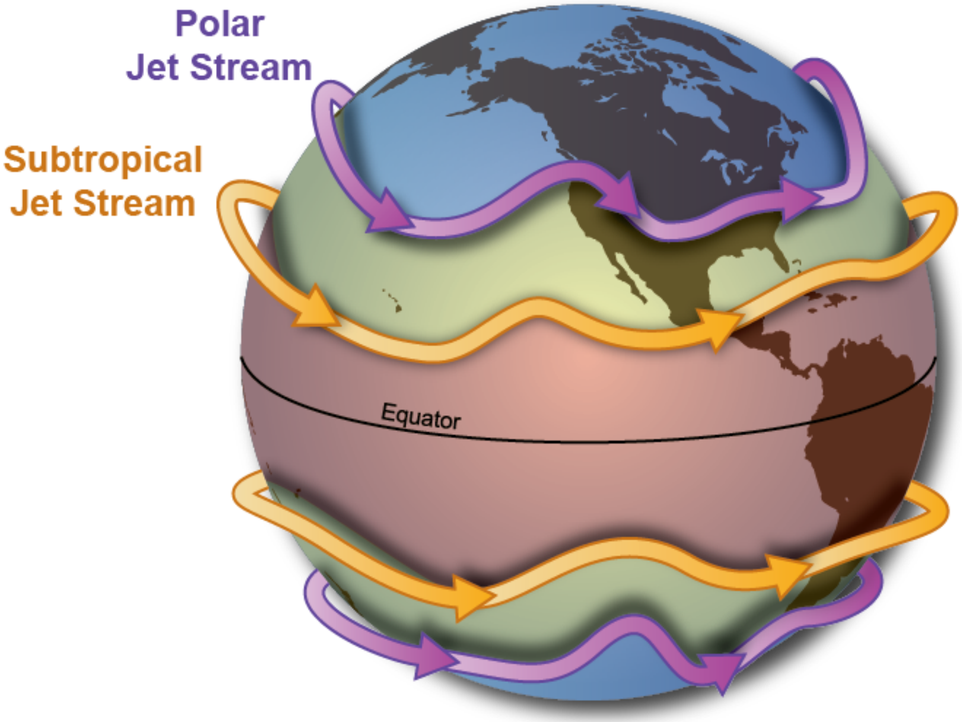


**Figure 1:** The locations of the northern and southern polar jet stream and subtropical jet stream. Note that the average temperature of the air mass between the two subtropical jet streams is very warm (nearest the equator). The average temperature of the air masses decreases as one moves towards the poles. It is the temperature difference between these air masses that drives the jet streams. (Courtesy of the National Weather Service).

The locations of the jet streams occur at the boundaries between the major circulation cells of the Earth. The subtropical jet stream forms at the boundary between the Hadley Cell and the Ferrel Cell. The polar jet stream forms at the boundary between the Ferrel Cell and the Polar Cell (see figure 2). It is also worth noting that the subtropical jet stream overlies a region of surface high pressure (called the **subtropical high**) and this high pressure is due to the descending air found at this boundary. Conversely, the polar jet stream overlies a region of surface low pressure (called the **polar front**) and this low pressure is due to the ascending air found at this boundary. All four jet streams on Earth move in a west to east direction as a result of the Coriolis force deflecting upper-level poleward-moving winds (moving down their pressure gradient) to the right (in the northern hemisphere). In the southern hemisphere, this deflection occurs to the left, but still results in a west to east movement of air.

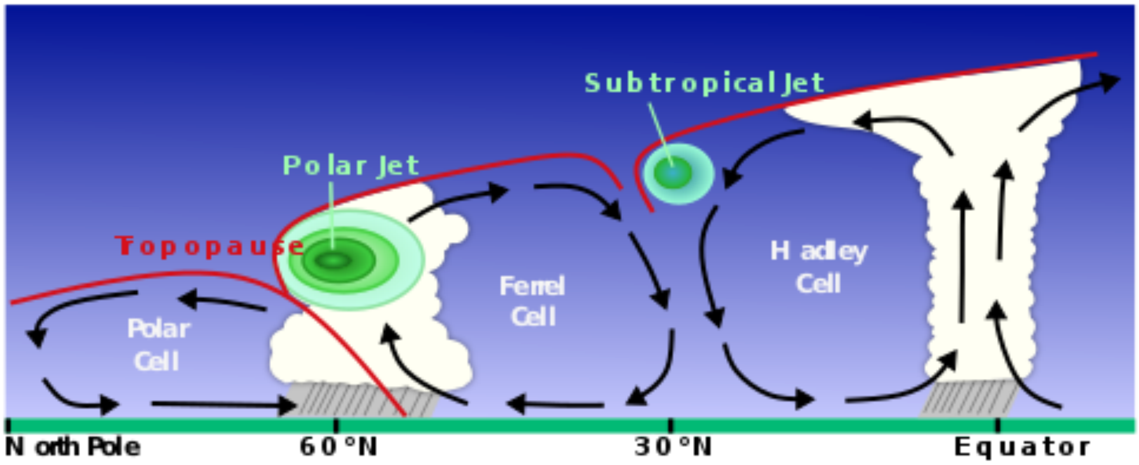


**Figure 2:** The locations of the jet streams in relation to their latitude and altitude. Note that jet streams form at the upper-level boundaries of the major circulation cells (Hadley, Ferrel, and Polar Cells), and just beneath the tropopause. Also note that the polar jet stream is more intense (higher winds) due to the greater difference in average air mass temperature between the Polar Cell and the Ferrel Cell, as well as the greater influence of the Coriolis effect at higher latitudes. (Courtesy of Wikipedia).

