Ocean Acidification

Hands-On Experiments to Explore the Causes and Consequences

by Barbara C. Bruno, Kimberly A. Tice, Noelani Puniwai, and Kate Achilles

Ocean acidification is one of the most serious environmental issues facing the planet (e.g., Doney 2006; Guinotte and Fabry 2009). It is caused by excess carbon dioxide (CO_2) in the atmosphere. Human activities such as burning fossil fuels put CO_2 and other heat-trapping gases into the atmosphere, which causes the Earth's average temperature to increase. This increase is commonly referred to as "global warming" or "climate change," but the problem doesn't stop there. Because there is no barrier between the atmosphere and the ocean, about one-third of this atmospheric CO_2 dissolves in the ocean, where it reacts with seawater to form carbonic acid (e.g., Doney 2006): $CO_2 + H_2O \rightarrow H_2CO_3$

Like any acid, carbonic acid (H_2CO_3) lowers the ocean's pH by releasing hydrogen ions. Monthly measurements taken by the Hawaii Ocean Time-series (HOT) program show that the ocean's CO_2 concentration has increased—and its pH has correspondingly decreased—since the program began in the late 1980s.

A more acidic ocean threatens coral reefs and calcareous plankton in several ways. First, both calcareous plankton and coral reefs are made of calcium carbonate, which dissolves in acid. Second, studies have shown that calcification (growth) rates can be slowed 20%–60% in a more acidic ocean (e.g., Kleypas et al. 2006; Kuffner et al. 2007). Thus, a more acidic ocean can dissolve existing coral reefs and calcareous plankton, and also slow future growth. This can have devastating effects on our ocean environment. Plankton form the base of the marine food web: With-

FIGURE 1 Pre- and postsurvey (*correct answers italicized*)

1. The average concentration of carbon dioxide (CO_2) in the atmosphere has ______________in recent years.

   a. increased
   b. decreased
   c. remained constant

2. When carbon dioxide (CO_2) dissolves in water, it forms a(n) ________________.

   a. base
   b. acid
   c. precipitate
   d. metalloid

3. When carbon dioxide dissolves in water, the pH ____________________.

   a. increases
   b. decreases
   c. stays the same

4. Bread dough rises because yeast in the dough produces _______________.

   a. hydrogen (H_2)
   b. carbon dioxide (CO_2)
   c. oxygen (O_2)
   d. nitrogen (N_2)

5. Increasing carbon dioxide (CO_2) in the ocean results in _____________.

   a. higher salinity
   b. lower salinity
   c. benefits for reef-building corals
   d. problems for reef-building corals

6. The pH scale ranges from 0 to 14 and is a measure of how acidic or basic a substance is. Pure water is ___________with a pH of 7. Solutions with a pH less than 7 are ___________, while solutions with a pH greater than 7 are ____________.

   a. neutral/basic/acidic
   b. acidic/basic/neutral
   c. basic/neutral/acidic
   d. neutral/acidic/basic
   e. acidic /neutral/basic

7. If the pH of a solution changes from 2 to 3, there is a ___________change in acidity.

   a. 1x
   b. 2x
   c. 10x
   d. 20x

8. The salmon-fishing industry is a multibillion-dollar business that supplies food for a large population of the world. How could ocean acidification affect this industry?

   a. It would not have any impact on the industry.
   b. It would increase fishing stocks.
   c. It would decrease fishing stocks.

9. Please share your opinion and circle how you feel about the following statement: Higher levels of carbon dioxide emissions are harmful to the ocean environment.

Strongly disagree	Disagree	Neutral	Agree	Strongly agree

out plankton, the entire marine food web collapses (C-MORE 2008). Coral reefs are among the oldest and most diverse ecosystems on the planet. Although they cover less than 0.1% of the ocean floor, they are home to over 25% of the world's marine species (Spalding, Ravilious, and Green 2001). For more detailed information on ocean acidification in nontechnical language, teachers are referred to Doney et al. 2009, Doney and Feely 2009, the *ACID TEST* documentary (NRDC 2009) and the special issue of *Current: The Journal of Marine Education* on ocean acidification (Guinotte and Sano 2009).

Note: Some students may disagree with the premise that carbon dioxide from fossil fuels is causing climate change and ocean acidification, so be prepared to have a discussion on this. The ScienceDaily website (*http://sciencedaily.com*) has excellent information in everyday language on facts and myths about climate change.

