

Traveling on a Rotating Sphere

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http://earthobservatory.nasa.gov/Newsroom/BlueMarble/BlueMarble_2002.html

Lesson Objectives	Performance Tasks
To demonstrate an understanding of convection.	Using a model of heating water on a stove, propose an explanation for the behavior of the movement of water. Predict how this applies to fluids moving on or near Earth's surface.
To demonstrate an understanding of how a rotating sphere affects speed at different locations on its surface.	Observe an animation of the rotating Earth and draw conclusions about the speed of objects at different latitudes.
To demonstrate an understanding of how motion appears to be affected by the rotating motion of a sphere.	Predict the effect of rotation on objects launched North/South, East/West in both the Northern and Southern Hemisphere.
To demonstrate an understanding of the Coriolis force and how it affects the trade winds.	Use an online visualizer to generate trajectories on the surface of a smooth Earth-like sphere. Judge if each trajectory follows Coriolis's rules.
To demonstrate an understanding of how the Coriolis force varies with latitude.	Use the online visualizer to generate trajectories on the surface of a smooth Earth-like sphere. Find the pattern of change in the strength of the Coriolis force with latitude.

Materials:

Student Guide (PDF)
 Internet access
 Computer, Web browser

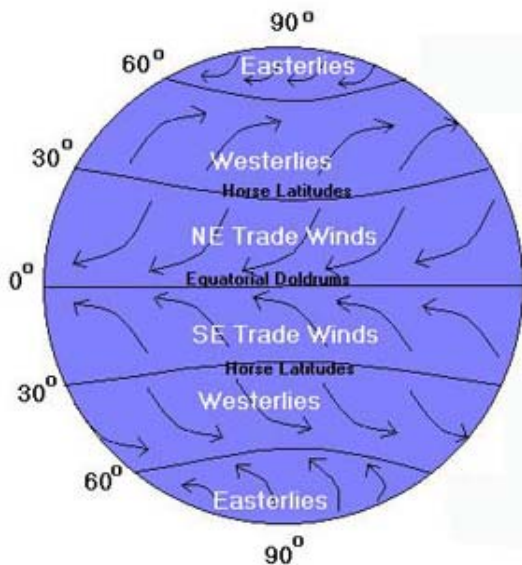
Grade Level: Levels 1 & 2, high school

Number of Pages: 14

Courses supported: Earth Science, Physics, Math

Glossary: convection, Coriolis force, El Niño, Equator, Hadley cell, latitude, and trade winds

Introduction: Spin-offs On A Rotating Sphere



The ocean and atmosphere are in constant motion. Powered by the Sun and a rotating Earth, their interactions play a critical role in shaping weather and climate. Natural variations in winds, currents, and ocean temperatures can temporarily affect weather patterns. For example, an **El Niño** event may develop when the trade winds diminish. The trade winds affect ocean travel both today and in the past by aiding early explorers and merchants traveling from Europe to the Americas. The **trade winds** are a pattern of wind found in bands around Earth's equatorial region. They are the prevailing winds in the tropics, blowing from the high-pressure area in the horse latitudes towards the low-pressure area around the Equator. The constancy of the trade winds makes them important phenomena to study. What causes these winds near the Equator and who developed the concepts that explain them?

Dr. Pamela J. W. Gore, Georgia Perimeter College

Lesson 2 will guide you through the history of scientists such as George Hadley, Edmond Halley and Gaspard-Gustave de Coriolis, who developed the early theories that explain the forces powering the trade winds and their effect on ocean surface currents. Computer models, found in this lesson, will help you understand these forces that influence the **weather** and **climate** that you experience everyday.

Engage: Preconceptions Survey, "What Do You Know?"

Quiz

Students are asked to take an online consisting of nine questions. When they submit their responses online, a pop-up window appears that shows the correct response to each question and provides additional, clarifying information for all nine questions. The correct responses, and additional information are provided below.

Engagement activities such as this are typically *not graded*.