## Activity 1 - Planetary wind patterns (taken from the "Investigating the Coriolis Effect" Globe Activity):

Winds are produced by the uneven heating of the Earth's surface by the Sun. Regions of the Earth near the equator receive the greatest amount of solar radiation on average. This is why regions near the Earth's equator tend to be warm year-round and change very little from season to season. Conversely, regions of the Earth near the poles receive the least amount of solar radiation on average. This is why regions near the Earth's poles tend to be cool or cold year-round.

As the Sun heats the Earth's surface, it warms up, gaining thermal (heat) energy. This thermal energy is then transferred to the air immediately above the Earth's surface, causing it to heat up as well. As the air heats up it becomes less dense, and so it begins to rise vertically. As it continues to rise it expands and cools, eventually spreading out horizontally once it reaches the same density as the atmosphere around it. As it cools further, the air becomes more dense than the surrounding atmosphere and so it begins to sink vertically. When the air reaches the surface, it spreads out horizontally along the surface, and eventually returns back to the location where it started. This cycle of convection forms what is known as a **convective cell** (see figure 3).

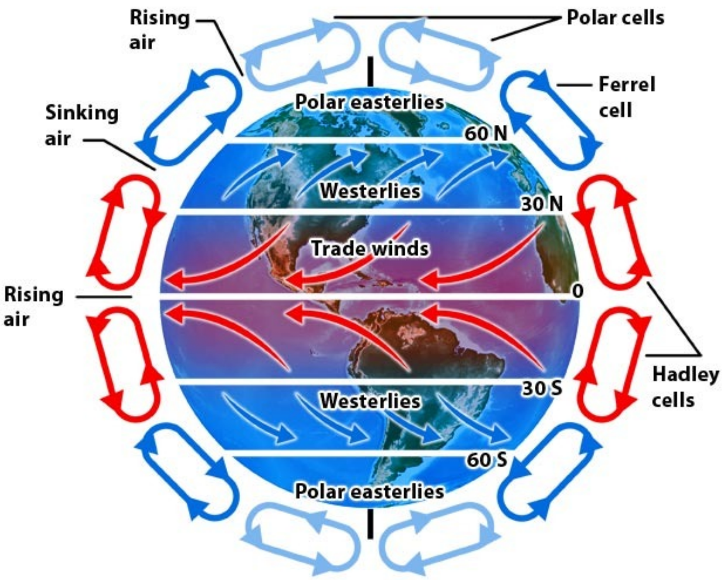


**Figure 3:** Earth's convective cells (represented by loops of air currents). Each hemisphere contains three convective cells that encircle it (called the Hadley, Ferrel, and Polar cell). The driving force for this circulation of air is the uneven heating of the Earth's surface by the Sun. (Courtesy of Quizlet).

**Hadley cell:**

At the equator, where warm air rises, it cools and flows poleward and eventually sinks back down to the surface. Along the surface it moves back toward the equator. This occurs between 0º and 30º N and S latitude.

1. On the globe, draw arrows representing the surface wind direction **AS IF THE EARTH WERE <u>NOT</u> ROTATING.** Do this around the entire globe.

2. Erase your arrows. Now, let's assume the Earth is rotating. Knowing how wind currents are deflected by the Coriolis force, draw arrows representing the surface wind direction. Do this around the entire globe. Which direction (east or west) do the arrows deflect? These are known as the **trade winds**. Why do you think mariners called them this?

   **The winds deflect to the west. European mariners called these winds the "trade winds" because they would first set sail south into the trade winds, and then allow these winds to carry them westward toward the new world (North America), where they could trade with indigenous peoples.**

**Ferrel cell:**

At about 30º latitude, the cooling air begins to sink toward the Earth's surface from the upper atmosphere. Once it reaches the surface, part of it moves equatorward (part of the Hadley cell) and part of it moves poleward (part of the Ferrel cell). The surface flow of the Ferrel cell occurs between 30º and 60º N and S latitude.

1. On the globe, draw arrows representing the surface wind direction between 30º and 60º latitude **AS IF THE EARTH WERE <u>NOT</u> ROTATING.** Do this around the entire globe.

2. Erase your arrows. Now, let's assume the Earth is rotating. Knowing how wind currents are deflected by the Coriolis force, draw arrows representing the surface wind direction. Do this around the entire globe at the same latitudes listed above. Which direction (east or west) do the arrows deflect? These are known as the **westerlies**.

