CORIOLIS EFFECT:

BECAUSE THE EARTH TURNS

TEACHER'S GUIDE

Project ATMOSPHERE

This guide is one of a series produced by Project ATMOSPHERE, an initiative of the American Meteorological Society. Project ATMOSPHERE has created and trained a network of resource agents who provide nationwide leadership in precollege atmospheric environment education. To support these agents in their teacher training, Project ATMOSPHERE develops and produces teacher's guides and other educational materials.

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Foreword

This guide has been prepared to introduce fundamental understandings about the guide topic. This guide is organized as follows:

Introduction

This is a narrative summary of background information to introduce the topic.

Basic Understandings

Basic understandings are statements of principles, concepts, and information. The basic understandings represent material to be mastered by the learner, and can be especially helpful in devising learning activities in writing learning objectives and test items. They are numbered so they can be keyed with activities, objectives and test items.

Activities

These are related investigations. Each activity typically provides learning objectives, directions useful for presenting and completing the activity and questions designed to reinforce the learning objectives.

Information Sources

A brief list of references related to the guide topic is given for further study.

Introduction: The Coriolis Effect

The Earth's atmosphere and ocean exhibit numerous instances of horizontal motions along curved paths. Near-surface winds spiral into low-pressure areas and out of high-pressure areas. Ocean currents flow in huge almost circular gyres thousands of kilometers across. Other objects, including planes and boats, freely moving horizontally almost everywhere on Earth (except at the equator) turn right or left. The turning of these moving object's paths as seen from our vantage point on Earth is the ***Coriolis effect***.

Why does this curved motion occur? Aren't objects that are moving "freely" (unconstrained) in horizontal directions supposed to move in straight paths? As described by Sir Isaac Newton's First Law of Motion, an object in motion should remain in motion in a straight line, unless acted upon by an outside force. But, there is no horizontal force acting on an object moving freely across the Earth's surface to cause it to turn right or left. Yet, except at the equator, the moving object is apparently deflected. If there is no horizontal force acting to make this happen, there must be another explanation. There is! Earth is turning underneath the moving object, that is, Earth rotates.

All motion must be measured with respect to something, and Earth is our *frame of reference*. Earth is so immense that we usually think of it as being stationary. That is why objects moving horizontally and freely appear to turn to the right or left. Actually, it is Earth that is doing the turning underneath as the object moves forward.

The effect of Earth's rotation on horizontally moving objects is greatest at the poles. The Coriolis deflection decreases as latitude decreases, until it is zero at the equator. In the Northern Hemisphere, the sense of Earth's rotation is counterclockwise as seen from above the North Pole. Consequently, moving objects always appear to turn rightward in the Northern Hemisphere. The reverse happens in the Southern Hemisphere because of the clockwise sense of our planet's rotation when looking down from above the South Pole. There, horizontally moving objects turn toward the left.

Scientists account for the Coriolis effect by inventing an imaginary force called the Coriolis force. This Coriolis force is applied in combination with real forces such as the pressure gradient force and friction to explain motions of objects in terms of Newton's laws. The Coriolis force is defined as always acting perpendicular to the direction of motion; to the right in the Northern Hemisphere to explain rightward turning, and to the left in the Southern Hemisphere to describe leftward turning. It is all necessary because Earth turns!

Basic Understandings

Motion

1. *Motion* describes the continuous change of location of an object.

2. All motion is relative, that is, motion must be measured from a frame of reference. Most of the time we use Earth as our frame of reference, such as when we measure the speed of a car. But persons walking in a traveling airliner, ship, or train car use the airliner, ship or train as their frame of reference.

3. The term *speed* describes how fast an object is moving. Speed is the magnitude of motion. Motion can be described fully by indicating both speed and direction. Such fully described motion is called *velocity*.

4. Motion results from forces (pushes or pulls) acting on an object. Sir Isaac Newton studied motion and devised basic laws to describe his findings. His first law indicates that an object at rest tends to stay at rest and a moving object travels in a straight line at a constant speed, unless acted upon by an outside force. Another of his laws describes how an outside force can speed up or slow down the object, or it can change the direction of the object's motion.

Horizontal Motion on the Earth

5. Objects moving horizontally and freely (unconstrained and not being acted upon by an outside horizontal force) across the surface of the Earth **at the equator** follow paths that are straight relative to Earth's surface, as described by Newton's First Law of Motion.

