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Ocean Circulation Activity that Incorporates Inquiry and the Use of Real-World Data

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Abstract

A multi-class period activity on the physical principals underlying ocean circulation was designed that utilizes real world data and inquiry pedagogies for use in an undergraduate, introductory oceanography course. Goals for the activity were for students to practice the scientific method, carry out an experiment of their own design, read and interpret real oceanographic data, and use their data, observations and relationships gleaned from these small-scale demonstrations, experiments, and activities to build an understanding of large-scale ocean circulation while practicing multiple inquiry process skills. Student outcomes related to both process skills and content knowledge improve as a result of the activity's implementation, as indicated by a 14-percentage point increase in student scores on the same ocean circulation homework assigned in years before and after the new activity was created. During the COVID pandemic of 2020 this learning activity was taught in a hybrid classroom in which students could attend in-person or virtually; modifications to facilitate the successful use of the activity in this hybrid learning environment are described.

Keywords: activity design, authentic STEM education, inquiry, oceanography, STEM practices

1. Introduction

A major focus of undergraduate oceanography, geology, and atmospheric science teaching pedagogies has become the use of real-world data and having students examine data presented in graphs and other modalities to identify trends and relationships (Greengrove et al., 2020). Data exploration in undergraduate science education using publicly available data sets has multiple demonstrated benefits, including the development of analytical skills, ability to visualize complex concepts, development of conceptual frameworks, facilitating knowledge construction, and development of advanced cognitive skills (Carey et al., 2015; Gougis et al., 2017; Klug et al., 2017; O'Reilly et al., 2017; Resnick et al., 2018; Soule et al., 2018). While teaching materials that incorporate real world data are often very effective at creating high-impact educational experiences and achieve simple learning goals related to students becoming proficient at visually interpreting graphs and other representations of real-world geoscience and oceanographic data, they do not always employ inquiry-based techniques or push students to explore underlying relationships and mechanisms in ways that allow them to practice and develop process skills. This situation represents a missed opportunity to leverage the potential of the rich data sets such lessons already utilize in order to also teach students important process skills that transcend disciplines.

Research on learning and teaching has resulted in the reevaluation of theories on best practices in teaching (e.g., National Research Council, 1999). Inquiry-based techniques have emerged as a group of teaching strategies derived from our understanding of the learning process that aim to enhance learning by increasing student involvement and recognizing multiple ways of learning and knowing. Student driven investigations, which characterize the inquiry process, are question driven and lead to active construction of meaningful knowledge, rather than passive acquisition of facts transmitted from a lecturer. By engaging students' multiple learning styles, more types of students are successful contributors and students are engaged on multiple levels, with inquiry-based teaching methods having been shown to support a diversity of learners and learning styles (Aikenhead and Jegede, 1999; Gay, 2000; Tretter and Jones, 2003; Moriarty, 2007).

The Institute for Scientists and Engineer Educators Professional Development Program (ISEE PDP) at UC Santa Cruz focuses on teaching through inquiry, which involves engaging students in a learning process which parallels the authentic practices of scientists and engineers (Metevier, et al., 2022). The ISEE PDP emphasizes opportunities for students to take ownership for their learning, such as by designing and carrying out their own experiments, as well as requiring that students learn to use evidence to support their explanations. These are both key elements of the oceanography inquiry activity described here. In addition, the inquiry process explicitly builds on previously learned knowledge, thereby leading to more complete cognition and knowledge retention, which is reflected in the multiday scaffolding and how the ocean circulation activity described here continually builds upon what students have experienced in their everyday life as well as what they have learned earlier in the activity. Effective inquiry activities require instructor facilitation throughout the process to coach students and model effective inquiry, reflection, and critical thinking. Evidence indicates that inquiry-based instruction improves student attitudes, increases achievement, facilitates understanding, and fosters critical thinking skills (National Research Council, 1999; Tretter and Jones, 2003).

The goal of this project was to design and implement a multicomponent learning activity to teach undergraduate students in an introductory oceanography class about ocean circulation and the underlying mechanisms that drive this. The activity was designed to incorporate real world data with inquiry pedagogies espoused by the ISEE PDP and the POGIL (Process Oriented Guided Inquiry Learning) movement (POGIL, n.d.) in order to teach both content knowledge and process skills.