   **The arrows deflect toward the east (their name "westerlies" can be confusing, because it is in reference to the direction from which the winds blow...from the west).**

**Polar cell:**

At about 60° latitude, the cool air begins to rise vertically again from the Earth's surface. As it rises and cools, it spreads out horizontally. Part of it moves equatorward (part of the Ferrel cell) and part of it moves poleward (part of the Polar cell). As it moves poleward, it cools further and begins to descend back towards the surface. Once it reaches the surface, it has no choice but to move equatorword along the surface. The surface flow of the Polar cell occurs between 60° and 90° N and S latitude.

1. On the globe, draw arrows representing the surface wind direction between 60º and 90º latitude **AS IF THE EARTH WERE NOT ROTATING.** Do this around the entire globe.

2. Erase your arrows. Now, let's assume the Earth is rotating. Knowing how wind currents are deflected by the Coriolis force, draw arrows representing the surface wind direction. Do this around the entire globe at the same latitudes listed above. Which direction (east or west) do the arrows deflect? These are known as the **polar easterlies**.

   **The arrows deflect toward the west (their name "polar easterlies" can be confusing, because it is in reference to the direction from which the winds blow...from the east).**

**Activity 2 - Mapping the jet streams:**

1. Go to [https://earth.nullschool.net/](https://earth.nullschool.net/)

2. In the bottom left corner of the screen you will see a button that says "earth" with three lines next to it. Click on it.

3. Under the Height category, select 250. (This represents the winds at an altitude of about 35,000 ft., right at the tropopause). The fastest wind speeds will be colored in red and pink. These bands will be the locations of the jet streams.

4. Using a dry erase marker, sketch on the globe the locations of the four jet streams (two in the northern hemisphere and two in the southern hemisphere.) Note that sometimes the two jet streams will appear to converge into one another and then separate. Make

sure you go around the entire globe (you can rotate the Earth on the website by clicking and dragging on the Earth).

5. Label each jet stream. The jet streams closest to the equator are the subtropical jet streams and the jet streams closest to the poles are the polar jet streams.

6. If you notice any regions where air currents appear to be swirling, draw them as circles on the globe, using arrows, to show their direction of rotation.

**Northern hemisphere:**

## Southern hemisphere:

7. Open a new tab on your computer and go to https://weather.com/maps/ustemperaturemap

8. Compare this temperature map of the coterminous United States on the website with the globe. Remember, colder air is usually found north of the jet stream while colder air is usually found south of the jet stream. Does the temperature map match with what you drew on the globe?

   **Students should notice that warmer temperatures should be seen to the south of the polar jet stream, and colder temperatures north of it.**

9. Open a new tab on your computer and go to https://weather.com/maps/ussatellitemap

10. Compare this satellite image map of the coterminous United States on the website with the globe. Oftentimes, clouds and stormy weather can be found along the polar jet stream. Do clouds and stormy weather on the weather map match with what you drew on the globe?

    **Students should notice that generally stormy weather is found along the polar jet stream, as the jet stream provides upper-air support for surface low pressure systems.**

### Activity 3 - Understanding planetary (Rossby) waves:

Sometimes, due to the underlying topography of the Earth’s surface and the presence of “blocking systems” (massive regions of high or low pressure), jet streams can be deflected into large meandering streams that resemble waves (see figure 4). These wave-like deflections are called **planetary (or Rossby) waves**, named after Swedish-American meteorologist Carl-Gustaf Rossby (see figure 5).