6. Objects moving horizontally and freely across the surface of the Earth **everywhere <u>except</u> at the equator** follow paths that are curved as measured from Earth. In the Northern Hemisphere, they turn towards the right of the direction of motion and in the Southern Hemisphere they turn left. This deflection is called the ***Coriolis effect***, after Gaspard Gustave de Coriolis.

7. The observed Coriolis effect arises because the Earth is rotating, and in non-equatorial locations, is actually turning underneath as a horizontally and freely moving object travels forward. Because the motion is being measured relative to Earth, the motion appears to be along a curved path.

8. Anywhere in the Northern Hemisphere, the sense of Earth's rotation is counterclockwise as seen from above the North Pole. Consequently, the observed curved motion is always to the right of the direction of motion.

9. Anywhere in the Southern Hemisphere, the sense of the Earth's rotation is clockwise as seen from above the South Pole. Consequently, the observed curved motion is always to the left of the direction of motion.

10. Because there is no turning of the surface of the Earth (sense of rotation) underneath a horizontally and freely moving object at the equator, there is no curving of the object's path as measured relative to Earth's surface. The object's path is straight, that is, there is no Coriolis effect.

11. Earth's rotational effects on horizontally and freely moving objects are greatest at the poles; therefore, the Coriolis effect is greatest at the poles.

12. As the latitude at which horizontally and freely moving objects are located decreases, the twisting of the underlying Earth's surface due to the planet's rotation decreases. That is, the Coriolis effect decreases as the latitude decreases. It is maximum at the poles and absent at the equator.

Coriolis Force

13. The Coriolis effect arises because motion is being measured from a rotating frame of reference. There are no outside forces acting on a horizontally moving object that causes the observed curved motion.

14. Scientists have invented an imaginary force, called the *Coriolis force*, to account for the Coriolis effect. This has been done so that Newton's Laws of Motion can be used to explain movements measured relative to Earth's surface.

15. The Coriolis force is defined as always acting perpendicular to the direction of motion. Because the sense of Earth's rotation as seen from above in the Northern Hemisphere is opposite to that in the Southern Hemisphere, it is further defined as always acting to the right in the Northern Hemisphere and always to the left in the Southern Hemisphere.

16. The Coriolis force is also defined as being directly proportional to the sine of the latitude to account for the increasing curvature of paths as latitude increases. The trigonometric function *sine* is zero at an angle of 0 degrees (equatorial latitude) and 1 (maximum) at an angle of 90 degrees (polar latitude).

Atmospheric and Oceanic Applications

17. Horizontally moving air in the Northern Hemisphere is continually pulled to the right of the direction of motion by the Coriolis force. This causes air being acted on by horizontal pressure forces to turn rightward rather than flowing directly towards lowest pressure. Around low-pressure centers, the combination of forces produces counterclockwise circulation patterns as seen from above. Around high-pressure centers, the outward flowing air is also forced rightward, producing a clockwise circulation.

18. The role of the Coriolis effect is of increasing importance as the distance over which it acts increases. The Coriolis effect is negligible in very small-scale motions such as water swirling down a drain. Broader-scale storm systems, including the wave cyclones of the midlatitudes and hurricanes, have circulations with Coriolis force components. These systems cannot exist at the equator and cannot cross between the Northern and Southern Hemispheres because they cannot exist without the Coriolis effect.

19. In the Southern Hemisphere, the continuous leftward pull of the Coriolis force produces clockwise circulation around low-pressure centers and counterclockwise patterns around high-pressure centers.

20. On a global scale, the Coriolis force contributes towards the maintenance of the wind belts and upper air circulations, including jet streams.

21. Surface water set in motion by the wind is deflected by the Coriolis effect, flowing to the right of the wind in the Northern Hemisphere and to the left in the Southern Hemisphere.

22. Driven by prevailing winds, large roughly circular current systems, called gyres, circulate clockwise as seen from above in the mid-latitude ocean basins of the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

23. Moving surface water acts on water below, which is further deflected by the Coriolis effect. That water acts on the water below it, which is deflected even more. The overall result is that the net transport of water over the wind-driven column is 90 degrees to the right of the wind direction in the Northern Hemisphere and to the left in the Southern Hemisphere. This is called Ekman transport.

24. Winds blowing parallel to coasts can transport surface water towards or away from the shore, depending on wind direction, coastal orientation, and hemisphere (which determines the direction the Coriolis force acts). Where winds move surface water away from shore, cold water rises to the surface. This process is called upwelling.

