SCIENCE ACTIVITIES
https://doi.org/10.1080/00368121.2017.1322031

Routledge
Taylor & Francis Group

Detangling spaghetti: Tracking deep ocean currents in the Gulf of Mexico

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ABSTRACT
Creation of physical models can help students learn science by enabling them to be more involved in the scientific process of discovery and to use multiple senses during investigations. This activity achieves these goals by having students model ocean currents in the Gulf of Mexico. In general, oceans play a key role in influencing weather patterns and climate. Water movement also affects fisheries through transport of various fish and invertebrate species as well as their predators and prey. Currents also impact the dispersion of pollutants, as in after an oil spill such as the catastrophe of the Deepwater Horizon oil rig in 2010. Currents exist deep in the ocean, and they do not always travel in the same direction as currents at the surface. This concept of the existence of ocean currents below the surface can be hard to explain, but we provide methodology for sharing this information in a way that is accessible to K–12 students, including the visually impaired. In addition to the NGSS standards and Ocean Literacy principles addressed, this activity has larger implications related to socioeconomics and international law.

KEYWORDS
Currents; Gulf of Mexico; oil spill; Deepwater Horizon; dispersion; eddy

Introduction

The movement of ocean waters in currents is important in several ways. It affects weather and climate. It also affects the survival of many marine organisms such as fishes because larvae are often transported to favorable habitat via this means. The most familiar currents are tidal currents. They cause the high and low tides that influence coastal regions and also move water into and out of a harbor or through a narrow channel. There are also much larger currents, carrying millions of cubic meters of water every second throughout the global ocean.

The system of currents encircling the Earth is referred to as the ocean "circulation." One of the most well-known ocean currents, at least off North America, is called the Gulf Stream, a current that transports warm water from the equator toward the North Pole in the North Atlantic Ocean (Figure 1A). As the Gulf Stream waters travel northward, they release their warmth to the atmosphere and cool down. In the far northern North Atlantic, these waters have become so dense that they sink to great depths below the sea surface (1,000–4,500 m), forming another, much colder current returning back to the equator under the Gulf Stream. This current is called the Deep Western Boundary Current. Most people are not aware that there are currents deep in the ocean, and that these deep currents are often not going in the same direction as the surface currents.

The Gulf Stream originates south of the Yucatan Channel in the Gulf of Mexico (Figure 1A, B), where it is called the Loop Current (Figure 1A). It has this name because it enters the Gulf of Mexico between Mexico and Cuba, "loops" through the eastern Gulf of Mexico, and then exits between Florida and Cuba. It carries about 25 million m^3 of water per second, or the equivalent of about 1,500 Mississippi Rivers. In comparison, the Gulf of Mexico contains a volume of 2,434,000 km^3 of water. Top speeds of the current are around 1.5 m/s, or about 3 miles/hr (human walking speed). The Loop Current decreases in speed (becomes weaker) at deeper depths. It is still detectable at 800 m, and it is more or less undetectable below 1,000 m (although there are other currents below this depth). At 800 m, the current is only about 0.3 m/s – or about 1/5 as strong as it is at the surface.

The loop in the Loop Current periodically (about every 3–17 months) grows very large and pinches off a large segment of the current, which forms a quasi-circular current feature with a diameter between 200

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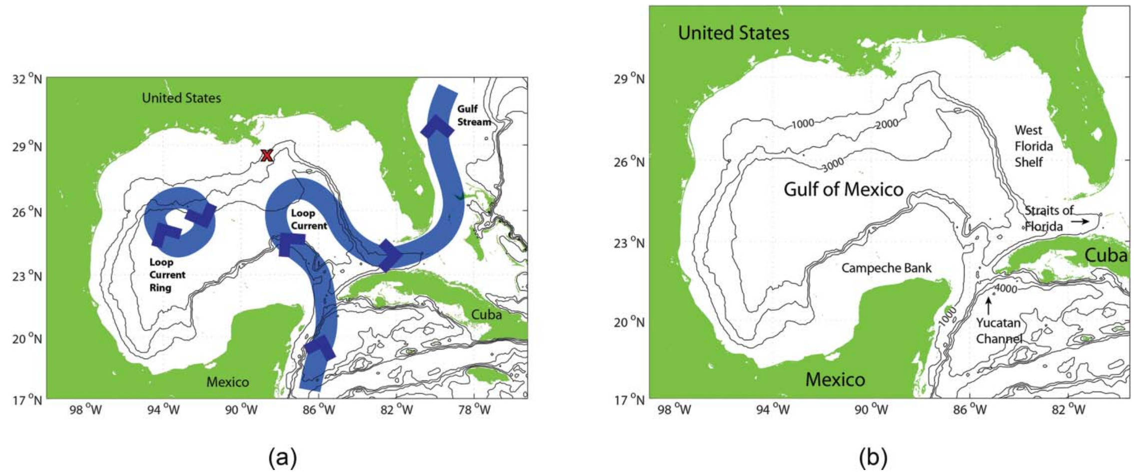