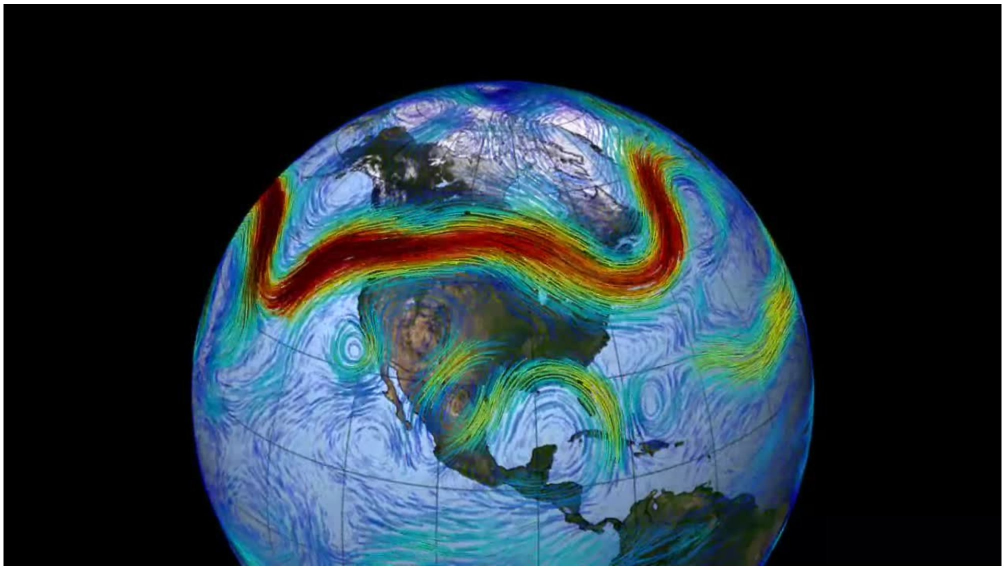


**Figure 4:** Planetary (Rossby) waves, shown as the red-colored stream of air here, are large curves and meanders in the jet stream. The amount of meandering is called the **amplitude** of the wave. Generally, the polar jet streams experience greater amplitudes than the subtropical jet streams. The “peaks” of the waves are called **ridges** and the “dips” are called **troughs**. Generally, high pressure systems are found at the ridges and low pressure systems are found at the troughs. (Courtesy of Wikipedia).

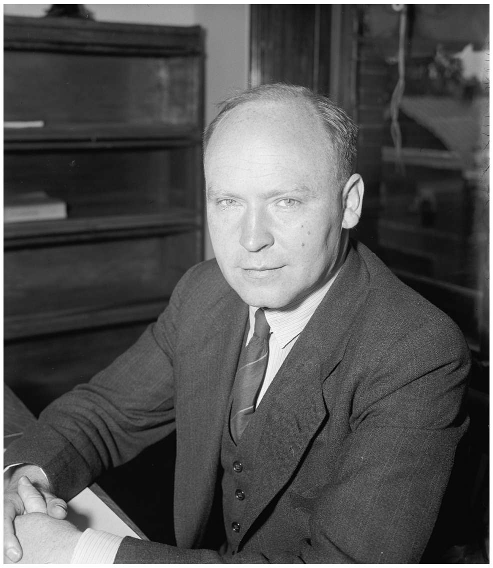


**Figure 5:** Swedish-born American meteorologist Carl-Gustaf Rossby (1898 - 1957). (Courtesy of Wikipedia).

As the Rossby waves are deflected, they bring cold, polar air toward the equator and warm, tropical air toward the poles (see figure 6). Sometimes, particularly in the winter, the sudden southward surge of the polar jet stream can make it down to as far south as Texas and Florida, bringing frigid air behind it and creating an **arctic blast** (the media often terms this the **polar vortex**). As Rossby waves exaggerate even further, they may sometimes pinch off from the main flow stream, creating large **cyclonic** (low pressure) weather systems, and **anticyclonic** (high pressure) weather systems (see figure 6).

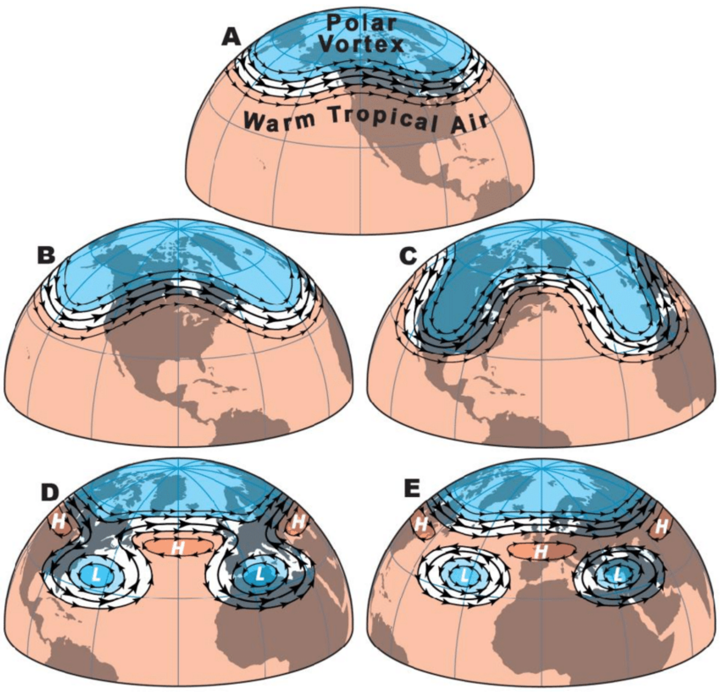


**Figure 6:** As Rossby waves exaggerate in amplitude, they may sometimes pinch off, creating large cyclonic (low pressure) and anticyclonic (high pressure) weather systems. These weather systems generally travel with the prevailing winds (west to east), with cyclonic systems moving faster than anticyclonic systems. (Taken from Harris, 2019).

1. Examine the jet streams that you drew on your globe. Count the number of Rossby wave low points (**troughs**) for the northern polar jet stream. (This number is usually between 3 and 5). How many did you count?

   **This number will vary, as the global weather patterns change over time. Below, looking down on the north pole, six Rossby waves can be seen (numbered 1 - 6).**

2. Compare the amplitude of the Rossby waves between the northern polar jet stream and the northern subtropical jet stream. What differences do you notice?