25. In estuaries, the Coriolis effect tends to swing the incoming tidal flow and the seaward flowing river water to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. This results in a higher concentration of inflowing seawater on one side of the estuary and fresh river water outflow on the other side.

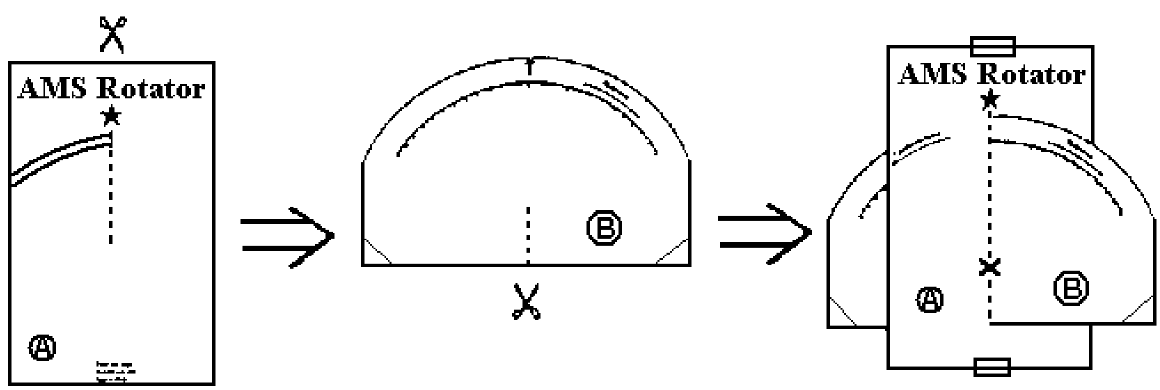
Activity: Because the Earth Turns

Introduction: Almost everywhere on Earth (except at the equator), objects moving horizontally and freely (unconstrained) across Earth's surface travel in curved paths. Planes, boats, bullets, air and water parcels, and other objects turn right or left as seen from our vantage point on Earth. This activity investigates the reason for this turning, a phenomenon known as the *Coriolis effect*.

Inquiry-Based Approach: This teacher enhancement activity provides a learning experience on fundamental understandings underlying the Coriolis effect. The goal is to provide teachers with a knowledge base enabling them to guide students in scientifically authentic learning experiences. The teacher is encouraged to employ the *constructivist* model of inquiry by introducing the activity in the classroom after (a) students have been confronted with, discussed, and posed questions relating to some of the effects of the Earth's rotation on moving objects and on the atmosphere and the ocean, and (b) the teacher has determined the appropriateness of the activity in stimulating student thinking, questioning, and scientific inquiry.

Materials: Photocopy of ***AMS Rotator*** sheet, scissors, tape, pencil

Directions: First construct the ***AMS Rotator***. Cut out the two large pieces, labeled **A** and **B** plus the "straight-edge." Cut along the dashed lines on **A** and **B** only as far as the dots. Fit **A** and **B** together as shown in the drawing, making sure that the dot on **A** coincides with the dot on **B**. Lay the device flat on the desk in front of you with the cut end of **A** positioned away from you. Now tape **A** to your desk at the two places indicated at the midpoints of the far and near edges of **A**, making sure that **B** can rotate freely. Fold up the bottom two corners of **B** as shown. Gripping these tabs, practice rotating **B** so that the two dots always coincide. Note that a *straight scale* is drawn on **A** along the cut-edge and a *curved scale* is drawn on **B**.



Investigations:

1. Orient **B** in the "cross" position as shown in the drawing. If positioned properly, a straight arrow should point towards the ★. Place your pencil point at the center of the S*tart Position* **X**. Carefully draw a line on **B** along the cut-edge and directly towards the ★. The line you drew represents a path that is **[(*straight*)(*curved*)]**.

2. Now investigate how rotation affects the path of your pencil lines. Again begin with **B** in the "cross" position with the direction arrow pointing towards the ★. Pulling the lower left tab towards you, rotate **B** counterclockwise through one division of the *curved scale* (on **B**). Make a pencil dot on **B** along the *straight scale* at one scale division above the *Start Position* **X**. Continue rotating **B** counterclockwise one division at a time along the *curved scale*, stopping each time to mark a pencil dot on **B** at each successive division along the *straight scale*. Repeat these steps until you reach the *curved scale*. Starting at **X**, connect the dots with a smooth curve. Place an arrowhead at the end of the line to show the direction of the motion. The line you drew on **B** is **[(*straight*)(*curved*)]**.