True or False	Statement
1 <input type="checkbox"/> FALSE	Viewed from above the North Pole, Earth rotates in a clockwise direction. <i>False. The Sun appears to move in the sky from east to west. This implies that Earth rotates counterclockwise when viewed from above the North Pole.</i>
2 <input type="checkbox"/> FALSE	Due to Earth's rotation, a person at the equator is moving about 110 miles per hour faster than a person standing at the poles. <i>False. Earth's circumference (distance around the Earth) at the Equator is 24902 mi/40076 km. Due to rotation motion; a person at the Equator moves this distance during 1 day (24 hours). So a person at the equator has a speed of $24902/24 = 1037$ mph (or $40076/24 = 1670$ km/hr).</i>
3 <input type="checkbox"/> TRUE	Earth's rotation affects the shape of Earth. <i>True. Earth's shape is close to that of an oblate spheroid - not exactly a perfect sphere. Its diameter is slightly larger at the equator (42 km) than at the poles. A mass on the surface of Earth experiences the force of gravity directed towards Earth's center and a centripetal acceleration directed perpendicular to Earth's rotation axis. To see a similar effect, fill a bucket with water and spin the bucket on a rotating table (or suspend the bucket with a twisted rope).</i>
4 <input type="checkbox"/> FALSE	Earth's climate does not affect the shape of Earth. <i>False. Climate events like El Nino-Southern Oscillation and the Pacific Decadal Oscillation affect weather and the way water is distributed on continents and in the ocean and atmosphere globally. Using NASA satellite laser ranging measurements, scientists connected El Nino-Southern Oscillation occurrences to bulges at the equator. This bulging also caused a slight change in the length of the day. Increasing the size of the bulge at the equator will slow Earth's rotation. This effect is similar to spinning ice skaters. They spin faster, when their arms move close to the rotation axis and slow down when their arms are extended.</i>
5 <input type="checkbox"/> FALSE	If Earth stopped rotating on its axis, life on Earth would not be affected much. <i>False. Since much of the water, air, landforms and human-built structures are rotating at a fairly high speed, a quick stop in Earth's rotation would have disastrous consequences. Even a gradual slowing to no rotation would have major consequences rendering Earth uninhabitable. The duration of a day would become the same as that of our year. Everyone would experience one period of darkness (night) and one period of sunlight (day) during the year (instead of 365 days and 365 nights). Earth's magnetic field, which is due to iron rotating in Earth's core, would weaken. This weakened field would no longer deflect dangerous particle radiation from the Sun as effectively as now.</i>

True or False	Statement
<p>6</p> <p>TRUE <input type="button" value="v"/></p>	<p>Measured by a bathroom scale, a person weighs less at the equator than at the poles. <i>True. A mass on the surface of Earth experiences the force of gravity directed towards Earth's center and a centripetal acceleration directed perpendicular to Earth's rotation axis. The downward vertical component of this acceleration causes you to weigh less. Try weighing yourself on an elevator accelerating downwards.</i></p>
<p>7</p> <p>FALSE <input type="button" value="v"/></p>	<p>The Earth's rotation has no effect on our weather. <i>False. Winds are primarily caused by solar heating. If solar heating were the only influence then prevailing winds would be from the north or the south. Earth's rotation has an effect of curving these winds in the east-west direction. Earth's rotation period of 24 hours means that most regions of Earth experience warming and cooling in a rapid cycle. If Earth stopped rotating, the length of a "day" would become the same as the year. Few existing species could adapt to a cycle of 6 months of sunlight then 6 months of darkness.</i></p>
<p>8</p> <p>TRUE <input type="button" value="v"/></p>	<p>Isaac Newton once predicted that an object dropped from a tower could demonstrate Earth's rotation. When dropped, the object should fall a little bit east of the tower base. <i>True. Due to the rotation motion, the top of the tower is traveling faster than the base of the tower. The Earth rotates from west to east. The speedier eastward moving object will fall slightly farther east than the tower base.</i></p>
<p>9</p> <p>FALSE <input type="button" value="v"/></p>	<p>Does the rotation of Earth determine the direction water rotates as it goes down the drain in your bathroom? <i>False. The direction (clockwise or counterclockwise) swirling motion that you observe in your bathtub, or toilet is largely determined by the random motion of water in the pool of water and not Earth's rotation. In a carefully controlled experiment (where random and other undesirable environmental effects are minimized by carefully constructing the pool shape and letting the water become still over several weeks time), water on the south side of a drain will be moving eastward faster than water on the north side (in the Northern Hemisphere). This will result in a counterclockwise swirling motion.</i></p>
<p>100</p>	<p>Overall Score (%)</p>

Explore: Heated Fluid Circulation

What drives the Trade Winds?

Heating fluids like air or water from beneath can make a fluid unstable. A warmed fluid becomes less dense and will rise opposite to the force of gravity. The cooler fluid above will move to replace the rising warm fluid and it will be warmed itself. This cycle repeats to mix the fluid. The process of convection describes motions in a fluid that result in the transport and mixing of the fluid properties. Suppose you heat a container of water on a stove burner.



1. What sort of motion happens in the water?

As the liquid on the bottom becomes hot, the water rises from the bottom of the pot to the top. This movement is called convection. It mixes the water so its temperature becomes more uniform.

2. Why does this kind of water motion occur?

The water on the bottom is heated directly by the stove burners so its temperature rises quickly compared to the cooler water above. The heated water has a lower density than the water above so the hot water moves up and the cooler water moves down.