   **Rossby waves formed in the polar jet stream tend to have larger amplitudes (a more exaggerated wavy appearance) compared to the subtropical jet stream, which tends to flow more zonally (in a straight east-west direction).**

3. What do you notice about where you drew the swirls on the globe? In relation to the Rossby waves, where do they generally occur?

   **Vortices (swirls) tend to occur at troughs (“equatorward dips”) and ridges (“poleward peaks”) in the Rossby waves. Vortices at troughs represent low pressure systems (cyclones). Vortices at ridges represent high pressure systems (anticyclones).**

4. Compare the northern and southern polar jet streams on the globe. Which one appears to have more Rossby waves? How does the shape of the Rossby waves differ between the two jet streams? Why do you think this is? (*Hint: Think about the geography of the northern hemisphere compared to the southern hemisphere*).

**Northern hemisphere**

**Southern hemisphere**

**Generally, the northern polar jet stream will tend to have more Rossby waves than the southern polar jet stream. The southern polar jet stream tends to flow more zonally (in a straight east-west direction). This is due to the fact that most of Earth's land masses are found in the northern hemisphere. Transitions between land and ocean, as well as variations in land topography, tend to cause the northern polar jet to meander more due to the presence of vertically propagating waves up into the upper atmosphere (see figure on next page).**

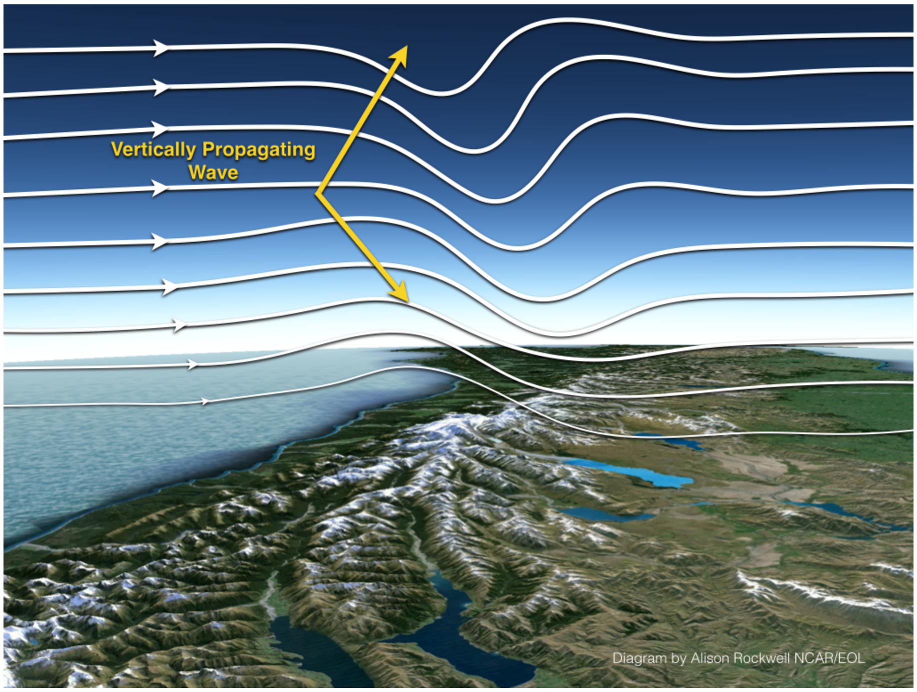
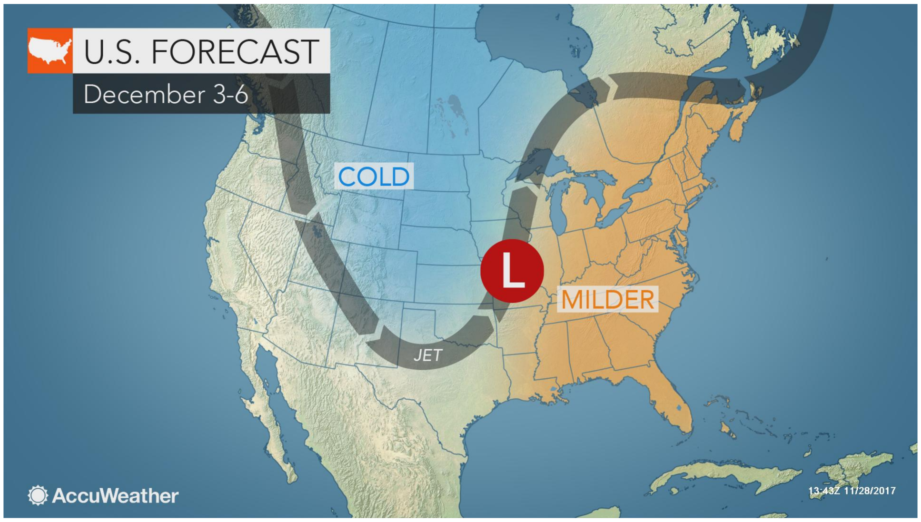