3. You actually moved the pencil point along a path that was both straight *and* curved at the same time! This is possible because motion is measured relative to a frame of reference. (A familiar frame of reference is east-west, north-south, up-down.) In this activity, you were using two different frames of reference, one fixed and the other rotating. When the pencil-point motion was observed relative to the fixed **A** and ★, its path was **[(*straight*)(*curved*)]**. When the pencil motion was measured relative to **B** which was rotating, the path was **[(*straight*)(*curved*)]**.

4. Begin again with **B** in the "cross" position and the arrow pointing towards the ★. Pulling the lower right tab towards you, rotate **B** clockwise one division of the *curved scale* and make a pencil dot on **B** along the *straight scale* at one scale division above the *Start Position* **X**. Continue in similar fashion as you did in Item 2 above to determine the path of the moving pencil point. The path was straight when the pencil-point motion was observed relative to **[(*A*)(*B*)]**. The path was curved when the pencil motion was measured relative to **[(*A*)(*B*)]**.

5. Imagine yourself shrunk down in size, located at **X**, and looking towards the ★. You observe all three situations described above (that is, no motion of **B**, counterclockwise rotation, and clockwise rotation). From your perspective at the X starting position, in all three cases the pencil point moved towards the ★ along a **[(*straight*)(*curved*)]** path.

6. Watching the same motion on **B**, the pencil path was straight in the absence of any rotation. However, the pencil path curved to the **[(*right*)(*left*)]** when **B**

rotated <u>counterclockwise</u>. When the rotation was <u>clockwise</u>, the pencil path curved to the **[(*right*)(*left*)]**.

This apparent deflection of motion from a straight line in a rotating coordinate system is called the Coriolis effect for Gaspard Gustave de Coriolis (1792-1843) who first explained it mathematically. Because the Earth rotates, objects moving freely across its surface, except at the equator, exhibit curved paths.

7. Imagine yourself <u>far above the North Pole</u>, looking down on the Earth below. Think of **B** in the ***AMS Rotator*** as representing Earth. As seen against the background stars, the Earth rotates in a counterclockwise direction. From your perspective, an object moving freely across the Earth's surface would move along a **[(*straight*)(*curved*)]** path relative to the background stars (depicted by the ★ on the ***AMS Rotator***).

   Now think of yourself <u>on the Earth's surface at the North Pole</u> at the dot position while watching the same motion. From this perspective, you observe the object's motion relative to the Earth's surface. You see the object moving along a path that **[(*is straight*)(*curves to the right*)(*curves to the left*)]**.

8. Imagine yourself located <u>far above the South Pole</u>. As seen against the background stars, the Earth rotates in a clockwise direction. The sense of rotation is reversed from the North Pole because you are now looking at the Earth from the opposite direction. An object moving freely across the Earth's surface is observed to move along a **[(*straight*)(*curved*)]** path relative to the background stars.

   Now think of yourself <u>on the Earth's surface at the South Pole</u> while watching the same motion. From this perspective, you observe the object's motion relative to the Earth's surface. You see the object moving along a path that **[(*is straight*)(*curves to the right*)(*curves to the left*)]**.

