Real World Globes - Investigating the Coriolis Effect

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Purpose:
- To understand the implications of the Coriolis force on rotating fluids.
- To investigate the Coriolis effect as it applies to planetary wind patterns and synoptic weather systems.
- To investigate the physical parameters governing the Coriolis force.
- To understand how the Coriolis force is responsible for the counterclockwise rotation of cyclones, and clockwise rotation of anticyclones in the northern hemisphere.

Target Audience:
- High school students

Materials:
- Mother Earth Globe™
- Clear 18” hemisphere
- Spherical protractor
- Dry-erase markers, eraser, calculator

Introduction:

The Earth is basically a large, complex fluidic system. A fluid is a material (liquid or gas) that is able to flow freely under the influence of forces. In the case of Earth, these surface fluids consist of the ocean and the atmosphere. Forces can be in the form of thermal gradients (differences in temperature between two locations within the fluid) or pressure gradients (differences in the pressure). When the fluid is not rotating, these forces act in straight lines, causing a mass of fluid to flow from a region of higher pressure to a region of lower pressure. Similarly, under the influence of a temperature gradient, warm portions of the fluid will rise up (against the downward pull of gravity) and cold portions will sink downward. This upward and downward flow process is known as **convection**, and it is a central driver of global ocean currents and atmospheric winds.

However, when the fluid system is rotating (as the Earth does about its axis), an additional force, called the **Coriolis force** acts to deflect the motion of fluids. While the flow of a fluid under non-rotating conditions is linear, under rotating conditions the fluid follows curved pathways.

It turns out that there are several physical parameters that govern the strength of the Coriolis force (F_C). The mass (m) of the parcel of fluid, the velocity (v) of the parcel, the angular velocity (ω) of the rotating system (basically how fast the fluid is being rotated) and the latitude (ϕ) at which the parcel is located. These parameters can be summarized in the equation below:

$$F_C = 2mv\omega(sin\phi)$$

From this equation, we can determine a few things. The Coriolis force acting on a mass of fluid increases as:

- The mass of the parcel increases.
- The velocity of the parcel increases (fluids moving faster experience more Coriolis force).
- The faster the system rotates.
- The higher the latitude of the parcel (zero at the equator, and maximum at the poles).

One interesting occurrence where the effects of the Coriolis force is very evident is on Jupiter. Jupiter has the fastest rate of rotation (ω) of any planet in the solar system, completing one rotation every 9.5 hours (compared to 24 hours for the Earth). As a result, the Coriolis force acting on the clouds of Jupiter is quite intense. At the Jovian equator (where the latitude is 0^o), there is no Coriolis force acting on the clouds, and so they flow in straight lines (bands) in the direction of the planet's rotation (see Figure 1). However, near the poles (high latitudes) complex vortices and eddies abound as a result of the increased Coriolis force deflecting the cloud bands into beautiful swirls (see Figure 2).

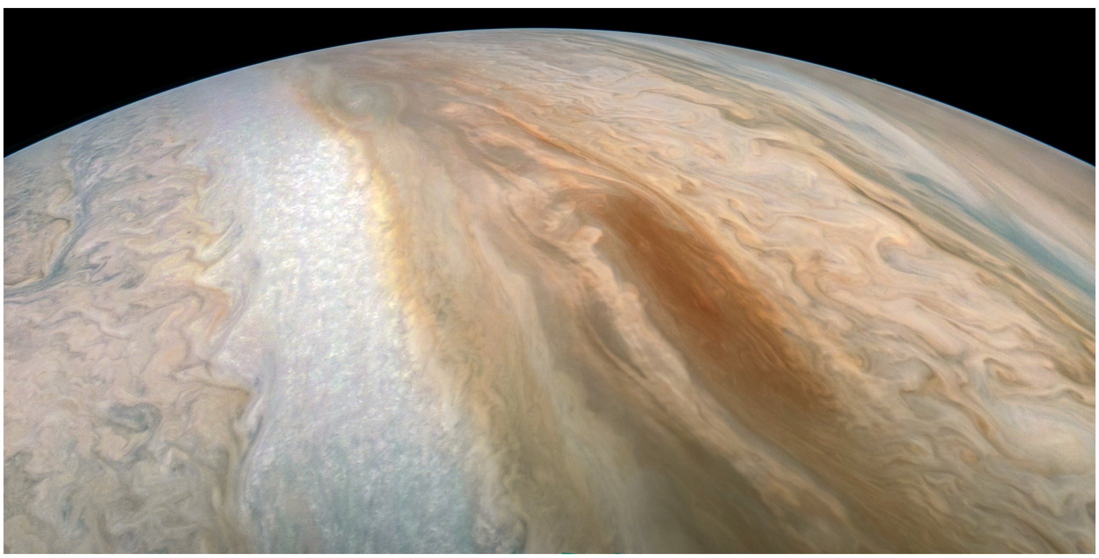

Figure 1: Equatorial cloud bands on Jupiter flow in relatively straight lines. (Taken from the orbiting Juno spacecraft).