Figure 1. Schematic of: (A) Surface ocean circulation in the Gulf of Mexico. Current in the center of the map is the Loop Current. The Loop Current becomes the Gulf Stream current on the eastern side of Florida, which brings warm water northward. Warm-core rings can pinch off the meandering current and rotate clockwise (called "anticyclonic" in the Northern Hemisphere). The location of the Deepwater Horizon oil rig is denoted by a red letter "X." (B) Bathymetry contours at 1,000 m, 2,000 m, 3,000 m, and 4,000 m are drawn as black lines and labeled. The most important feature to note is the shallow continental shelf surrounding the land, particularly west of Florida and north of Mexico.

and 400 km that is called a Loop Current Ring (Figure 1A). The water flows around inside the Loop Current Ring (which is a special name for an eddy that pinches off from the Loop Current) in a clockwise direction. After it forms, the Loop Current Ring usually drifts slowly westward, taking about one year to reach the coast of Mexico or Texas and then disintegrating. After the ring separates from the Loop Current and moves away, the Loop Current contracts back to the south. The Loop Current and its rings are very important for transporting marine organisms and pollutants near the sea surface. Their warm waters also influence the intensity of hurricanes in the Gulf of Mexico.

The Loop Current and Loop Current Rings are relatively easy for scientists to observe because they are strong at the sea surface, where we can measure them using ships, drifting buoys, and satellites orbiting overhead. It is much more difficult to measure the currents below the surface. Scientists use a variety of specialized technologies to study deep ocean currents. One example is a device called a "float" (Figure 2). After a float is deployed from a ship, it sinks down to a pre-set depth in the ocean, and then drifts with the currents at that specified depth. It is tracked underwater using a system of moored sound beacons. After a pre-programmed amount of time, the float automatically drops a ballast weight, rises to the surface, and transmits all the data it has collected to a communications satellite. Scientists use this

Figure 2. Technician on deck preparing float for deployment at sea. (Photo courtesy of Heather Furey, Woods Hole Oceanographic Institution).

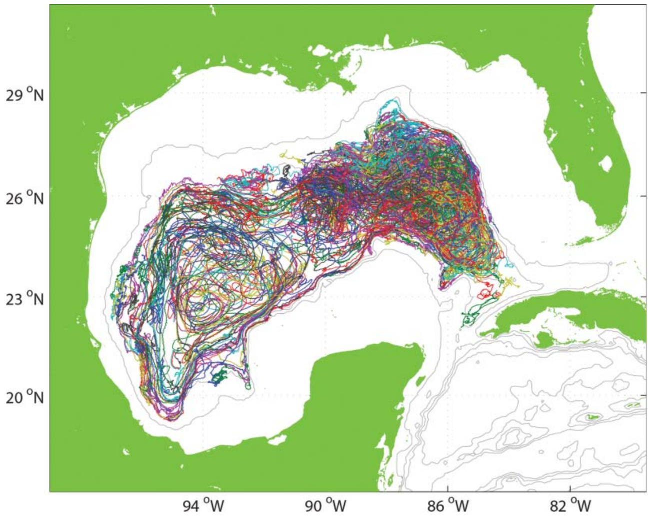


Figure 3. Detangling Spaghetti. This map depicts movement of many floats that recorded ocean circulation at depths between approximately 1,500 and 2,500 m. In this activity, students will tease some of this spaghetti apart to analyze trends in current direction at different depths.

information to reconstruct where the float moved while it was underwater. The track of the float is called a trajectory. Multiple floats can be deployed at once, and their trajectories can look like tangled spaghetti (Figure 3). In fact, scientists often call this kind of picture a "spaghetti diagram." However, upon closer inspection, general patterns can be deciphered.

The importance of understanding ocean circulation in the Gulf of Mexico was highlighted by the oil spill that occurred at the Deepwater Horizon oil rig in 2010. This spill, which is also called the BP oil spill or the Macondo blowout, released 210 million US gallons (780,000 m^3) of oil. Some of the oil rose to the sea surface and eventually washed ashore, causing harm to marshes and the organisms that live there. However, some of the oil remained suspended in the water column and was carried away by deep currents. Understanding sub-surface ocean circulation is crucial in predicting whether oil from accidents like the Deepwater Horizon will be carried out of the Gulf or to other regions inside the Gulf, where it could impact marine life in the water and on the sea floor, causing harm to the ocean environment and the fishing industry. Just as weather observations are used with mathematical models to generate weather forecasts, observations of the currents in the Gulf of Mexico are being used with math models to predict how the currents will change in the future. With more measurements of ocean current pathways, scientists can improve predictions of where spilled oil will spread, and this in turn will lead to faster and more complete clean-up.