3. Imagine now that you put the same pot of water into an oven with a top broiler (heat source above the water surface). How would you expect the water to move?

The top surface of the liquid is closest to the broiler and you would expect this surface to heat fastest. The temperature of this surface water would increase, the surface water's density would decrease and it would remain at the surface. The cooler, denser water below the surface would remain thermally isolated. In this case, heating causes more fluid stability. The warm surface water will not tend to mix with cooler water below.

4. Suppose you were asked to make a prediction about how water temperature in the ocean varies with the depth of the water. Which model – pot heated from the bottom or from the top – applies to the ocean? As you go deeper in the ocean, will the water become cooler or warmer? What effect will the temperature of the surface water have on the air above?

The ocean is heated from above by the Sun, so the model of the pot heated from above is correct. The surface water will not easily mix with the deeper cold water. Heat energy will accumulate at the surface. One can expect that the ocean water will become cooler with depth. Seawater is not transparent and so sunlight will not penetrate far below the surface. The warm surface water will heat the air above.



The Intertropical Convergence Zone, or ITCZ, is the region that circles Earth. Notice the band of bright white clouds in center of the image near the Equator, where the trade winds of the Northern and Southern Hemispheres come together. The intense sun and warm water

of the Equator heats the air in the ITCZ, raising its humidity and causing it to rise. As the air rises it cools, releasing the accumulated moisture in an almost perpetual series of thunderstorms. This image is a combination of cloud data from NOAA's Geostationary Operational Environmental Satellite (GOES-11) and color land cover classification data.

http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=4028

Explain: Where Do The Trade Winds Blow?

Who Developed The Early Theories About The Trade Winds?

The name, trade winds, derives from the Old English "trade", meaning path or track. The trade winds helped ensure that European sailing vessels, including those that [Columbus](#) sailed, reached North American shores.



Edmond Halley (1656-1742), pictured on the left, correctly understood the role of the Sun in atmospheric circulation. He reasoned that intense solar radiation heated the air near the Equator and caused it to expand and rise up. This rising air is replaced by cooler air converging on the Equator from the northern and southern hemispheres. Circulation of the air is driven by a pressure-gradient force, which causes high-pressure (cooler, more dense) air to move into regions of low-pressure (warmer, less dense) air. Under static conditions, fluids reach equilibrium when pressure is the same at each depth. His theory predicted a flow of air from the poles to the Equator where the air masses converge. But the explanation does not account for the steady westward flow.

George Hadley (1685-1768), was an English lawyer and amateur meteorologist, who first recognized the reason the trade winds, preferentially blow westward. His explanation depended on the fact that Earth is a rotating sphere and that sites on the surface of rotating sphere travel with different speeds (travel different distances in equal times).

Hadley earned fame by realizing that Earth's rotation played a crucial role in the direction taken by a moving airmass. He provided a description of the equatorial trade winds that was essentially correct.

Weather, which describes the current state of the atmosphere, normally fluctuates daily due to a complex interplay of forces and processes. Any steady or cyclic weather phenomena could be the result a dominating process. These phenomena provide opportunities to test scientific models and hypotheses. In the following pages you will work with the equations that help us understand how objects and air masses move on a rotating sphere.

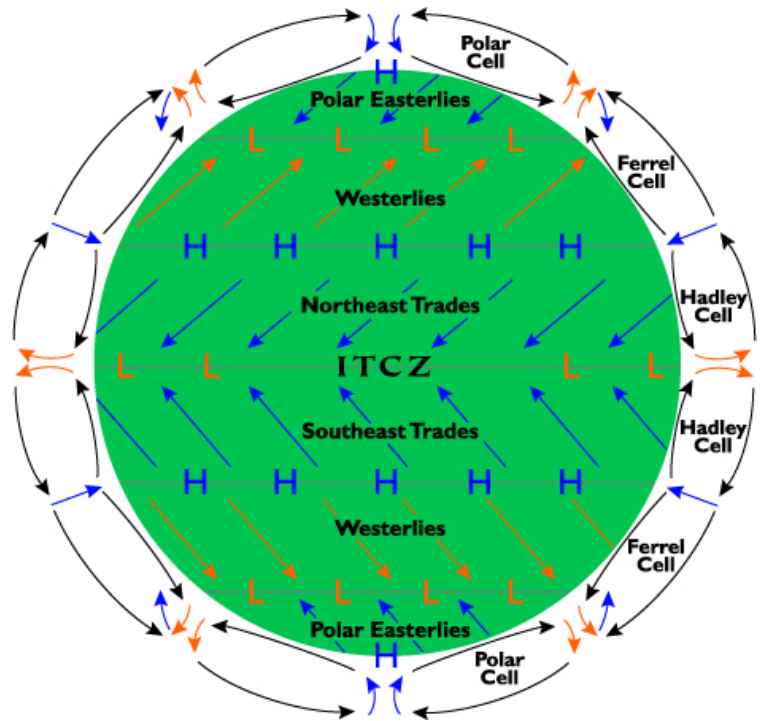
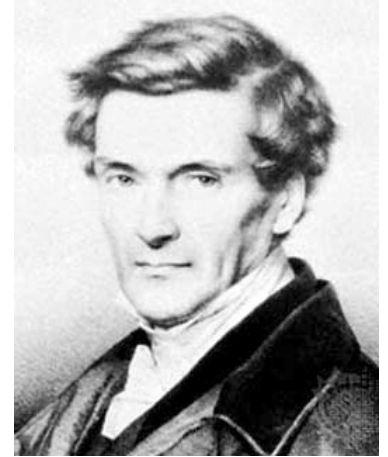