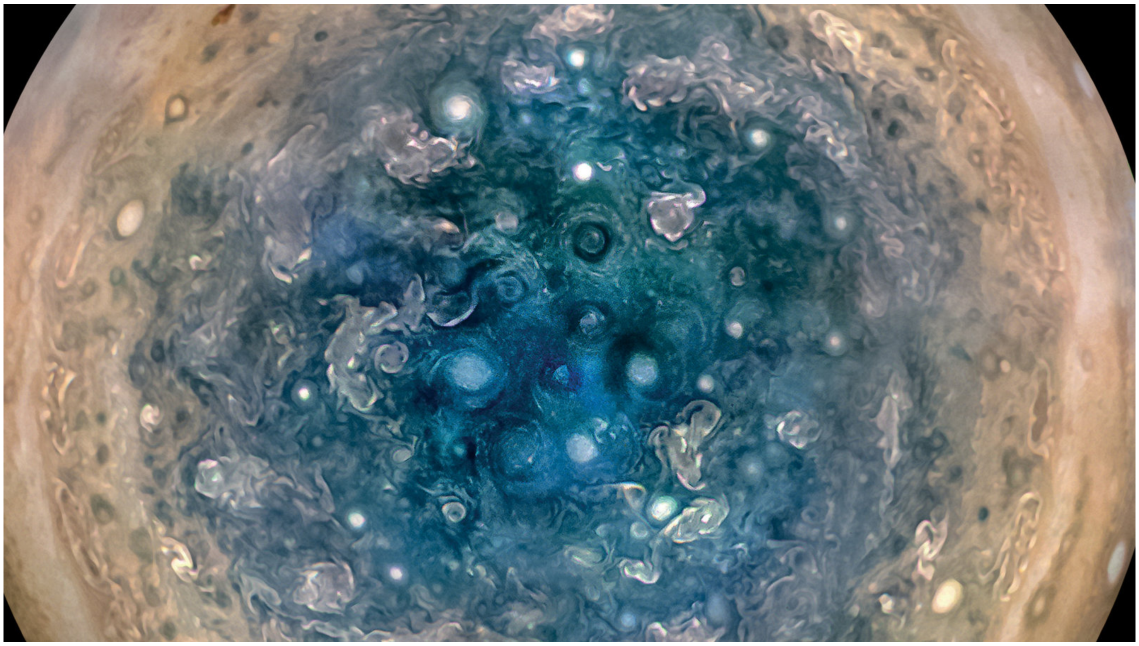

Figure 2: View over the south pole of Jupiter shows the many complex, swirling eddies produced by the strong deflecting Coriolis force at high latitudes. (Taken from the orbiting Juno spacecraft).

Key points to remember:

- In the **northern hemisphere** of a planet rotating from west to east (such as the Earth), the direction of the Coriolis force acts perpendicularly (90°) to the **RIGHT** of the direction of fluid flow.
- In the **southern hemisphere** of a planet rotating from west to east (such as the Earth), the direction of the Coriolis force acts perpendicularly (90°) to the **LEFT** of the direction of fluid flow.

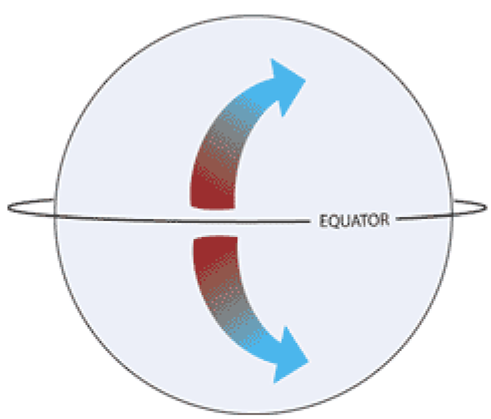

Figure 3: Fluids (such as the movement of air) deflect to the right in the northern hemisphere. In the southern hemisphere, they deflect toward the left.