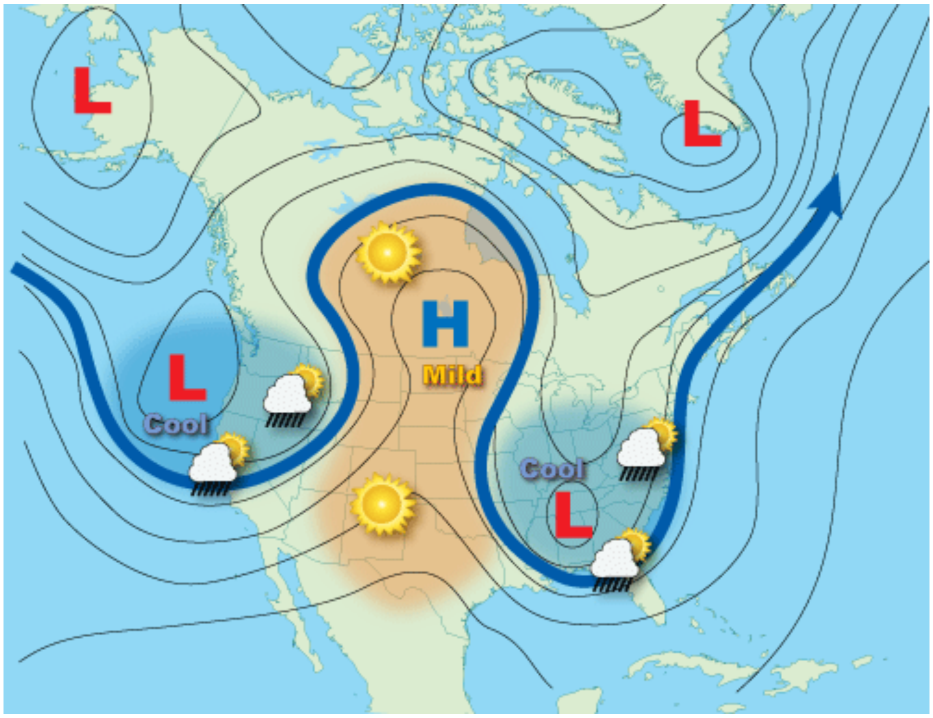
Diagram by Alison Rockwell NCAR/EOL

**Follow-up questions:**

1. Examine the current weather conditions at your particular location. Compare to where the polar jet stream is currently located. Do the weather conditions at your location correlate with what you would expect given the current location of the polar jet stream?

   **This will vary depending on your current time and location. But in general, warmer/milder air masses can be found south of the polar jet stream, while colder air masses are found to the north. Furthermore, low pressure systems (cyclones) tend to set up to the east of troughs. In the "bottom" of a trough, and along its eastern edge, weather tends to be stormy. Conversely, in the "peak" of a ridge, high pressure systems (anticyclones) tend to set up, producing fair weather. (See figures on the next page).**





2. How do you think the latitude of the polar jet stream changes with the seasons (summer vs. winter?) What might cause this shift in latitude?

   **During the summer, the polar jet stream tends to shift toward the pole (to the north in the northern hemisphere summer). In the winter, the polar jet stream tends to shift toward the equator (to the south in the northern hemisphere winter). Furthermore, wind speeds found in the polar jet stream tend to be faster in the winter, due to the larger difference in air mass temperatures north and south of the jet.**

**Supplementary Analysis Activity (Optional) - Jet Streams on Mars:**

The Mars Atmosphere and Volatile Evolution (MAVEN) satellite, currently orbiting Mars, has taken measurements of wind speeds on Mars using remote-sensing techniques. Like Earth, Mars' axis of rotation is tilted with respect to the plane of its orbit (by about 25°), resulting in seasons. Figures 7 - 9 show how the wind speed and direction vary on Mars at different latitudes and altitudes, and during different seasons.