Illustration Credit: Tinka Sloss, New Media Studio, Inc.

Elaborate: Traveling On A Rotating Sphere

How Did Coriolis Use Math To Understand The Movement Of Objects on a Rotating Sphere?

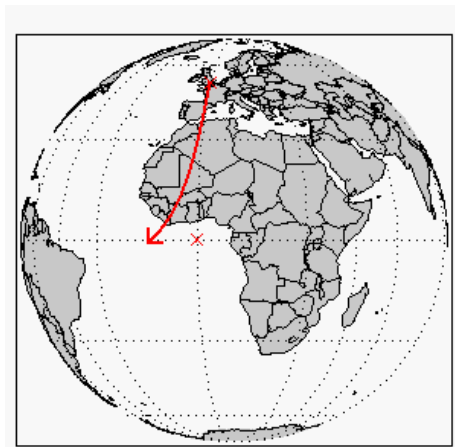
Gaspard-Gustave de Coriolis (1792-1843), pictured on the right, a French mathematician, mechanical engineer, and scientist, worked out the general formulas for motion of objects measured from rotating systems of coordinates. Coriolis was able to determine the following simple rules for the direction of moving objects on the surface of a rotating sphere, now known as the Coriolis effect:



- The apparent force (or Coriolis force) on moving objects on a rotating sphere is perpendicular to the velocity of the object and the rotation axis.
- A **balance of forces** cause objects traveling in the Northern Hemisphere curve to the right.
- A balance of forces cause objects traveling in the Southern Hemisphere to curve to the left.

5. Consider the speed at which Earth rotates at different locations. Click to see an animation of the [Rotating Earth](#) during the course of one day. Locate the following sites: a marked site on the Equator and London, England. Which site travels the greatest distance during one revolution (24 hours)? Which site has the greatest speed?

Both sites travel in a circle. The site located on the Equator travels the greater distance since the radius of its circle is larger. Both sites make one full revolution (rotation) in 24 hours. The site that moves the greater distance in 24 hours has the higher speed so the Equator site has the higher speed.



6. Imagine an object launched at a high-speed southward from London towards the equator. The object will have two components or parts to its velocity: a high-speed southward (meridional) launch velocity component and an eastward (zonal) velocity component due to the rotation of Earth. Comparing London with a location on the equator, which location has the higher eastward velocity component due to the Earth's rotation?

During the same 24 hours, London rotates through a smaller radius circle than a location on the equator so London has the slower eastward velocity component.

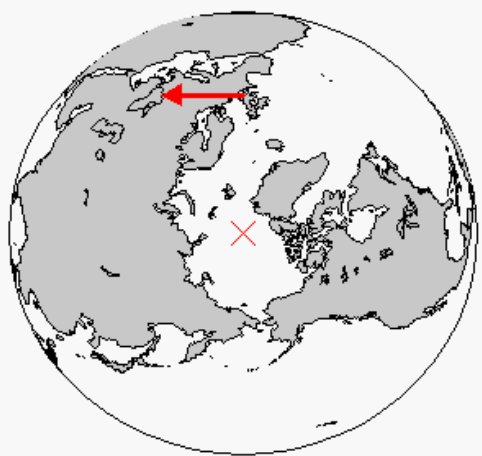
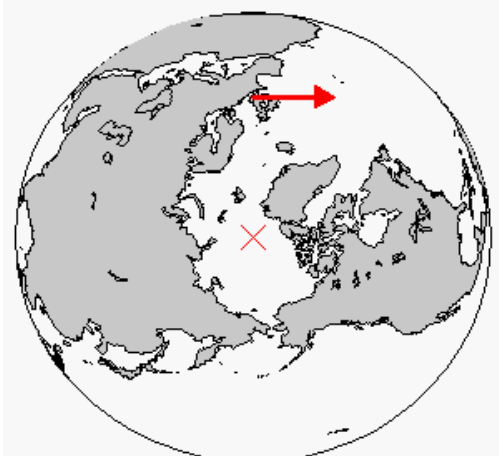
As the object travels southward from London, it will pass over regions of Earth that are moving faster eastward due to the rotation of Earth and the object will appear to fall behind the rotating surface below. This means that the object will appear to curve westward as shown in the figure (curving to the right as viewed by someone facing the direction of the object's motion).