2. Venue and audience

The activity described was implemented in an introductory oceanography course (Explorations in Oceanography) at Westminster College. This course has no pre-requisites, is open students of all majors and years, and counts towards the W-Core Science and Math requirement (i.e.., general education/liberal education requirement). The course meets for 1 hour 50 minutes twice a week. While science majors can, and do, enroll in this course, the majority of students are non-science majors. Rather than being a typical survey course of the entire field of oceanography, it instead takes an interdisciplinary approach and focuses on (1) a small number of themes fundamental to the field of oceanography (similar to PDP “Core Concepts”, in this case thermohaline circulation, etc.), and (2) oceanography “hot topics” that commonly appear in the national news (El Nino Southern Oscillation, hurricanes, harmful algal blooms, etc.). This module on ocean circulation module is taught at the very beginning of the semester, and multiple modules taught later in the semester use the concepts on ocean circulation as prior knowledge.

3. Activity learning goals

Learning goals for this multi-class period learning activity include:

- Students will practice and model the scientific method by designing and carrying out their own experiment on the factors that affect the density of water. (similar to the ISEE PDP's focus on mirroring authentic research and design).
- Students will use real oceanographic data to identify relationships and trends, and to evaluate hypotheses related to ocean circulation. Students will explain their logic and conclusions to peers and the instructor and use appropriate data and evidence to support their arguments or to evaluate arguments made by others (similar to the PDP's focus on explaining using evidence).
- Students will be able to explain the following key concepts (content knowledge) related to ocean circulation:
    - The vertical migration of a parcel of water is controlled by density.
    - The density of water is controlled primarily by (1) salinity and (2) temperature.
    - Parcels of water with different densities do not readily mix, and instead form distinct layers in the water column that results in stratification.
    - Differences in water density can give rise to vertical circulation, and in the ocean this results in thermohaline circulation (ocean conveyer belt).
    - The primary factors that control variations in sea surface height include water density and gyres.
    - The primary regions of deep-water formation in the ocean include the North Atlantic near Greenland and the South Atlantic near Antarctica.
    - The Atlantic basin contains multiple distinct water masses that can be differentiated by their physical properties, where they originate, and where they migrate.
    - The activity of ^{14}C can be used to date deep water in the ocean, and trends in the ages of deep water can be explained by locations of deep-water formation and thermohaline circulation.

5. Ocean circulation activity description

5.1. Overview of the multi-day activity

During this multipart activity that is taught over three class periods, students switch between making observations of brief demonstrations, designing and conducting their own experiments on the factors that control the density of seawater, interpreting real world oceanographic data on seawater temperature, salinity, density, and the activity of ^{14}C across vertical and horizonal transects of the world's oceans while answering inquiry oriented questions to foster learning.

The entire activity can be found in the supplemental materials.

Day 1

- Introduction to the scientific method discussion and flow chart.
- Fish tank density demonstration, hypothesis formation of factors that control the density of water.

- Students design and conduct experiments on the factors controlling the density of water.
- Student presentations on their findings, class summary of what controls the density of seawater.

Day 2

- Guided student exploration of density stratification with small tanks with divider.
- Use of oceanographic data to identify locations of deep-water formation. Use of water temperature, salinity, and density to identify water masses in Atlantic basin, their origin, and direction of migration.
- Demonstration of circulation cell created by interaction of water masses with different densities.
- Student summary of key elements that control ocean circulation learned in Days 1 and 2.

Day 3

- Guided exploration with U-shaped manometer of the effects of density on water column height and sea surface height.
- Inquiry activity using oceanographic data on ocean gyres and other factors controlling sea surface height.
- Application based module using ^{14}C data to calculate ventilation ages for deep waters throughout the ocean, then evaluate if these data are consistent with students' current understanding of ocean circulation.
- Student summary of the ocean conveyer belt using multiple pieces of evidence, opportunities for formative assessment.

Day 1 (1 hour 50 minutes)

5.1. Discussion of the scientific method

This activity begins with an overview of the scientific method, in which a class discussion leads to the class collectively crating a flow chart depicting the steps in the scientific method.