How oil will spread out in the Gulf of Mexico depends critically on where the spill takes place. The Deepwater Horizon blowout occurred in the far northeastern part of the Gulf. This location is relatively far from the typical places where the strong currents associated with the Loop Current and its eddies are present. A more vulnerable site would be south of the Mississippi River Delta, where the Loop Current and Loop Current eddies have been observed to come closer to the continental slope where there are many offshore oil rigs. The western side of the Gulf is also vulnerable (along the coasts of Texas and Mexico) because the Loop Current eddies frequently drift westward and hit the seafloor there. This is why it is important to be able to predict surface and deep currents throughout the Gulf.

This activity is designed to teach students about subsurface ocean circulation under the overarching and relevant framework of ocean pollution (oil spills). It has been tested in a classroom of visually impaired students, and modifications are provided to include their participation.

The activity is based on new measurements of deep ocean currents that were made in the Gulf of Mexico during 2011–2015 using the acoustically tracked floats described above. About 160 floats were deployed in many locations all over the Gulf during nine different research cruises by US and Mexican oceanographers working together. Most of the floats were programmed to sink to 1,500 m below the sea surface and drift with the currents at that depth, although a small number were sent deeper, to 2,500 m. Four sound beacons were set up throughout the Gulf at the beginning of the study. The floats "listened" for and recorded the time of the signals transmitted by the sound beacons, and researchers were able to track the underwater floats based on this information. Most of the floats stayed underwater for nearly 2 years, although some did so for much shorter times due to technical problems. While underwater, the floats do not touch the seafloor; instead, they drift passively (much like a feather in the wind) along with the deep currents, above the seafloor at the pre-set depth.

As can be seen from the spaghetti diagram (Figure 3), the deep currents do not appear as organized or as coherent as the Loop Current. At first glance, they look random and chaotic, but, in fact, they

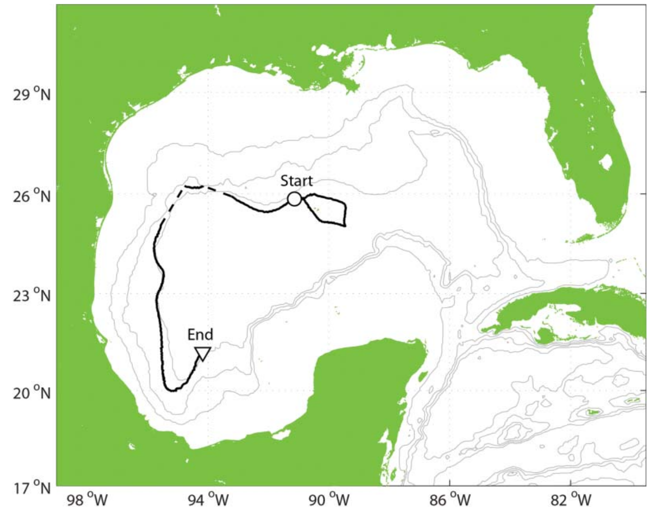


Figure 4. For Paper Plate 3. Trajectory of float 1081 that drifted in the water at approximately 2,000 m depth. This float was launched September 13, 2012, surfaced June 5, 2014, and traveled 2,452 km along the float's trajectory. Note that the dashed line segments in the trajectory show where there are no data, indicating that float position data were lost over brief distances.

reveal some organized currents along the boundaries of the Gulf as well as looping motions (Figures 4–6).

Some floats (see Figure 4 for an example) show that a deep current exists around the perimeter of the western Gulf of Mexico. This deep boundary current flows counterclockwise around the Gulf and is most clearly seen along the northern boundary starting at about 90°W—halfway across the Gulf—and continues along the western and southern sides of the gulf, following closely along the bathymetry. The float shown in Figure 4 was deployed off a research ship at the point denoted by the open circle, labeled "Start." The float sank to its pre-set depth of approximately 2,000 m, and then it drifted with the deep current first in one small clockwise loop then along a long southward path in a persistent boundary current, flowing at about 10–20 cm/s. About 8 months after launch, the float "grounded," which means the float got stuck in some rough bathymetry in the southwestern Gulf, at about 21.5°N 94°W. It remained grounded for a few months and then surfaced (triangle marker labeled "End").