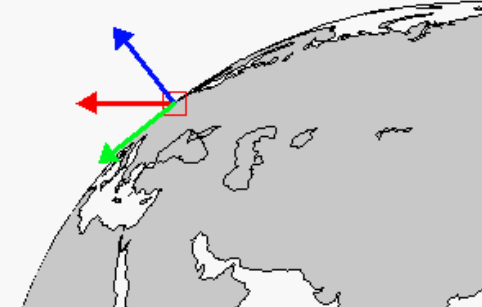
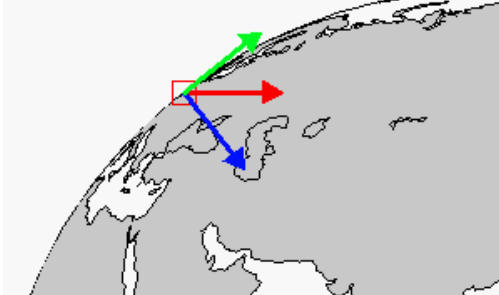
7. Imagine the same object launched northward from the [Equator](#). As it travels northward, it will pass over a surface that moves slower in an eastward direction. Will the object appear to follow a straight line? Curve to the left? Or curve to the right?

The object would be moving faster eastward than the surface below so it would curve eastward – curve to the right as seen facing in the direction of motion of the object.

You have studied the motion of an object launched in the Northern Hemisphere and have seen that the object appears to curve to the right as measured by observers rotating with Earth. You will create additional examples of motion in the Northern Hemisphere in the following investigations and will learn that each one follows the same rule: *In the Northern Hemisphere, moving objects appear to curve to the right on the rotating Earth.*

The case of objects launched directly eastward or westward requires special attention. Examine the following figures to verify that in both cases the object's trajectory follows the same rule.

North Pole View/Eastward Launch	North Pole View/Westward Launch
	
<p>Objects launched eastward from London will appear to curve outward as you rotate eastward with Earth.</p>	<p>Objects launched westward from London will appear to curve downward as you rotate eastward with Earth.</p>

Westward View/Eastward Launch	Westward View/Westward Launch
	
<p>In this view, the launched object (in the small red box) is moving eastward (towards you, out of the paper). It appears to curve outward (red arrow) as you rotate with the Earth after the launch. The object's apparent velocity in the plane of the paper (red arrow) has two components: an upward (blue) component and a southward (green) component. This southward component will cause the eastward-moving object's path bend southward.</p> <p>It follows the <i>curve right rule</i>.</p>	<p>In this view, the launched object (in the small red box) is moving westward (away from you, into the paper). It appears to curve towards the Earth's axis (red arrow) as you rotate with the Earth after the launch. The object's apparent velocity in the plane of the paper (red arrow) has two components: a downward (blue) component and a northward (green) component. This northward component will cause the westward-moving object's path bend northward.</p> <p>It follows the <i>curve right rule</i>.</p>

8. Imagine the same object traveling southward from the Equator. As it moves southward, it will pass over a surface that moves slower in an eastward direction. Will an object appear to follow a straight line? Curve to the left? Or curve to the right?

The object would be moving faster eastward than the surface so it would curve eastward – curve to the left as seen facing in the direction of motion of the air mass.

The general rules for moving objects on a rotating sphere are:

- **In the Northern Hemisphere, a balance of forces on the rotating Earth influence moving objects to curve right.**
- **In the Southern Hemisphere, a balance of forces on the rotating Earth influence moving objects to curve left.**

Elaborate: Sizing-up Inertial Circles (Oscillations) **Level 2, More Challenging**