5.2. Introductory density demonstration and discussion

Students are shown a simple demonstration and asked to make observations. The demonstration involves (Figure 1):

- A fish tank is filled with room temperature tap water.
- White paper is taped to the back of the fish tank to improve visualization.
- 2 small jars (baby food jars) are prepared ahead of time. One jar is filled with hot water with red dye. The second jar is filled with cold salty water with blue dye.
- Both jars are placed on the bottom of the fish tank and each is opened.

Students observe that the warm, deionized, red water migrated up to the top of the water tank when

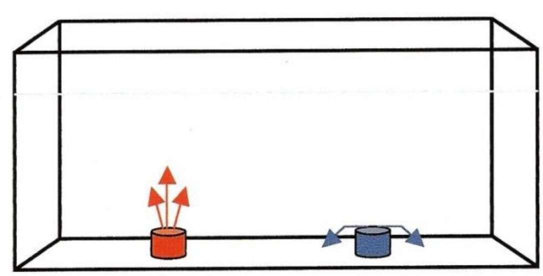

Figure 1: Introductory demonstration of vertical movement of fluids of different densities. A jar of deionized, hot water (red) and a jar containing cold, salty water (blue) are opened in the bottom of a fish tank filled with room temperature tap water.

the cap was removed, while the cold, salty, blue water stayed in the jar and flowed down to the bottom of the tank when the cap was removed.

Students are asked to explain why the red water rose up through the water column while the blue water sank down or stayed in its jar. With facilitation, the group eventually concludes that less dense fluids rise, and more dense fluids sink.

5.3. Hypothesis formation

Students are then asked to develop a hypothesis (H1) to explain what factors control the density of a parcel of seawater. They do this first in groups of 3–4 (groups they'll work in for the rest of the activity), then they share out with the group to create a master list. Typical answers include temperature, salinity, and pressure.

Student are then asked to develop a hypothesis (H2) to describe what factors or processes control the temperature of a parcel of seawater (typical answers include solar radiation, inputs of ice from glaciers, air temperature, heating from underwater ridges/volcanoes), as well as a hypothesis (H3) to explain what factors or processes control the salinity of seawater (typical answers: evaporation, precipitation, inputs from rivers, freezing/thawing).

5.4. Student designed experiments to test hypotheses of factors controlling the density of seawater

Students then test a subset of their hypotheses that they developed above on the factors controlling the density of seawater. Students are tasked with designing and carrying out their own experiments with the goal of creating a graph using the data they generate that displays the relationship between their single chosen factor and density. Students carry out these investigations in groups of 3–4, with each group deciding which of the following four factors they will explore (multiple factors will have two student groups working on them depending upon the size of the class):

- Relationship between water temperature and water density.
- Relationship between salinity and water density.
- Effect of partial evaporation on density of the liquid seawater left behind.
- Effect of partial freezing on the density of the liquid seawater left behind.

If time constraints did not exist, students would be allowed to pursue and test any hypothesis of their choosing in a more open inquiry environment, which would involve some students exploring factors that have no impact on the density of water. However, time constraints prevent this approach in this particular course, but by allowing students to choose which of a set of four possible factors they wish to explore and test they are still able to maintain ownership or agency over their learning, which is a central tenet of the ISEE PDP.

Each student group must design and conduct an experiment to test their chosen hypothesis and characterize their chosen relationship. A range of materials and measuring devices are provided for them to use. By the end of end of class each group needs to present a graph of their data describing the relationship they investigated, and give a short presentation in which they describe if their data supports or refutes their original hypothesis. Their rough experimental design must be approved by the instructor before they start the experiment. While this inherently limits student guided exploration and open/unguided inquiry, this is done to ensure that students have generally thought through what they are going to do, and have a design that could at least possibly yield usable results in the roughly 1 hour 15-minute time allotted. The experimental design must include what will be measured, how the measurements will be made, and how many data points will be collected.

As students are designing their experiments a discussion with the entire group points out that all groups will be investigating the density of water, and are asked how density is calculated, and how will they measure density. Once students identify that density = mass/volume, they may need to modify their nascent experimental design to measure both the mass and volume of water. Students are also reminding of the previous discussion about the scientific method, and the need to apply this in their current experiment.