Activity 1 - Low pressure (cyclones) and high pressure (anticyclone) systems:

High pressure:

Regions of high atmospheric pressure are places where air is "piled up" and the atmosphere is thicker over that region of the Earth. Fluids (such as air) will tend to flow from regions of higher pressure to regions of lower pressure.

1. On the globe, draw a capital letter "H" (to represent the center of high pressure) at a location somewhere between Bermuda and the Azores in the Northern Atlantic Ocean (this is known as the **Bermuda-Azores High**, and is a relatively permanent feature of the planet). Knowing that this region is surrounded by a region of lower pressure, draw arrows from the "H" to represent how air would move **IF THE EARTH WERE <u>NOT</u> ROTATING.**

2. Now, erase your arrows, and re-draw them to represent how the air would actually flow (because the Earth is rotating, you will need to draw how they will deflect due to the Coriolis force acting on this air).

Low pressure:

Regions of low atmospheric pressure are places where air is "deficient" and the atmosphere is thinner over that region of the Earth. Fluids (such as air) will tend to flow from regions of higher pressure to regions of lower pressure. Therefore, winds will generally be in the direction of a region of high pressure to a region of low pressure.

1. On the globe, draw a capital letter "L" (to represent the center of low pressure) at a location somewhere near Iceland (this is known as the **Icelandic Low**, and is also a relatively permanent feature of the planet). Knowing this region is surrounded by a region of higher pressure, draw arrows toward the "L" to represent how air would move **IF THE EARTH WERE <u>NOT</u> ROTATING.**

2. Now, erase your arrows, and re-draw them to represent how the air would actually flow (because the Earth is rotating, you will need to draw how they will deflect due to the Coriolis force acting on this air).

Do you notice something strange about this one? What happens as the arrows get closer to the "L"? Will they eventually converge on the "L" or will they be deflected away from the "L" before they even get there?

How might the sum of all of these deflections cause the air immediately surrounding the "L" to rotate? In which direction (clockwise or counterclockwise) would that air start to rotate? Is this the same as or different from the rotation of air surrounding a "H"?

Activity 2 - Planetary wind patterns

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 4).

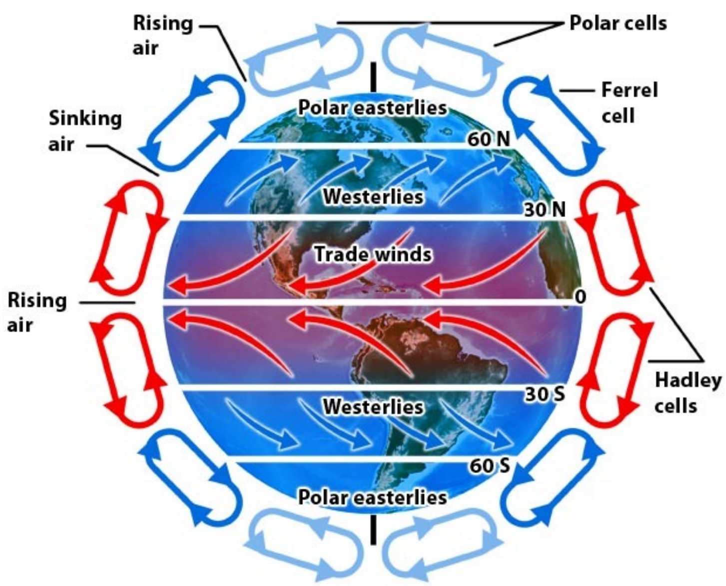

Figure 4: Earth's convective cells (represented by loops of air currents). Each hemisphere contains three convective cells that encircle it (called the Hadley, Ferrel, and Polar cell). The driving force for this circulation of air is the uneven heating of the Earth's surface by the Sun.

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 0° and 30° 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?

Ferrel cell:

At about 30° 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 30° and 60° N and S latitude.

1. On the globe, draw arrows representing the surface wind direction between 30° and 60° 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**.

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 60° and 90° 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 **polar easterlies**.