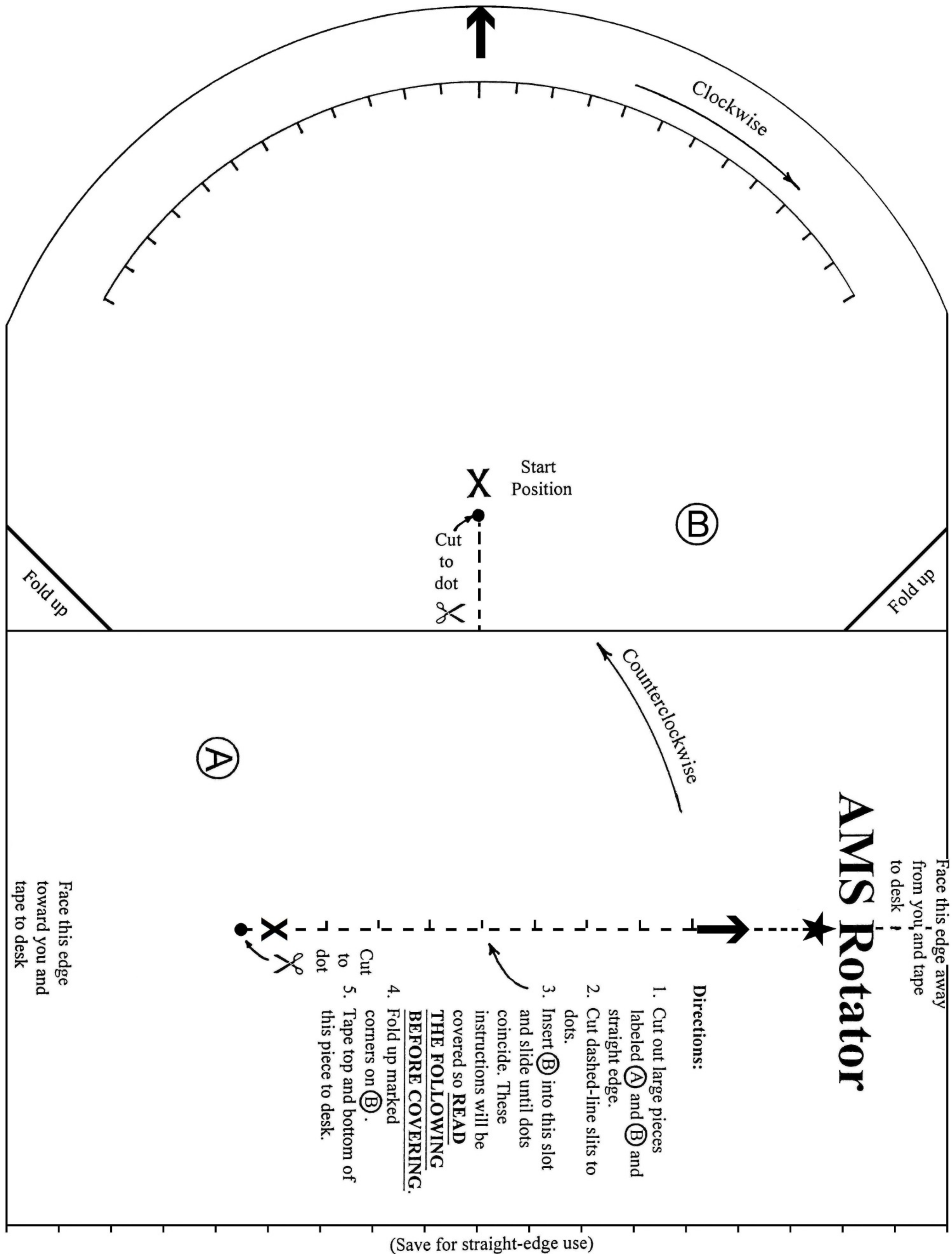
9. In summary, the Coriolis effect causes objects freely moving horizontally over Earth's surface to curve to the **[(*right*)(*left*)]** in the Northern Hemisphere and to curve to the **[(*right*)(*left*)]** in the Southern Hemisphere.

Further Investigations:

1. Again begin with **B** in the "cross" position. Create paths that originate on the *straight scale* at one division below the *curved scale* and move toward the original *Start Position(X)*. Do this for **B** rotating clockwise and then counterclockwise. Earlier we found that curvature to the right was associated with counterclockwise rotation and curvature to the left was associated with clockwise rotation. In these cases, the same associations between curvature and direction of rotation **[(*apply*)(*do not apply*)]**.

2. Try moving across **B** while it rotates by using the “straight edge” as a pencil guide. Orient the “straight edge” at a right angle to the cut edge in **A** about half way between **X** and the ★ and tape its ends so that **B** rotates freely. While rotating **B** counterclockwise, draw a line several scale units long from left to right beginning at the cut-edge. Repeat the process for **B** rotating clockwise. Curvature was to the **[(*right*)(*left*)]** with counterclockwise rotation and to the **[(*right*)(*left*)]** with clockwise rotation.

3. Investigate changes in the relative speed of rotation and the curvature by moving one division along the *straight scale* for every two divisions of the *curved scale* or two divisions of the *straight* scale for every one of the *curved scale*. Does the direction of curvature change? Does the amount of curvature change?