The instructor's review of experimental designs with individual groups often leads to a discussion of uncertainty in scientific measurements and the need for more than two data points to accurately characterize the relationship between two variables. Facilitation with individual groups also involves steering them towards thinking about what factors they may need to control for and how they might do this. Even with instructor guidance and facilitation at this point, students are still given plenty of latitude to make mistakes, learn from them, and redesign or repeat part, or all, of their experiments as they take part in a process that mirrors authentic research. As many of the students are non-science majors, these changes often come in response to overlooking things such as measuring the mass of the solution plus the glassware rather than just the solution, using a beaker with inaccurate and imprecise markings to measure volume rather than a graduated cylinder or other more appropriate piece of glassware, when measuring the temperature of a solution being heated on a hot plate the thermometer or thermocouple should not be allowed to touch the bottom of the container, which may be noticeably hotter than the solution, or considering when testing for the effect of evaporation that simply measuring the decrease in the volume of the solution may be less meaningful than expressing this as a percent decrease in the solution volume.

Once students have completed their experiments, each group shares the graph they created using the data they collected and gives a short presentation to the class on the relationship they identified between their factor and the density of seawater. They also summarize their conclusions as to if their data supported or refuted their original hypothesis, and what they would do differently in their experiment if they had more time or were going to redo it. The class period ends with students collectively summarizing the results of all experiments conducted by all groups, resulting in the conclusions that:

- The vertical migration of a parcel of water is controlled by density.
- The density of water increases with decreasing temperature.
- The density of water increases with increasing salinity.
- The density of liquid seawater left behind following partial evaporation increases due to an increase in the salinity.
- The density of liquid seawater left behind following partial freezing increases due to an increase in the salinity (the ice that forms excludes salt and has a lower salinity than the seawater it freezes from).

Day 2 (1 hour 50 minutes)

5.5. Student exploration of density stratification and how water masses of different densities interact

Having previously identified that temperature and salinity are the primary factors that control the density of seawater and the nature of those relationships, during this subsequent class period, students explore how water masses of different densities interact, and how this can result in density stratification. This begins with a guided activity using a tank with a removable divider (Figure 2), an activity adapted from one described previously (Karp-Boss et al., 2009).

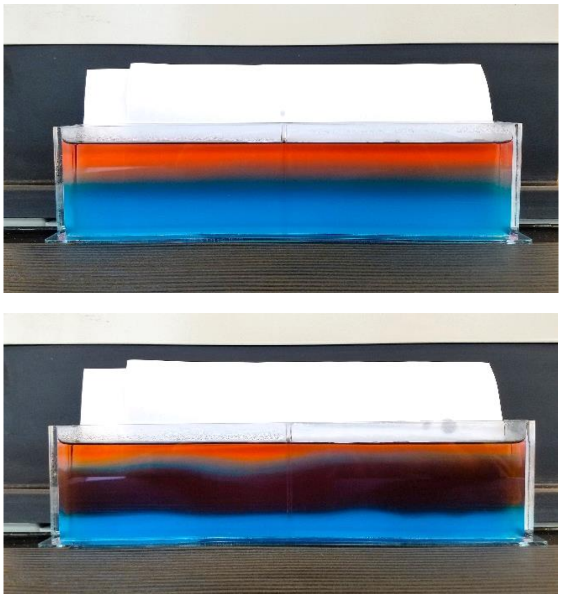

Figure 2: Top: tank after divider has been removed and two distinct layers have formed due to density stratification. **Bottom:** tank after one side of the tank has been homogenized and divider removed a second time resulting in three distinct layers forming. Internal waves are present.

This activity involves students, in their same groups of 3–4, filling one side of the divided tank with cold salty water dyed blue, and the other side with hot fresh water dyed red to assist in visualization. Students observe what happens when they remove the divider and the two masses of water are allowed to mix, resulting in a density stratified water column (Figure 2). The mixing often results in the creation of internal waves, which while not related to the learning goals of this activity, allows for a discussion with individual groups on this topic when they observe their formation. Given Westminster College's proximity to the Great Salt Lake, this often involves describing internal waves and seiches that occur in the nearby stratified Great Salt Lake and the effect this has on mixing of the upper brine layer and deep brine layer, a discussion that often extends to the cycling of mercury in the Great Salt Lake (e.g., Valdes et al., 2017; Yang et al., 2019), which helps makes the concepts more topical and allow student to make connections between density stratification and a real-world example in a system students are at least somewhat familiar with locally.