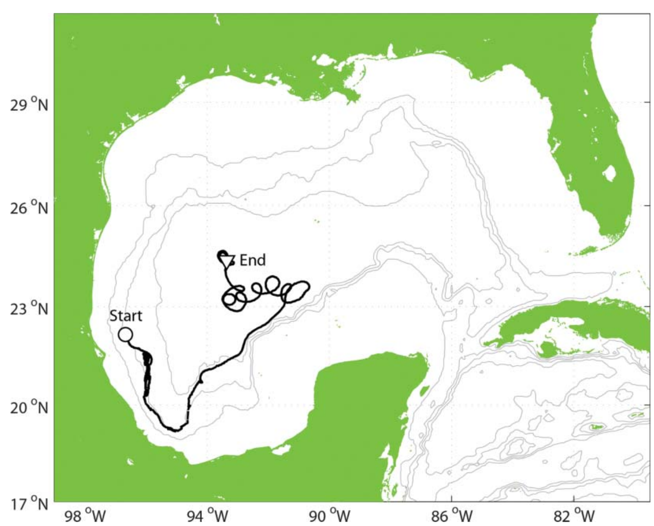


Figure 5. For Paper Plate 3. Trajectory of float 1060 deployed in the western Gulf of Mexico and drifted in the water at approximately 2,000 m. This float was launched January 16, 2012, surfaced March 22, 2013, and traveled 3,934 km along the float's trajectory.

Other floats show the formation of deep eddies off the Campeche Bank (see Figure 1B for subsurface geographic feature names). The float in Figure 5 was launched along the western boundary of the Gulf and floated at 1,500 meters for about 2 years. This shallower float also followed the boundary current around the western Gulf at about 10 cm/s. This float traveled farther to the east than the float shown in Figure 4. Once the float traveled about halfway along the Campeche Bank, it was transported off the shelf at about 20–30 cm/s into deeper water and then began looping in an eddy, rotating at about 20 cm/s. This eddy (with the float in it) drifted westward and then northward. The float's mission ended and it surfaced while it was still in the eddy. The eddies at this location transport water in a clockwise direction.

Float trajectories in the eastern Gulf do not show smooth boundary currents like the float trajectories in the west. The float shown in Figure 6 spent 2 years underwater, but it surfaced only a relatively short distance from where it was launched. During the two years spent underwater, it drifts aimlessly around in the eastern Gulf, traveling at about 5–10 cm/s, indicating that the water in this region and at this depth is very well mixed. However, there is a 3-month period of time during this float's 2-year mission when it got caught in a deep eddy and made repeated loops at a faster speed, about 30–40 cm/s. Different than the deep eddies found off the Campeche Bank, these deep eddies often rotate counter-clockwise, or in a cyclonic sense.

These three examples of deep circulation give researchers a much different picture of the currents in the deep Gulf compared to the surface Gulf circulation shown in Figure 1A. Differences between surface and deep current patterns like we see in the Gulf of Mexico exist in all the world's oceans.

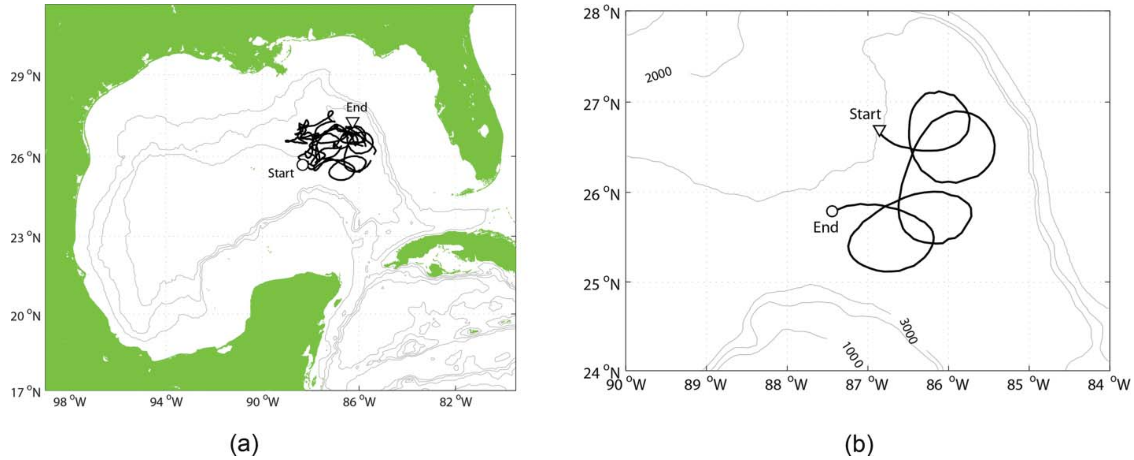


Figure 6. For Paper Plate 3. (A) Trajectory of float 1224 deployed in the eastern Gulf of Mexico at approximately 2,000 m. This float was launched August 22, 2013, surfaced May 14, 2015, and traveled 4,275 km along the float's trajectory. Students can use the close-up view of the eddy (B) for their paper plate.