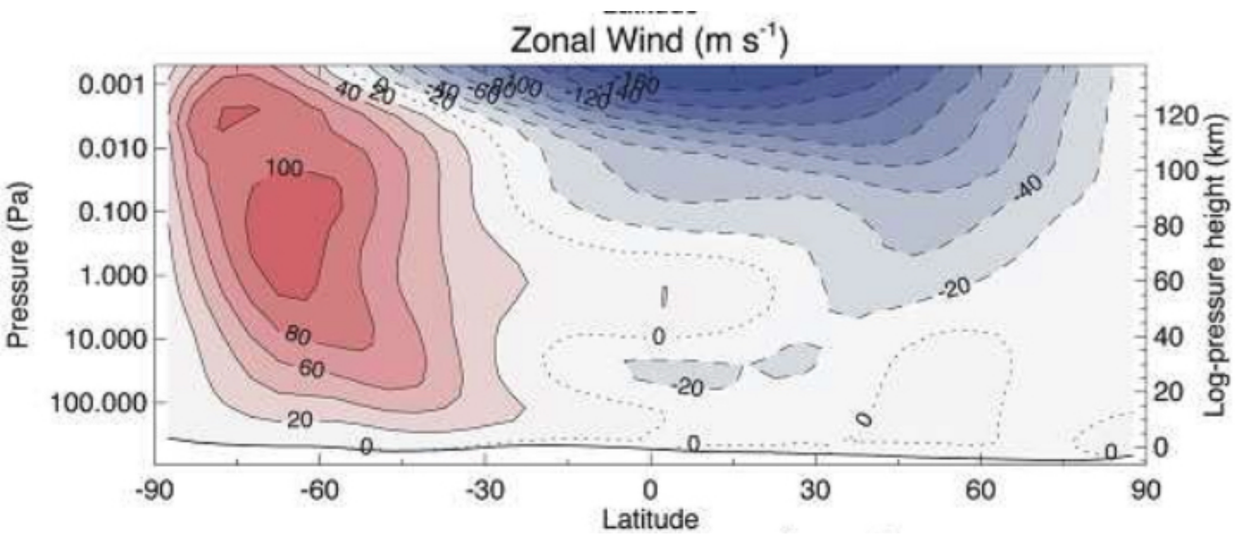


**Figure 7:** Vertical profile of wind patterns on Mars during the southern hemisphere winter (northern hemisphere summer). Red shading indicates prograde winds (moving with the planet's spin - toward the east). Blue shading indicates retrograde winds (moving against the planet's spin - toward the west). (Courtesy of NASA).

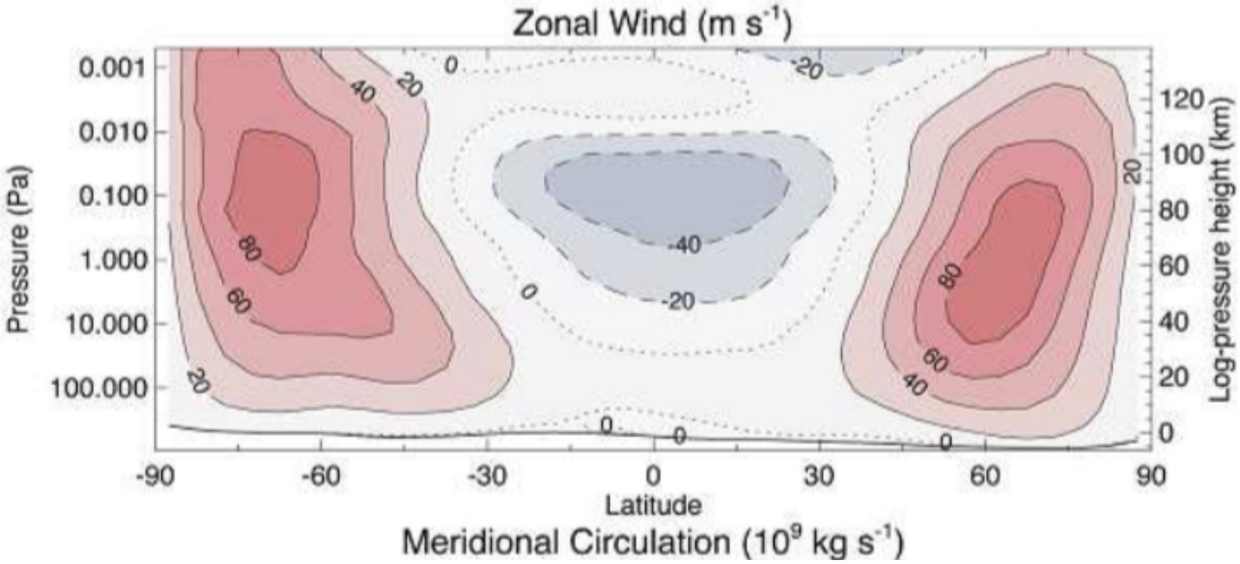


**Figure 8:** Vertical profile of wind patterns on Mars during the equinox. Red shading indicates prograde winds (moving with the planet's spin - toward the east). Blue shading indicates retrograde winds (moving against the planet's spin - toward the west). (Courtesy of NASA).