As students observe the formation of density stratification, questions prompt them to describe both what happens and explain why this occurred. Subsequent questions guide students to probe the new state of affairs in their tank to help them better understand and confirm the state of the system, including sliding their hand down through the water column to feel the presence of a thermocline. They are asked to draw a depth profile of temperature in their tank, and the concept of a thermocline is introduced and the connection between the presence of a thermocline at the small scale in their tank is made to the presence of a thermocline in the larger scale ocean is made. Students are then directed to replace the divider in the tank, stir and homogenize one side, and predict what will happen when they remove the divider again. When carried out, this creates a stratified system with three distinct layers of water. Students are asked to explain why this formed rather than a single well mixed layer, with them having to explain using the data, observations, and conclusions gleaned from their previous experiments as evidence to support their conclusions. A class discussion allows students to use their collective observations to come to conclusions about how fluids with different densities interact, specifically that denser parcels of water sink below less dense ones and give rise to stratification that resists mixing (prior knowledge required for future lessons on both the El Niño Southern Oscillation as well as biological productivity in the ocean). At this point it is emphasized that the processes at work in these small-scale explorations are the same that function at much larger scales in the ocean, which leads to the subsequent parts of the learning activity.

5.6. Inquiry activity on deep water formation and density driven thermohaline migration

The student groups then complete a written inquiry activity that uses three real world oceanographic data sets: (1) sea surface water density, (2) seawater temperature with depth across a north-south cross section of the Atlantic Ocean, and (3) seawater salinity with depth across the same north-south cross section of the Atlantic Ocean. This guided inquiry begins by having students combine their newly developed understanding of the vertical migration of parcels of water of differing densities with a map of sea surface water potential density to identify areas of the ocean where surface waters may be dense enough to sink to depth. Students also discuss why those regions may have very dense surface waters during at least part of the year. The figures with cross sections of temperature and salinities across the Atlantic Ocean then serve as models for students to consider the effect of these two separate variables on the density of seawater. This includes students assessing if the data in the cross sections of temperature and salinity are consistent with what they would expect based on their developing understanding of how parcels of water with different densities interact. The process forces students to more carefully consider simultaneously the relationships between (1) salinity and density, and (2) temperature and density given that salinity and temperature influence density independently of each other. These relationships become apparent as students answer questions that lead them to observe that water at the surface of the equatorial Atlantic has a higher salinity than the water at depth immediately below it, which is initially counterintuitive for some students. However, they then remember that temperature also influences density, and they then inspect the figure of water temperature and notice that these surface waters are also very warm. Students eventually conclude that in this case the effect of temperature must outweigh the effect of salinity on the overall density of these surface waters.

The activity then introduces students to the presence of three of the major water masses in the Atlantic Ocean that differ in density and where they form and migrate: North Atlantic Deep Water, Antarctic Bottom Water, and Antarctic Intermediate Water. Students are directed to attempt to map and label each mass of water on the cross sections of temperature and salinity, with some water masses being more easily distinguished on one figure or the other.

5.7. Demonstration of circulation created by interaction of water masses of differing densities

In this short demonstration students observe how the interaction of water masses of different densities can create vertical circulation.

The circulation apparatus (Figure 3) is filled with room temperature tap water. The reservoir around the leg of one side is filled with hot water, while the other is filled with ice water. A few drops of red food coloring are added to the side being warmed by the hot water, while a few drops of blue food