Background

Students are interested in the effect of pollution, including oil spills, on the marine environment, and there are many resources available to them. Some recent resources have been developed using funds mandated to be provided by BP for their role in the Deepwater Horizon oil spill while drilling at their Macondo Prospect site in the Gulf of Mexico. Although we provide an activity that stands on its own, the teacher is free to further develop the background to emphasize the real-world relevancy of this work. Therefore, this activity can fit into a broader framework related to marine resources, socioeconomics, and international law. Some useful websites are provided in the Web Resources section.

To assess what students may already know about the topic, teacher can ask questions such as:

- Where is the Gulf of Mexico?
- Which states border the Gulf of Mexico?
- Which countries border the Gulf of Mexico (see Figure 1)?
- What is the general movement pattern of water at the surface (see Figure 1A)?
- How deep is the Gulf of Mexico at its deepest point? (about 12,000 feet or about 3,658 m)
- Why should we care about the Gulf of Mexico?
- What was the name of the big oil spill that occurred in the Gulf of Mexico in 2010?
- What were some problems that occurred as a result of the oil spill?
- How was the spill stopped, and how long did it last?

Central driving question

The purpose of this activity is to learn about the ocean circulation patterns in the Gulf of Mexico and to use this knowledge to understand how pollution from oil spills, such as from the Deepwater Horizon, is dispersed via ocean currents. Students will have the opportunity to create their own physical model of ocean circulation in this region.

Vocabulary

Bathymetry - ocean's depth relative to sea level and/or the shape of underwater features
Current - a volume of water moving in a defined direction
Loop Current - a current carrying warm water that enters the Gulf of Mexico between Mexico and Cuba, "loops" through the Gulf of Mexico and exits south of Florida. The warm water then turns northward along the U.S. east coast and eventually becomes the Gulf Stream. (http://oceanservice.noaa.gov/facts/loopcurrent.html)
Eddy - a circular movement of water
Loop Current Ring - a type of warm water eddy that pinches off from the Loop Current
Deep (sub-surface) eddy - an eddy that is formed below the sea surface
Sub-surface floats - passive drifting oceanographic instruments that measure ocean currents, temperature, and pressure below the sea surface
Trajectory - the path, or track, that an object or current takes
Ocean circulation – the system of currents that exist within an ocean basin.

Grade level

The grade level is fourth and fifth grade with modifications for more advanced students

The activity addresses the following standards in science, mathematics, and geography:

Next Generation Science Standards (http://www.nextgenscience.org/)

4-ESS2-2. Analyze and interpret data from maps to describe patterns of Earth's features. [Clarification Statement: Maps can include topographic maps of Earth's land and ocean floor, as well as maps of the locations of mountains, continental boundaries, volcanoes, and earthquakes.]

4-ESS3-1 Earth and Human Activity

Obtain and combine information to describe that energy and fuels are derived from natural resources and their uses affect the environment.

5-ESS2-1 Earth's Systems

Develop a model using an example to describe ways the geosphere, biosphere, hydrosphere, and/or atmosphere interact.

5-ESS2-2 Earth's Systems

Describe and graph the amounts and percentages of water and fresh water in various reservoirs to provide evidence about the distribution of water on Earth.

Mathematics through the National Council of Teachers of Mathematics

(http://www.nctm.org/Standards-and-Positions/Principles-and-Standards/Principles,-Standards,-and-Expectations/)

Grade 5 standards:

Operations and Algebraic Thinking

- Analyze patterns and relationships.

Measurement and Data

- Convert like measurement units within a given measurement system.
- Represent and interpret data.
- Geometric measurement: understand concepts of volume and relate volume to multiplication and to addition.

Geometry

- Graph points on the coordinate plane to solve real-world and mathematical problems.

Geography National Council for Geographic Education

(https://netforum.avectra.com/eweb/DynamicPage.aspx?Site = Test%20One&WebCode = GeographyStandards)

From the eighteen national standards and six essential elements, the geographically informed person knows and understands:

Essential Element I. The world in spatial terms

Standard 1. How to use maps and other geographic representations, tools, and technologies to acquire, process, and report information from a spatial perspective.

Essential Element II. Places and regions

Standard 4. The physical and human characteristics of places.

Essential Element IV. Human systems

Standard 14. How human actions modify the physical environment.

Ocean Literacy Principles (http://www.coexploration.org/oceanliteracy/documents/OceanLitChart.pdf)

1. The Earth has one big ocean with many features.
5. The ocean supports a great diversity of life and ecosystems.
6. The ocean and humans are inextricably interconnected.

Materials list to allow replication (see subsequent supplemental materials for visually impaired students for modifications for accessibility)

- 6-inch (15.2 cm) paper plate for each student
- Pipe cleaners – approximately 20 per group of students
- Glue and/or tape for each group
- 1–2 rulers per group
- Colored pencils or markers – 1 pack per group
- Scissors – at least 1 per group
- 1 Detangling Spaghetti Packet per student

Optional:

Stickers, sea shells, or small model fish to decorate the bottom layer (plate).