Clockwise
Start Position
B
Cut to dot
Fold up
Fold up
Counterclockwise
A
AMS Rotator
Face this edge away from you and tape to desk
Face this edge toward you and tape to desk
Directions:
1. Cut out large pieces labeled (A) and (B) and straight edge.
2. Cut dashed-line slits to dots.
3. Insert (B) into this slot and slide until dots coincide. These instructions will be covered so READ THE FOLLOWING BEFORE COVERING.
4. Fold up marked corners on (B).
5. Tape top and bottom of this piece to desk.
Cut to dot
(Save for straight-edge use)

Optional Activity: Coriolis Deflection and Earth Latitude

Introduction: The Coriolis deflection is greatest at the North and South Poles and is absent at the equator. What happens to the Coriolis deflection at latitudes in between? The purpose of this activity is to investigate how the Coriolis effect changes with latitude. In this activity, you will construct generalizations concerning the influence of the Coriolis effect on objects moving horizontally and freely over different latitudes.

Materials: Transparent plastic **hemispheric shape** 10 to 15 cm (4 to 6 inches) in diameter, scissors, tape, washable overhead-projection pen or other washable-ink pen that writes on plastic, ***AMS Rotator***.

Directions: The plastic hemisphere represents the Earth's Northern Hemisphere surface. Place the hemisphere on the ***AMS Rotator*** (taped flat on your desk) so that the pole position of the hemisphere is directly above the rotational axis (dot location) of the ***AMS Rotator***.

1. With your eyes about two feet directly above the hemisphere, look down at the curved line you drew on **B** in Item 2 of the ***Because the Earth Turns*** activity in this module. Using the overhead-projection pen, draw on the hemisphere surface the path of the curved line as viewed from your perspective. Examine the curve that you drew on the hemisphere's surface. The curvature of the path **[(*decreases*)(*increases*)]** as the latitude decreases. This happens because the effect of the Earth's rotation on freely-moving objects is greatest in a plane (flat surface) oriented perpendicular to Earth's rotational axis, that is, at one of the poles. As the plane representing the surface of the Earth tilts more and more from this perpendicular position, the effects of the rotation on motion along that plane decreases. This activity visually depicts this change.

2. Consequently, the effect of the Earth's rotation on horizontally moving objects becomes less and less with decreasing latitude. At the equator, an object moving freely across the Earth's surface would exhibit no deflection due to the Earth's rotation. Stating it another way, the Coriolis deflection increases with increasing latitude. The change in deflection varies as the sine of the latitude. The sine of 0 degrees (equator) is 0, no Coriolis deflection; the sine of 90 degrees (poles) is 1, the maximum Coriolis deflection. The sine of 45 degrees is 0.707, so at 45 degrees latitude the Coriolis deflection is 0.707 of what it is at 90 degrees latitude.

Real World Applications

Fluids moving over Earth's surface are subject to forces that drive them as well as the rotational effect of Earth (Coriolis). In the atmosphere, horizontal pressure gradients put air into motion. It is subsequently influenced by Earth's rotation (Coriolis effect), to the right in the Northern Hemisphere. The flow from high toward low pressure, deflecting to the right, is evidenced in clockwise and outward flows around high-pressure centers and counterclockwise and inward flow around low-pressure centers. **Figure 1** is a regional weather map for the North Pacific at 06Z (2 a.m. EDT) 3 April 2012 from the Honolulu National Weather Service Forecast Office.