The equations governing the magnitude (strength) of the Coriolis force, F_C , are:

$$F_C = m \cdot f \cdot v$$

$$f \equiv 2 \cdot \omega \cdot \sin(\phi)$$

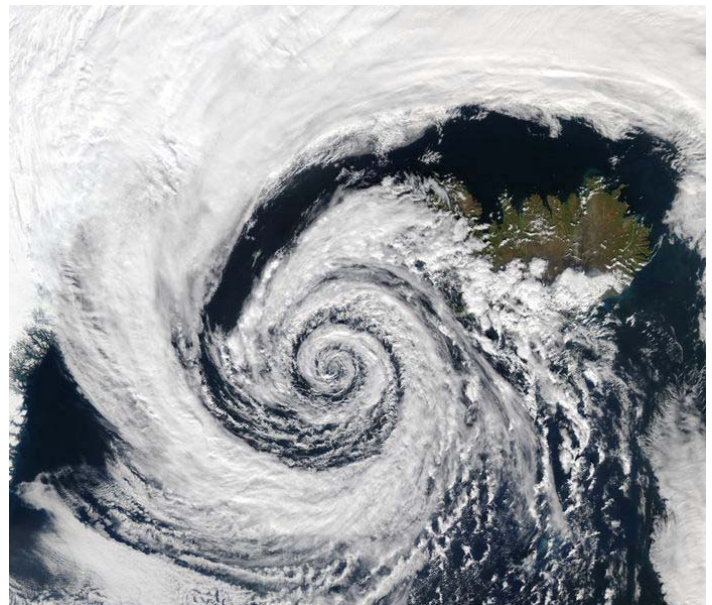
Where m is the mass of the object, v is the horizontal component of its velocity, ω is the rotational speed of the Earth (7.27×10^{-5} radians/second), f is the frequency of the motion and ϕ is the latitude of the moving object. Under the influence of the Coriolis force, objects follow curved, near-circular paths, called inertial circles. Their motions repeating patterns or inertial oscillations that repeat with a frequency, f , during a time period $T=1/f$. The radius of the Coriolis inertial circle is:

$$R = \frac{v}{f}$$

The Coriolis force is evident in swirling vortex weather patterns (like hurricanes), leading to a counter-clockwise rotation in the Northern Hemisphere and a clockwise rotation on the Southern Hemisphere.

An example, right, is the beautifully formed low-pressure system swirling off the southwestern coast of Iceland. Because this low-pressure system occurred in the Northern Hemisphere, the winds spun in toward the center of the low-pressure system in a counter-clockwise direction.

The Aqua MODIS instrument took the image on September 4, 2003.



9. Use the formulas in the table below, to estimate the frequency of the inertial oscillations and the size of the inertial circles at several latitudes. Do this for both air currents (typical wind speed 10 m/s) and ocean currents (typical ocean current 0.2 m/s). Once you have found the frequency for the latitude, use that number (f in the equation) to find the radius of the inertial circle. Compute the missing values in the following table:

Latitude (ϕ , degrees)	Frequency, f $f=2(7.27 \times 10^{-5})\sin(\phi)$	Current Fluid	Speed (m/s)	Inertial Circle Radius $R=v/f$ (m)
20	4.97×10^{-5}	Air	10	2.01×10^5
20	4.97×10^{-5}	Water	.2	4.02×10^3
50	1.11×10^{-4}	Air	10	9.01×10^4
50	1.11×10^{-4}	Water	.2	1.80×10^3
80	1.43×10^{-4}	Air	10	6.99×10^4
80	1.43×10^{-4}	Water	.2	1.40×10^3

Explore: Take A Spin With The Coriolis Model

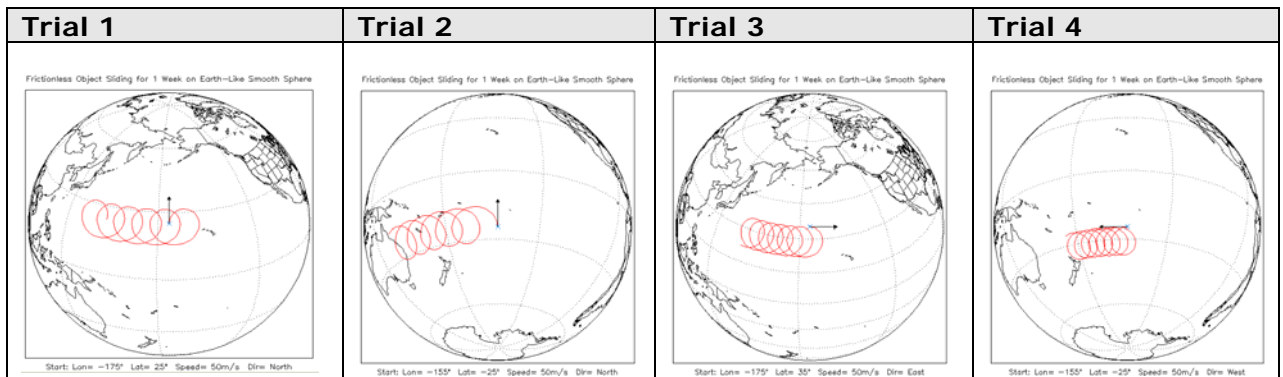
To help you better understand the Coriolis forces on a rotating sphere, a Coriolis Model has been provided to simulate the motion of an object sliding without friction on a sphere with the same size and rotational speed as Earth. The object is allowed to slide freely for 7 days and you are allowed to set the object's starting velocity (speed and direction) and position.