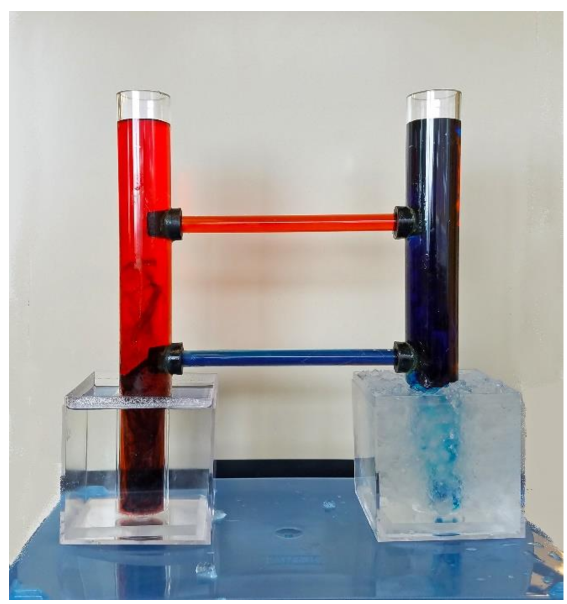

Figure 3: **Demonstration of density driven circulation** created by the interaction of water warmed on one side (red) and water cooled on the other side (blue).

coloring are added to the side being cooled by the ice water. Students observe what occurs over the next few minutes and are asked to describe what happens as the convection cell begins circulation. They're also asked to explain why this occurs, using examples or data collected in their previous experiments or earlier parts of the activity, either from the small-scale demos or from the real-world oceanographic data.

These observations serve to link the locations of deep-water formation that students identified in the previous part of the learning activity to the process of denser water sinking and driving large scale ocean circulation globally, i.e., the "ocean conveyer belt." A class discussion is used to have students summarize what they have learned thus far about thermohaline circulation in the Atlantic basin. Students then are given a blank cross section of the Atlantic Ocean and must sketch the major water masses present based on what they've learned, including areas of deep water formation, where each water mass originates and which direction each migrates. At this point most groups are able to successful map North Atlantic Deep Water, Antarctic Bottom Water, Antarctic Intermediate Water, and the Gulf Stream.

The class period ends with students summarizing in their own words the key points learned thus far, namely:

- The density of seawater controls its vertical migration in the water column.
- The density of seawater is primarily controlled by temperature and salinity.
- When two parcels of seawater of different densities meet they form two distinct layers that resist mixing.
- Vertical circulation can be caused by changes in the density of seawater in different parts of the ocean.

Day 3 (1 hour 50 minutes)

5.8. Horizontal pressure gradients and sea surface height

The third day of this learning activity has students explore how differences in seawater density give rise to differences in sea surface height, then use real world ^{14}C data to evaluate the accuracy of their developing mental model of ocean circulation, and determine the time since a deep-water mass was last at the ocean surface (time scale of ocean ventilation).

5.9. Guided exploration of the effect of density on water column height

This part of the learning activity begins with a guided exploration of the influence of water density on horizonal pressure gradients using a U-shaped manometer. Students first add 15 mL of high salinity water (dyed blue) of unknown density to a U-shaped manometer, then carefully add pure water to the other side (Figure 4). Students sketch the system that results, measure the height of the column of

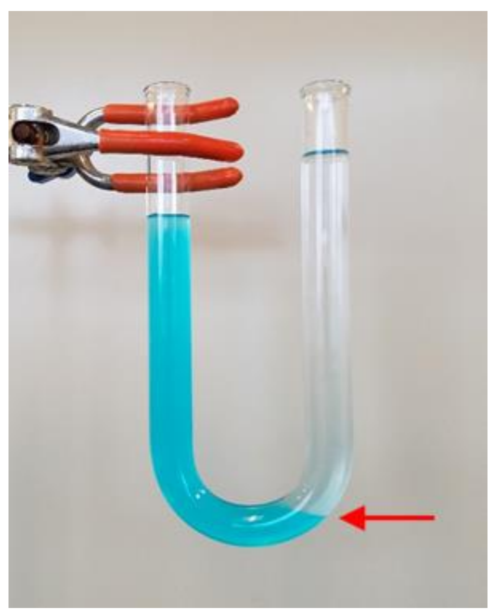

Figure 4: U-shaped manometer filled with two liquids of different densities. The arrow indicates the interface between the two liquids.

water on each side above their interface, and calculate the difference in the heights, as is often done in physics labs that use a similar approach.