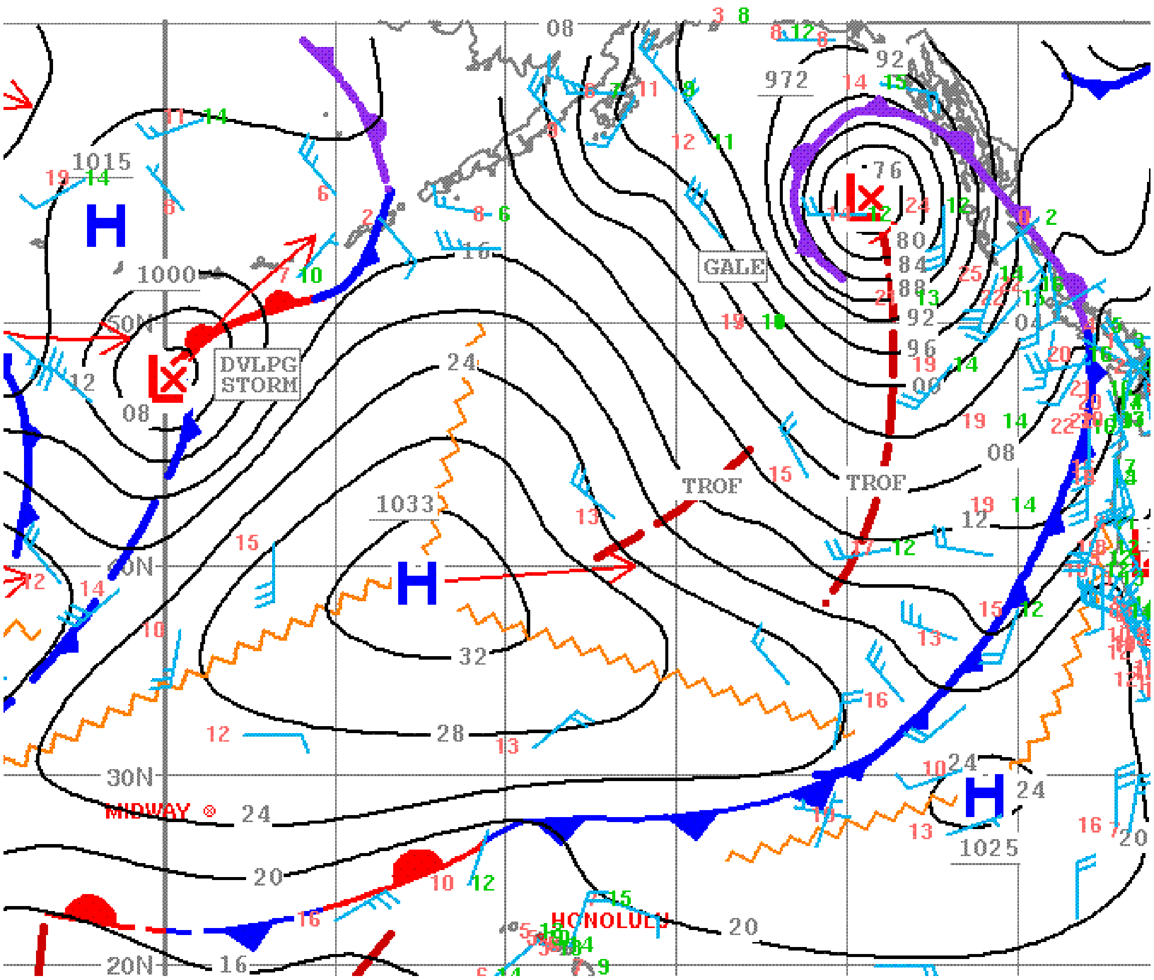


Figure 1. North Pacific regional weather map for 06Z 3 APR 2012. [NOAA]

Light blue wind arrows show observations where the air is moving toward the direction of the arrow head and the speed is shown by the combination of feathers on the tail, long for 10 knots, short for 5 knots.

Imagine yourself at the center of the high pressure (**H** within the "32" line, 1032 mb isobar) near the map center. The horizontal pressure gradient force would begin your motion toward the center of low pressure (**L** within the "76" line, 976 mb isobar) in the upper right. As you travel, you would turn toward your right (Northern Hemisphere).

1. Does your direction of motion match the light blue wind arrows a few centimeters out from the center of the High? **[(*Yes*)(*No*)]**.

Next, imagine yourself between the high pressure **H** and the **L**. The horizontal pressure gradient force would begin your motion toward the center of low pressure to the upper right. As you travel, you would turn toward your right.

2. Does your direction of motion match the light blue wind arrows a few centimeters out from the center of the Low? **[(*Yes*)(*No*)]**.

3. The overall pattern of wind arrows surrounding the center of the High is **[(*clockwise*)(*counterclockwise*)]** as would be result of the combination of horizontal pressure gradient force and Coriolis effect on air motion.

4. The overall pattern of wind arrows surrounding the center of the Low is **[(*clockwise*)(*counterclockwise*)]** as would be result of the combination of horizontal pressure gradient force and Coriolis effect on air motion..

Note the winds to the lower right of the map area. The persistent Pacific (or Hawaiian) High with its clockwise flow would often drive winds along the U.S. West Coast from north toward south such as those shown. A generally north-to-south wind flow would drive ocean waters southward. In turn, the waters would also turn to the right (Coriolis effect) to move them offshore. In the ocean this is called *Ekman transport*. In the California coastal region this offshore movement would draw water upward from greater depths in replacement. This deeper water is cooler and contains nutrients feeding biological growth.