Click on the hypertext word [Coriolis Model](#) to open a new window containing the model. Complete the following four trials to determine if the trajectory follows the two Coriolis Rules—illustrated below. For each trial:

- First, Select the object's starting direction and starting speed from the drop down menus.
- Second, click on the map at a site in the hemisphere indicated in the table below.
- A pop-up window will appear showing the trajectory of the object tracked over a 1-week time period.

10. Next, use the following table to make your model settings. Click the map over the ocean at the correct starting latitude and decide if the trajectory follows our curvature rules for the Northern and Southern Hemispheres. Put your answer in the table below.

Coriolis Model Initial Settings				Your Analysis of the Trajectory	
Trial	Starting Speed (m/sec)	Starting Direction	Starting Latitude	Trajectory Follows Rules	Direction Trajectory Curves
1	50	North	+30° Northern Hemisphere	Yes	Right
2	50	North	-30° Southern Hemisphere	Yes	Left
3	50	East	+30° Northern Hemisphere	Yes	Right
4	50	West	-30° Southern Hemisphere	Yes	Left

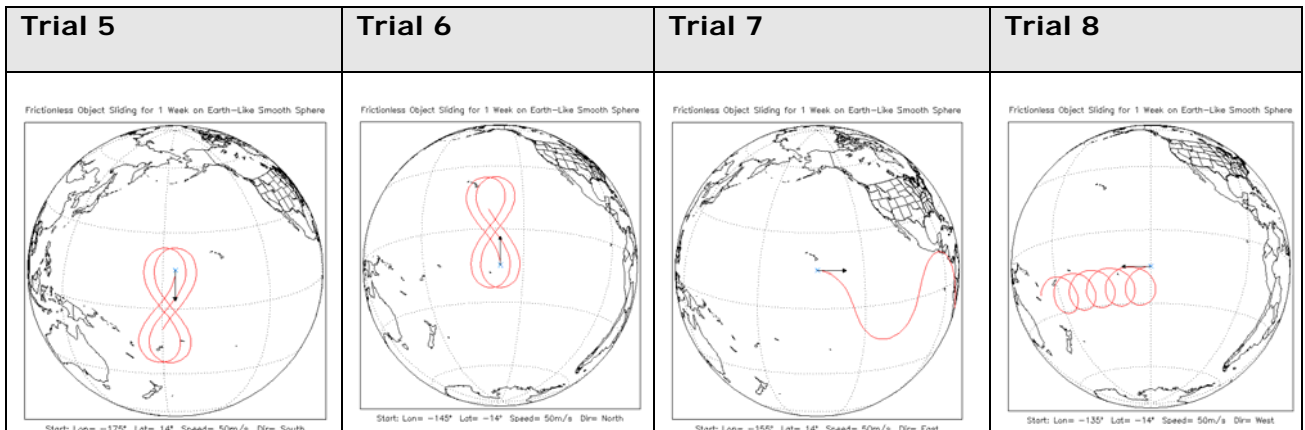


11. The Equator is the dividing line for the two rules that apply to moving objects. What might happen if an object is launched in either hemisphere but crosses over the equator during its trajectory?

12. To test your understanding, make a prediction of what will happen to an object when it is launched in the manner specified in each row of the following table. Check your predictions using the Coriolis Accelerated Motion [visualizer](#).

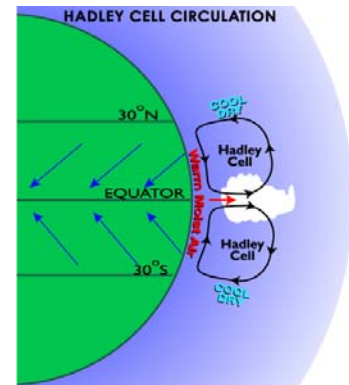
Trial	Starting Speed (m/sec)	Starting Direction	Starting Location	Predicted Trajectory if object crosses Equator	Does your prediction agree or disagree with visualizer?
5	50	South	15° North	<i>The object is launched towards the Equator. Above the Equator it should curve to the right. After it crosses the Equator it will curve left.</i>	<i>Agrees</i>