Supplemental materials for visually impaired students

- Wikki Stix
- Puff paint
- Materials, including figures, printed using raised ink

Procedure

Time requirement: approximately 2 class periods of 50 minutes each.

Advanced preparation: The activity is designed to provide students with a sense of how ocean currents move in the Gulf of Mexico both at the surface and at depth. The shape of a paper plate is roughly the shape of the Gulf of Mexico and can be used to model water movement in that region. If a more realistic shape of the Gulf is preferred, students can cut the outline of the land features using the map in Figure 7, which can

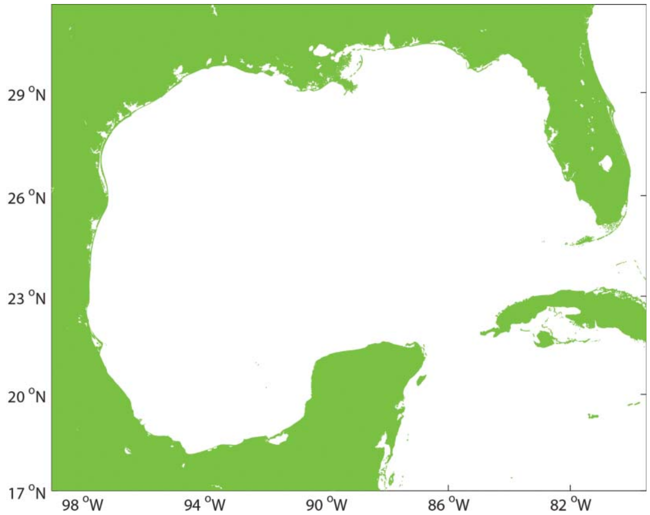


Figure 7. Students can use this figure to cut out the continental land feature and glue it onto a 6-inch (15.2 cm) paper plate.

be scaled to the size of the paper plate when photocopies are made.

See Detangling Spaghetti Packet for student instructions.

Observations and discussion

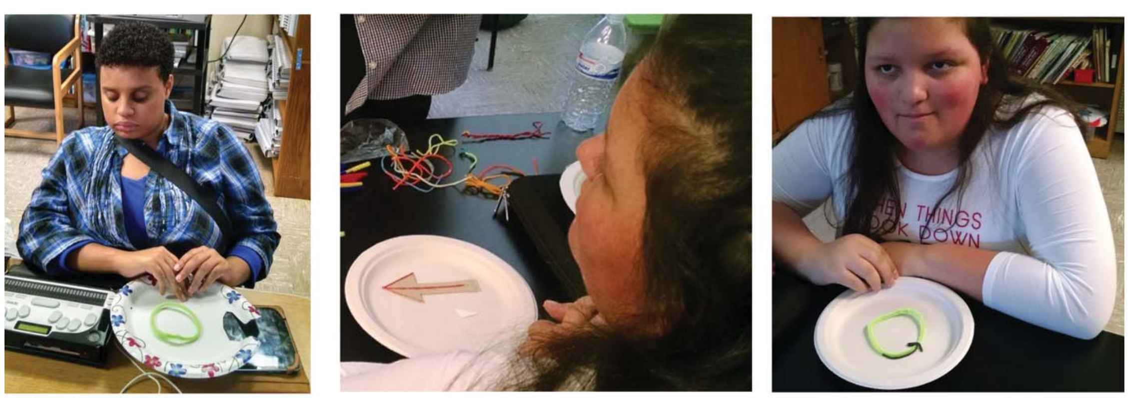
This activity was designed to be accessible to visually impaired students through modifications using raised features (pipe cleaners, Wikki Stix, or using a print-raised machine). The time needed to complete the activity depends on the visual acuity and dexterity of the students, and more than two class periods may be needed for certain groups. We received positive feedback from teachers regarding the opportunity for student participants to generate their own models, as this is often excluded from activities for the visually impaired. The creation of the paper plate layers can take quite a bit of time, so the teacher may choose to complete some of the cutting or creation ahead of time. Less dexterous students had trouble cutting out the land around the Gulf of Mexico, so we altered the maps to provide more land to tape to the paper plates.

Conclusions and/or implications

Students learned that water moves at depth, and we cannot "see" that happening. Instead, we study deep-ocean circulation using tools such as floats to track water movement and to interpret trends, as was seen with the increase in eddy formation in the eastern Gulf. Students enjoyed making the ocean layers and drawing animals on the ocean floor. They learned about geography and plotting while observing general patterns in ocean circulation. This activity has larger implications related to socioeconomics and international law, and the teacher can incorporate such cross-curricular content at his or her discretion. The pros and cons of fossil fuel use, the unequal distribution of resources across the globe, and the chain of responsibility for environmental disasters are all topics for students to consider that have impacts beyond the United States.