Figure 2 is a composite of three images of the southern California coastal region. Fig 2(a) is a visible view of water, clouds and land areas. Fig 2(b) is an image of chlorophyll amounts where yellows and reds represent the highest chlorophyll levels and greatest biological productivity (brown is land). Fig 2(c) is a map of ocean surface temperatures where the blue and lightest green shades are coolest temperatures (gray is land surfaces while black is cloud cover).

5. Imagine yourself moving in the direction of the winds (northwest to southeast) along the California coast driving the waters to the right by Ekman transport. The general direction of water transport in the coast California region is **[(*toward*)(*away from*)]** shore.

6. Water movement away from the shore is replaced by water coming up from depth in a process called *upwelling*. This cooler water **[(*__is__*)(*__is not__*)]** consistent with the blue and lighter green shadings of temperature seen in Figure 2c.

7. Upwelling brings nutrients that had sunk in the waters back into the sunlit surface regions to spur productivity. The increased amounts of chlorophyll **[(*__is__*)(*__is not__*)]** consistent with the yellow and red shadings of chlorophyll seen in Figure 2b.

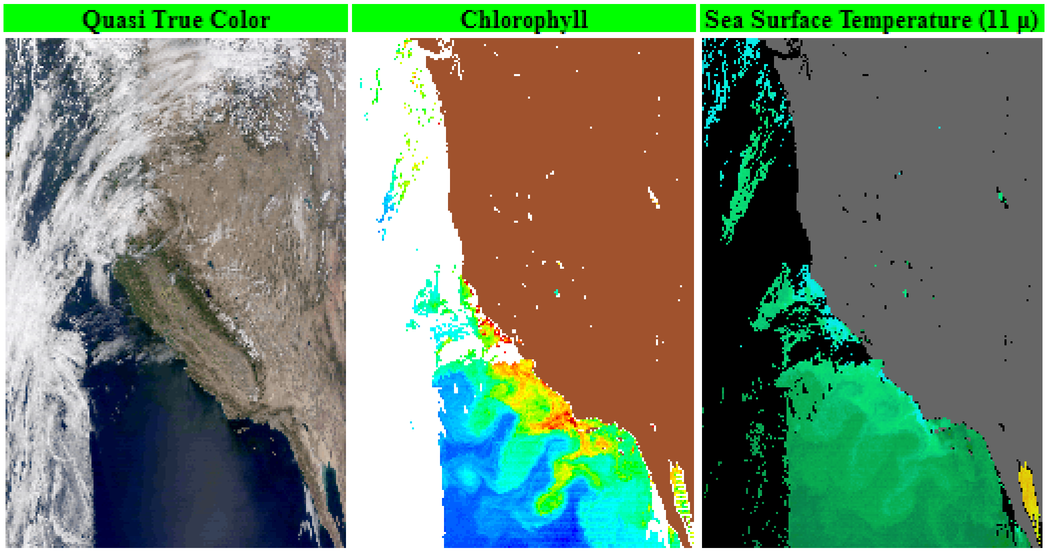


Figure 2. Composite views of (a) visible coastal features, (b) chlorophyll levels, and (c) sea surface temperatures. [SeaWiFS]

Information Sources

Books

Moran, Joseph M. Weather Studies: Introduction to Atmospheric Science, 5th Ed. Boston, MA: American Meteorological Society, 2012.

Periodicals

Weatherwise. Bimonthly magazine written in association with the American Meteorological Society for the layperson. Weatherwise, 1319 Eighteenth St., NW, Washington, DC 20036.

USA Today. National newspaper with extensive weather page. Available at local newsstands and by subscription.

Radio and Television

NOAA Weather Radio. The voice of the National Weather Service and All Hazards Emergency Alert System. Local continuous broadcasts from over 1000 transmitting stations nationwide.

The Weather Channel. A continuous cable television program devoted to reporting weather. Includes frequent broadcast of local official National Weather Service forecasts.

Internet

DataStreme Atmosphere (*www.ametsoc.org/amsedu/dstreme/*). Atmospheric education distance-learning website of the AMS Education Program.

JetStream – Online School for Weather (*www.srh.noaa.gov/jetstream/*). Background weather information site from the National Weather Service.