Follow-up questions:

Massive tropical storms have incredibly low pressures as their centers. Their paths are steered by the prevailing winds at their particular latitude. Depending on their geographic location, they go by different names (hurricanes, typhoons, or cyclones). See Figure 5 below:

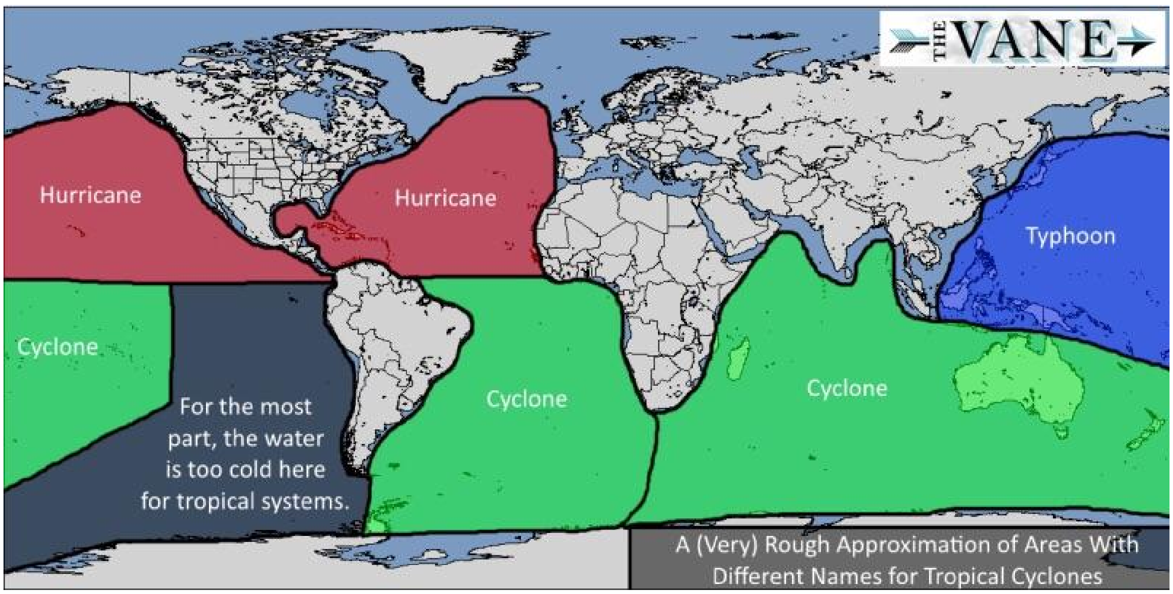

Figure 5: Map of tropical storm classification names.

1. Hurricanes that form in the North Atlantic often form off the west coast of Africa (near Cape Verde). Using your exploration from the previous activity, which winds do you think are responsible for steering these hurricanes toward the east coast of the United States?

2. Often, these North Atlantic hurricanes will begin to shift their track toward the north, and then toward the northeast as they approach the Caribbean and east coast of the United States. What winds are responsible for this rapid reversal in the hurricane's path?

3. In which direction (clockwise or counterclockwise) would a hurricane or typhoon rotate? (Use the map in Figure 5 to help you).

4. In which direction (clockwise or counterclockwise) would a cyclone rotate? (Use the map in Figure 5 to help you).

5. Lower central pressures of tropical storms mean there is a larger pressure gradient between the storm's center and the surrounding atmosphere. This larger pressure gradient results in faster winds. Using your knowledge of the physical parameters governing the strength of the Coriolis force, would a tropical storm with a lower central pressure spin faster or slower compared to a similar storm with a higher central pressure? Which storm would experience the greater Coriolis force acting on it?

6. **Myth alert!!** It has been said that when toilets flush in the northern hemisphere, the water goes down the bowl in a counterclockwise direction (and the opposite direction in the southern hemisphere). However, **this is a myth!!** Using the equation for the Coriolis force, explain why there is simply not enough of an effect of the Earth's rotation on the water in a toilet bowl. (Think about the physical parameters that govern the strength of the Coriolis force).

7. On a planet such as Venus, which rotates in the **opposite direction of the Earth** (east to west), which direction (right or left) would the Coriolis force deflect the winds in the northern hemisphere? What about in the southern hemisphere? Is this similar to or different from the effects observed on Earth?

8. **Critical thinking questions:**

    a. If the Earth did not rotate, would there be any tropical storms? If so, how would they move (would they move?)

    b. If the Earth did not rotate, how would our daily weather be affected? As a reminder, weather systems move across the United States (from west to east), producing repeating patterns of atmospheric changes in our weather over time. How might this change?

    c. On a planet such as Uranus, where its axis of rotation is tilted at 98^{o} to the plane of its orbit (compared to Earth's 23.5^{o}), would this high degree of tilt have an effect on the Coriolis force present in the atmosphere of Uranus? (To help you answer this question, reference the Coriolis force equation).