The inquiry activity then guides students through a series of questions related to the density of the two solutions in the manometer, relating this back to their prior knowledge about how fluids with different densities interact. This involves students carrying out a series of thought experiments about how the system would behave if different things occurred (e.g., what if a downward force was applied to one side, etc.). Students are guided to consider what the equilibrium state implies about the downward pressure on the two sides of the manometer, eventually concluding the pressure at the interface of the two fluids must be the same on the two sides. At this point the equation used to calculate pressure is then introduced:

Pressure = (density of fluid) × (gravitational force) × (height of overlying column of fluid)

Based on their responses to the previous questions, students then calculate the density of the high salinity water in the manometer.

Invoking students' prior knowledge from earlier in the activity regarding areas of the ocean with high sea surface temperatures, they're asked to predict if those regions with a thick layer of warm, low density seawater at the surface would be expected to be areas with high sea surface height or low sea surface height.

Students then inspect two figures with real world data of sea surface height (SSH) above geoid and sea surface temperature (SST). They are first asked to describe the nature of the relationship between SSH and SST. They are also asked to determine if their previous prediction was correct or not. They then identify areas of the ocean where the relationship between SSH and SST is strong, and areas when the relationship does not appear to exist as expected. Instructor facilitation results in students forming hypotheses for what might be different in those areas of the ocean where the relationship between SSH and SST is weak or seemingly non-existent.

Students next explore the possibility that other factors might influence SSH other than just SST, and these may include subtropical gyres formed by the Coriolis Effect. As part of this process students inspect a map depicting surface ocean currents and large ocean gyres, and comparing this first to the figure of SSH, then to the figure of SST, and in each identify features present in both. Students describe how SST changes as water moves around a gyre, hypothesize why this would occur, and consider what implications this might have for heat transport globally by the oceans (this topic is explored further in a unit later in the semester on the role of the ocean in global climate and climate change). Students then must decide which, SST or ocean gyres, have a larger impact on SSH, using data and evidence to support their conclusion. This is discussed first within their group, then with the entire class with individual groups sharing out.

5.10. Using real world ^{14}C data to evaluate prior predictions of ocean circulation and determine the time since deep water was last at the ocean surface

In this last part of the multi-day ocean circulation activity students are introduced to isotopes and the activity of ^{14}C as tools for studying ocean circulation and timescales of ocean turnover.

Students read background information on the isotopes of carbon, the formation and radioactive decay of ^{14}C, half-lives, and the half-life equation. Because this oceanography course has no pre-requisites and students are not expected to have a background in science or math, this introduction is designed to be at a relatively basic level to be appropriate to the target audience, and students are assured that it's not as complicated as it may initially seem, and they shouldn't be intimidated because we're more interested in using ^{14}C data simply as a tool to understand ocean circulation. Students are walked through examples of radioactive decay measurements, calculations, and delta notation.

With students able to refer back to this background information on ^{14}C decay, the learning activity pivots to the behavior of radiocarbon in the ocean, in particular its source from the atmosphere and decay once a parcel of water is subducted, giving rise to our ability to use the activity of ^{14}C to date parcels of water in the ocean. Students then inspect a figure with real data on the natural abundance of ^{14}C measured at 3500 m depth in the water column of the ocean (Matsumoto and Key, 2004). After describing the pattern of ^{14}C abundance in the deep ocean, they then use the equations presented to them previously to calculate the age of deep waters in the equatorial Atlantic from the activity of ^{14}C. While students with a science background often find these calculations to be straightforward, substantial instructor facilitation and guidance is needed to assist other students. Students then calculate the age of the deep waters at the equatorial Pacific Ocean, then develop explanations for why the ages of deep water in the two ocean basins are so different. This requires students use their recently developed understanding of the locations of deep-water formation and thermohaline circulation in the ocean. As part of this process students evaluate if the ages they calculated for deep water in the two ocean basins is consistent with their mental model of ocean circulation developed earlier in the learning activity.

Additional questions act as precursors to a future unit on the role of the ocean in global climate and climate change, with students asked to describe all mechanism by which the ocean transports heat from low to high latitudes. They are then guided through a thought experiment in which if all deep-water forms in the North Atlantic and all upwelling of deep water occurs in the southern hemisphere, which hemisphere would they expect to be warmer, and why.