Trial	Starting Speed (m/sec)	Starting Direction	Starting Location	Predicted Trajectory if object crosses Equator	Does your prediction agree or disagree with visualizer?
6	50	North	15° South	<i>The object is launched towards the Equator. Below the Equator it should curve to the left. After it crosses the Equator it will curve right.</i>	<i>Agrees</i>
7	50	East	15° North	<i>The object is launched eastward near the equator. Above the Equator it should curve to the right. After it crosses the Equator it should curve left.</i>	<i>Agrees</i>
8	50	West	15° South	<i>The object is launched near the Equator. Below the Equator it should curve to the left. After it crosses the Equator it should curve right.</i>	<i>Agrees</i>



As discussed previously in this lesson, the trade winds are driven by heated, light air at the Equator rising up and drawing in cooler surface air slightly north and south of the Equator.

It should be clear from the trajectories in trial 5 and trial 6 that air rushing towards the Equator will curve towards the west whether the air comes from the north or south. This creates a pattern of easterly winds (winds blowing from the east) at the Equator. Note that the air masses from the north and south will collide at the Equator and that interaction will strengthen the equatorial wind pattern. The computer model you have been using models a sliding object freely moving over a smooth Earth-sized sphere with nothing blocking its path as it slides above or below the Equator. This is not the case for the air in the atmosphere. The air rushing to the Equator will be driven further in the westward direction by the converging air masses and will not significantly cross the Equator.



Tinka Sloss, NewMedia Studio, Inc.

13. Next, use the [Coriolis Model](#) to do a study of how the Coriolis force varies with latitude. You will use the computer model to launch objects at various latitudes. By observing the curvature of the trajectory, you can estimate the relative strength of the deflecting force: strongly deflecting forces result in small, tight circular paths, weakly deflecting forces result on large circular paths. As we have seen, these near-circular paths are called inertial circles and the frequency of rotation, f , and the speed, v , determine the radius of the circle:

$$\text{Radius} = \frac{\text{speed}}{\text{frequency}} = \frac{v}{f}$$

On a rotating planet, the frequency increases with latitude, ϕ :

$$f = 2 \cdot (7.292 \times 10^{-5}) \cdot \sin(\phi)$$

These equations predict that, for constant speed, the radius of a moving object trajectory should decrease with latitude.

14. Fill in the following table and draw a conclusion about how the Coriolis force varies with latitude. Indicate your estimates of radius and force, use the subjective relative scale: small/weak, medium, or large/strong.

Note: The speed of the object is kept constant. In this case, the radius and acceleration are inversely proportional (large R gives a small A; small R gives a large A):

Starting Position	Starting Speed (m/sec)	Starting Direction	Radius of Curvature of Trajectory (small, medium, large)	Coriolis Force (small, medium, large)
85 N	50	East	<i>Small</i>	<i>Large</i>
45 N	50	East	<i>Medium</i>	<i>Medium</i>
15 N	50	East	<i>Large</i>	<i>Small</i>
15 S	50	East	<i>Large</i>	<i>Small</i>
45 S	50	East	<i>Medium</i>	<i>Medium</i>
85 S	50	East	<i>Small</i>	<i>Large</i>

15. What do you conclude about the effect of latitude on the Coriolis acceleration?
The Coriolis force increases at higher latitudes.

Elaborate: Additional Investigations for the Coriolis Force and Travel

How does the Coriolis force impact travel on a rotating sphere?

Do airline pilots need to consider the Coriolis force when making their flight plan?

Do ship captains need to consider the Coriolis force when charting their course?

Evaluation: Matrix for Grading Lesson 2

4 Expert	Responses show an in-depth understanding of models and explorations used to explain scientific concepts and processes used in the lesson. Proficient manipulation of computer models. Data collection and analysis of data are complete and accurate. Predictions and follow through with accuracy of predictions are explained and fully supported with relevant data and examples.
3 Proficient	Responses show a solid understanding of models and explorations used to explain scientific concepts and processes used in the lesson. Mostly proficient manipulation of computer models. Data collection and analysis of data are mostly complete and accurate. Predictions and follow through with accuracy of predictions are explained and mostly supported with relevant data and examples.
2 Emergent	Responses show a partial understanding of models and explorations used to explain scientific concepts and processes used in the lesson. Some proficiency in manipulation of computer models. Data collection and analysis of data are partially complete and sometimes accurate. Predictions and follow through with accuracy of predictions are sometimes explained and supported with relevant data and examples.
1 Novice	Responses show a very limited understanding of models used to explain scientific concepts and processes used in the lesson. Little or no ability shown to manipulate computer models. Data collection and analysis of data are partially complete and sometimes accurate. Predictions and follow through with accuracy of predictions are not well explained and are not supported with relevant data and examples.