Extensions and cross-curricular applications

Further questions can be asked to supplement the math and physics of this activity that are more challenging than the ones posed in this activity. For example, students could complete word problems in which they have to convert from different units about the



(a) (b) (c)

Figure 8. Examples of visually impaired students after construction of surface eddy. A) Anicia finishes construction of an eddy made with a pipe cleaner. Also in view is her Braille reader. (B) Bella could feel the arrow cutout and place it over an eddy rotating in a counterclockwise direction; (C) Bella demonstrates the rotation of the eddy using a black Wikki Stix shaped into an arrow.

volume or flow of water in the Gulf of Mexico. If time allows, geography questions can be asked:

- What major river flows into the Gulf of Mexico?
- What states border the Gulf of Mexico?
- What countries border the Gulf of Mexico?

Students interested in further information may use the Web Resources, including the United States' response from the NOAA Office of Response and Restoration (http://response.restoration.noaa.gov/oil-and-chemical-spills/significant-incidents/deepwater-horizon-oil-spill).

Students interested in marshes bordering the Gulf can create a model as described in Fogleman and Curran (2007). Students interested in generating a brochure on the topic can follow the procedure described in Fogleman and Curran (2006). Other activities that incorporate model creation and the sense of feel that can be adapted for the visually impaired include Sukkestad and Curran (2012) and Thompson et al. (2016). For more information about accessible science for the visually impaired see http://www.perkinselearning.org/accessible-science.

Acknowledgments

Funding for this work was generously provided by the Bureau of Ocean Energy Management, administered by Leidos Inc. of Raleigh, North Carolina. The authors would like to thank teacher Kate Fraser and the students at Perkins School for the Blind in Watertown, MA for feedback related to the activity. We would also like to thank teacher Trent Kissinger and the students at Charles Ellis Montessori Academy in Savannah, GA for testing out the activity and providing feedback. Dr. Chris Hintz and students in his Aquarium Systems course at Savannah State University also provided valuable input to the activity. This publication is also listed as Contribution Number 1846 of the Belle W. Baruch Institute for Marine and Coastal Science.

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Web Resources

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Where Did Deepwater Horizon Oil Go? http://www.whoi.edu/oceanus/feature/where-did-deepwater-horizon-oil-go (accessed 16 December 2016).

Appendix

Detangling Spaghetti Packet **Student Name** ___________

Classroom Activity

Divide the class into groups of approximately 4 students each and pass out the Detangling Spaghetti Packet to each student.

Depending on classroom dynamics, each of the students can be assigned one of the four layers or they can decide amongst themselves

Each of the students responsible for layer 3 must be assigned one of the choices for that layer (Figure 4–6). This will provide the foundation for some of the discussion questions.

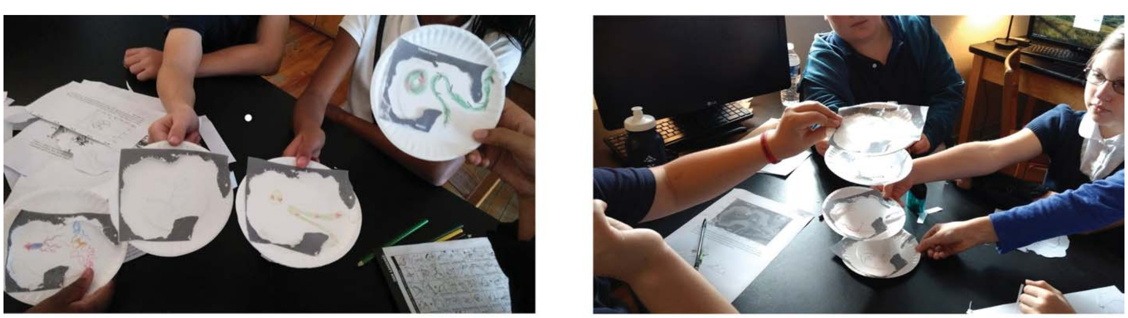
Instructions

Have students observe the shape of the Gulf of Mexico (Figure 1A) and observe the sub-surface trajectories denoting sub-surface ocean circulation in Figure 3. Students can cut out the shape of the land around the Gulf of Mexico (Figure 7) and affix it to each of the paper plates.

Students who are responsible for the surface currents (Paper Plate 1; 0 m deep) should use the pipe cleaners or markers to create the shape of the trajectories on Figure 1A. These students should make a thick line similar to the width displayed on Figure 1A. They could also use two pipe cleaners to thicken the shapes they make on their model to indicate that these currents are stronger than those at depth. Alternatively, they can outline the width of the current with one pipe cleaner on each side (about 1 cm apart). Pipe cleaners, Wikki Stix, and/or cardboard arrows can be used to help visually impaired students feel the shape and direction of rings and currents (Figure 8).