The learning activity ends with students summarizing their current understanding of thermohaline circulation of the ocean, where and why deep-water forms, and the path it takes through the ocean interior. In doing this final summary, students are required to use the figures and other real-world data from earlier in the activity to support their arguments and conclusions. This process of summarizing what was learned is done first within the groups of 3–4, then as a larger class discussion. While many students may refer to one figure or set of data when describing and supporting their explanation, instructor facilitation and prompts are often required to get them to use multiple pieces of evidence to support the different parts of their explanation. The process of requiring students to use evidence to support scientific claims is a central theme both of this oceanography course and the ISEE PDP. As this ocean circulation activity occurs early in the semester, many students are still mastering this skill, but they demonstrate notable improvements both during this activity and throughout the semester. This final summary also provides a key point at which formative assessment can take place, including to evaluate the extent to which students may still be incorporating common misconceptions into their developing understanding of ocean circulation.

6. Assessment

The same homework assignment consisting of seven essay questions on thermohaline ocean circulation was completed by students in three sequential years: one year before the full implementation of the learning activity described here, and in each of the two years after it was designed and incorporated into the course. Only minor changes to the wording of a few questions were made over this time for purposes of clarity, and the same grading rubric was employed in evaluation. The questions were designed to evaluate both process skills (ability to create graphs accurately depicting relationships, ability to read, interpret, and explain data presenting in a figure of sea surface height across the ocean, describe how they would design an experiment, etc.) and the ability to apply content knowledge to new situations (draw a cross section of the Pacific Ocean and label what water masses might exist at depth with their origin and direction of migration noted, etc.). While scores on individual questions were not recorded across the three years, student scores for the entire homework were. Student scores on the ocean circulation homework in the year before the implementation of the inquiry activity average 67.5 ± 13.1 % (mean ± standard deviation, n = 16), compared to 81.4 ± 10.8 % (n = 35) in the two years after the activity was designed and implemented, with this increase being statistically significant (*t*-test, $p < 0.001$). While these data are limited and represent only one means of assessing student outcomes, they suggest that the use of the activity using real world data and an inquiry approach improved students' development of both content knowledge and process skills.

7. Modifications to a hybrid classroom due to COVID-19

In the fall of 2020, this oceanography course and learning activity were taught in a hybrid learning environment in which students could choose to attend class in-person in a socially distanced classroom (minimum 6 feet between individuals) or to join the class virtually via Zoom. At the beginning of the semester there were more students that wanted to attend the class in person than there were spots available due to space constraints, but as the semester progressed an increasing number of students attended class virtually. Modifications were required to meet the same learning goals in this hybrid environment, in particular in order to have students still collaborate and work in teams to carry out the experiments and inquiry activity. One class stipulation was that all students were to join the class meeting on Zoom and leave their video camera on at all times unless unique circumstances prevented this, regardless of if they were attending class in-person or virtually online. Students were encouraged to do this by explaining to them how this improved the learning environment for everyone, and by giving students extra credit for keeping their video cameras on.

During discussions involving the entire class, students online joining via Zoom were included either by the instructor using a microphone and video conferencing camera capable of showing multiple locations in the classroom at the same time, or by sharing the instructor's screen, depending upon the nature of the discussion and materials being presented. Students online and in-person were able to interact with the entire class and ask questions freely during these times. To ensure students joining online could adequately view any demonstrations, these were also pre-recorded and were available as short videos posted online before class. When students worked in smaller groups, the instructor created breakout rooms in Zoom, and assigned students to ensure that each group had at least one individual attending the class in person. Students in breakout groups could still discuss their experimental design and answers to questions throughout the activity. When conducting an experiment or making observations with physical materials, the student(s) present in-person would carry out the experiments and report their measurements to their peers online, which would then record the data for their group. By breaking up the group duties in such a manner, students that were online were still invested in the process and kept engaged rather than simply observing from afar. The instructor would still migrate around the room asking each group about their answers to specific questions, aspects of their experimental design, or their interpretation of their results, with this being done in such a way that all students were asked to respond for their group at different times rather than it always being the student present in-person doing so.

Student scores on the ocean circulation homework described above indicated that student learning and performance was not significantly different between students that routinely attended class in person and those that always attended class online. However, student comments on the midcourse and end of semester evaluations suggested that students that attended in person were somewhat more engaged in class and the learning activities at times.

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