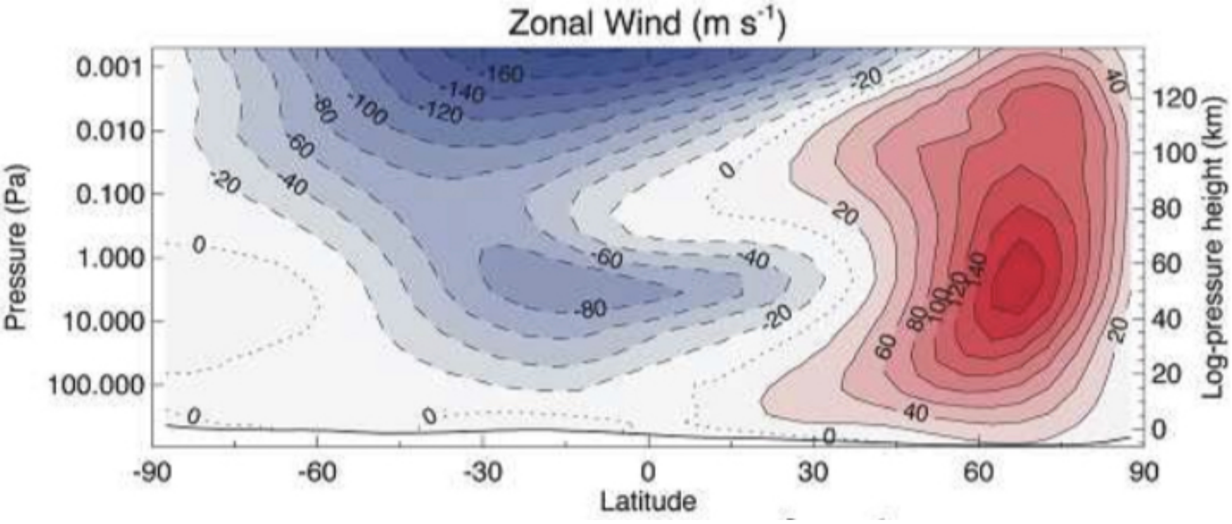


**Figure 9:** Vertical profile of wind patterns on Mars during the northern hemisphere winter (southern hemisphere summer). Red shading indicates prograde winds (moving with the planet's spin - toward the east). Blue shading indicates retrograde winds (moving against the planet's spin - toward the west). (Courtesy of NASA).

1. Using either the Mars Albedo Globe$^{TM}$ or Mars Topo Globe$^{TM}$ and a dry erase marker, trace out the approximate location of the prograde (red shaded) jet stream during the southern hemisphere winter (see figure 7). Trace this jet stream around the entire planet. Along it, label "southern winter jet."

2. On the same globe, trace out the approximate location of the prograde (red shaded) jet stream during the northern hemisphere winter (see figure 9). Trace this jet stream around the entire planet. Along it, label "northern winter jet."

3. In the latitudes between the two jet streams, draw arrows that indicate the direction of the retrograde winds (blowing toward the west).

**Follow-up questions:**

1. Why might scientists and engineers working at NASA's Jet Propulsion Laboratory (JPL) need to know about the wind profile on Mars?

   **When landing rovers on Mars, for a period of time during the descent the vehicle is subject to fast-moving winds in the upper atmosphere. Having a knowledge of the location, direction and velocity of these winds during a given season on Mars, engineers can anticipate and program automated corrective maneuvers so that the vehicle will land as close to the target zone as possible.**

2. Why do you think the jet streams on Mars only show up during the winter season in their particular hemisphere? (*Hint: Think about what drives the jet streams on Earth.)*

   **Just like on Earth, strong circumpolar jets are formed during the winter season due to the large temperature difference between the polar region and mid-latitudes.**

**Critical thinking questions:**

1. Jet streams on Earth occur at the boundaries between convective cells (on Earth these are the Hadley, Ferrel, and Polar Cells). However, jet streams also occur on other planets, such as the gas giant Jupiter, which has up to 8 convective cells in each hemisphere! How might the jet streams look different on Jupiter?

   **Jupiter would have many more jet streams, which in turn drive a complex circulation pattern in the upper atmosphere of Jupiter. These jet streams are found at the boundaries between light-colored cloud regions ("zones") and reddish-brown-colored cloud regions ("belts"). (See Jovian Jets Globe Activity).**

2. What would happen to the Earth's jet streams if the Sun were able to heat all surfaces of the Earth evenly?

   **With the even, equal heating of all of Earth's surfaces, there would be no temperature differences to induce the movement of air. Jet streams would stop.**

3. What would happen to the Earth's jet streams if the Earth were to all of a sudden stop rotating?

   **Without the rotation of the Earth, the Coriolis effect would be absent and there would be no eastward deflection of air at boundaries between convective cells. Air would move from regions of higher pressure (and temperature) to regions of lower pressure (and temperature) in a north-south direction of flow. There would be no channels of air moving in an eastward direction.**

4. Often, transcontinental flights make use of the jet stream when flying toward the east. Pilots will intentionally alter their course and fly into the jet stream, even if it takes them along a longer route over the ground. Why might they do this?

   **By flying into an eastward-moving jet stream, eastbound flights receive a beneficial tailwind that allows the pilot to throttle back and save fuel. It may also reduce the total flight time, since the plane's ground speed will be faster due to the additional "push" from the tailwind.**

5. Interestingly, pilots will try to avoid flying into the jet stream when flying toward the west, even if it takes them along a longer route over the ground. Why?

   **By avoiding the eastward-moving jet stream, westbound flights do not have to contend with a headwind that would require the pilot to throttle up and consume more fuel in order to maintain a given ground speed. Flying against the jet stream would lengthen the total flight time, and is considerably less fuel efficient.**