Students working on Paper Plate 2 (800 m deep) should also use Figure 1A to generate their model, but should make their lines about 1/5th (20%) as thick as the ones on Paper Plate 1. Or, students could use single-thickness pipe cleaners to indicate the current is weaker.

Students working on Paper Plate 3 (2000 m deep) should use one of the assigned trajectories in Figures 4–6.



(a) (b)

Figure 9. Examples of the paper plates generated by students. (A) Surface (at the right) to the bottom (at the left) with animals drawn. Currents are weaker with depth, which is depicted by thinner lines. (B) Plates stacked from surface to the bottom to observe the direction of the currents at different depths in a 3-D view.

Students working on Paper Plate 4 (the ocean bottom; 4000 m deep) can begin decorating and/or coloring the ocean floor.

When the plates are complete, students should stack them one above each other and observe the direction of the currents relative to each other (Figure 9).

Answer the following questions in the Detangling Spaghetti Packet.

1. Plot the location of Deepwater Horizon oil rig (28°44′N, 88°21′W).

2. Using Figure 3, what patterns do you see in these float trajectories? Why are the trajectories limited to the central portion of the Gulf? Hint: look at depth scale in Figure 3.

3. Draw a vertical line through 90°W. Does it look like there are more circular rotations (eddies) on the eastern or western side of the Gulf?

Now look at Figure 10, which shows only the trajectories with eddies. Is the answer more clear here? ______Are there more eddies in the eastern or western Gulf? ___________ Why would that be? Hint: look at Figure 1A and its caption.

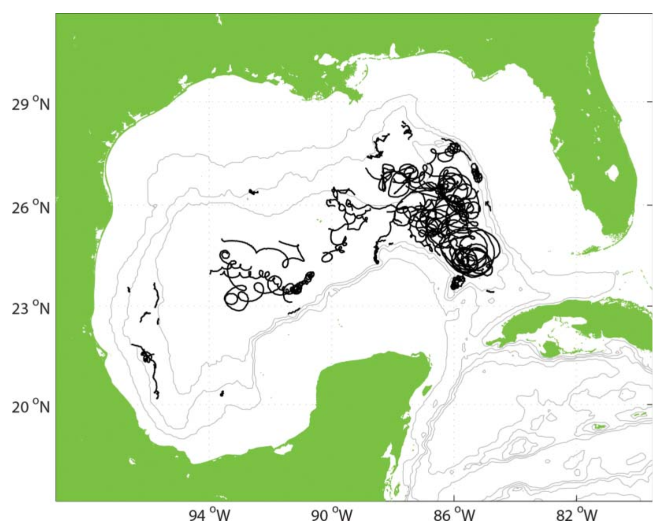


Figure 10. Depiction of eddies formed in the Gulf of Mexico at approximately 2,000 m measured by the floats shown in Figure 3.

4. The answer to the above may be skewed because more effort was placed in the eastern Gulf vs. western Gulf. The following table depicts the % of the observations in eddies for each of those locations after accounting for the difference in effort, are there more circular rotations (eddies) on the eastern or western portion of the Gulf? _____________

   Is this the same response as in Question 3? _____ If not, explain why that is.

	% of observations in an eddy
eastern Gulf	5%
western Gulf	2%

After the trajectories are finished being placed on the paper plates, answer these questions:

5. What direction is the current going at the surface (Paper Plate 1)?

6. What direction is the current going on Paper Plate 2 (800 m depth)?

7. What direction is the current going on Paper Plate 3 (2000 m depth)?

8. Are all currents moving in the same direction? If not, why do you think that is?

Once your group is finished answering these questions, exchange plates with another group and answer these questions about Plate 3 (2000 m depth).

9. Why wasn't the flow on this paper plate the same as the one your group drew?

10. What direction were the floats in the western Gulf moving?

Was there any relationship to the bathymetry? Look at the depth lines in the figures.

11. Why do you think the float in Figure 6 was moving in circles? Hint: review your earlier answers about eddy formation.

Critical Thinking (time permitting) or as bonus or homework using the information below.

The Loop Current carries about 25 million cubic meters per second, or the equivalent of about 1,500 Mississippi Rivers. (The Gulf contains a volume of 2,434,000 cubic kilometers of water.) The Deepwater Horizon oil spill released 210 million US gallons (780,000 m^3) of oil.

12. Is the volume of water coming from the Mississippi River a lot when compared to the volume of the Gulf of Mexico (Hint: look at the units). Justify your answer.

13. Is the volume of oil spilled a lot when compared to the volume of the Gulf of Mexico (Hint: look at the units). Justify your answer.

14. How do you think the fate of the spill would have differed if the location of the spill was in a different part of the Gulf of Mexico?