FIGURE 2 Coral sand releases carbon dioxide bubbles as it dissolves in vinegar (Lesson 1)

Curriculum placement and alignment with standards

The two lessons presented here familiarize middle school students with the causes and consequences of ocean acidification. They also provide students with an opportunity to generate hypotheses, collect data through hands-on experimentation, and analyze results. These lessons can be successfully integrated into Earth science, biology, environmental science, marine science, or chemistry curricula. For Earth science classes, these lessons highlight how compounds such as CO_2 move between the ocean and the atmosphere as part of a geochemical cycle. For biology classes, students learn how changes in these cycles affect organisms and ecosystems. For environmental science courses, these lessons emphasize the effects of human activities on the environment. For marine science classes, students learn about the physical characteristics of the ocean. Finally, for chemistry classes, these lessons help students understand the importance of pH and can follow a lesson on acids and bases. These lessons are aligned with the National Science Education Standards (NRC 1996) and the Ocean Literacy Principles (NGS and NOAA 2006). They are also aligned with science and mathematics standards for the states of Hawaii, California, and Oregon, where ocean acidification is of particular relevance.

Hands-on science lessons

The first lesson includes a simple hands-on experiment using everyday materials, a short narrated PowerPoint presentation, and a press release with an accompanying worksheet. In Lesson 2, students conduct a more in-depth experiment with electronic probes to simulate the process of ocean acidification. Each lesson requires approximately an hour. Teachers located in the following areas can borrow science kits containing all materials and supplies free of charge: Hawaii (Big Island, Kauai, Maui, and Oahu), Oregon (Newport), California (Monterey Bay), and Massachusetts (Woods Hole). Please see *http://cmore.soest.hawaii.edu/education/teachers/science_kits.htm* for borrowing instructions.

Lesson 1

To begin, students take a presurvey (Figure 1), which is given again as a postsurvey at the end of Lesson 2. After taking the presurvey, students perform a simple hands-on experiment with vinegar, two types of beach sand (A and B), and magnifying glasses (optional). Students must also wear indirectly vented chemical spash goggles during this activity. Sand A is coral sand; Sand B can be any type of sand that does not contain calcium carbonate. Students put a pinch of Sand A into a Petri dish, add a few drops of acid (vinegar), and watch as the sand begins to produce CO_2 bubbles as it dissolves (Figure 2). They repeat the experiment with Sand B and note that it does not dissolve (because it does not contain carbonate). Students then watch a short, narrated PowerPoint presentation that explains how their experiment relates to ocean acidification. This presentation may be downloaded from *http://cmore.soest.hawaii.edu/education/teachers/science_kits/ocean_acid_kit.htm*. Finally, students read a summary of a press release about key findings and recommendations to tackle ocean acidification (Figure 3); students with advanced reading skills can read the original article (TNC 2008). Teachers can lead a discussion on the reading or have students complete the worksheet provided to evaluate their reading comprehension (Figure 4).

FIGURE 3 **Middle-school-level summary of press release "Scientists unveil 'Honolulu Declaration' to address ocean acidification" (TNC 2008)**

Burning coal, oil, and gas produces carbon dioxide (CO_2). Every time we drive our cars, we put CO_2 in the atmosphere. CO_2 traps heat and causes the Earth to get warmer. We call this "global warming" or "climate change." But this is only part of the problem.

There is no fence between the ocean and the atmosphere. About one-third of the CO_2 dissolves in the ocean. The dissolved CO_2 combines with seawater to form carbonic acid. This lowers the pH of the ocean. We call this "ocean acidification." Many scientists consider ocean acidification to be the biggest threat facing our oceans.

Ocean acidification causes problems for coral reefs. Coral reefs are the "rainforests of the ocean." They are home to over one-fourth of the ocean's species, so they are very important. But coral reefs dissolve in acid. We could lose all coral reefs by the end of the century, and maybe sooner.

Hawaii's reefs are in great danger. They exist at higher latitude in cooler waters, where CO_2 is absorbed more readily. Also, Hawaii's reefs are at the very edge of the region where reefs can grow—so any change in water temperature or chemistry can be deadly.

The Honolulu Declaration tells us how we can protect Hawaii's coral reefs from ocean acidification. It suggests two major strategies:

- Limit CO_2 emissions
- Help coral reefs stay healthy, so they can resist and recover

Lesson 2

In this second lesson, students work in small groups to simulate the process of ocean acidification. Again, students must wear indirectly vented chemical splash goggles during this activity. First, students activate yeast by adding warm water and sugar, causing the yeast to produce CO_2 gas. This CO_2 can be directed through rubber tubing into a chamber that contains air to simulate the increase in atmospheric CO_2 due to burning fossil fuels. This CO_2 can also be directed into a chamber that contains tap water: As the CO_2 reacts with water to form carbonic acid, the water's pH decreases. If electronic probes for measuring CO_2 and pH are available, students can measure both the increase in "atmospheric" CO_2 and the decrease in the water's pH, as shown in Figure 5. However, rather than simply showing students Figure 5, we recommend they be allowed to design the experimental setup and data-collection procedures themselves. Be sure to have them activate the yeast in the round bottles, and to stop the experiment when the yeast reaches the red line. The CO_2 probe must not get wet, and the top (black) part of the pH probe must stay dry, as well. During and after the experiment, students complete a worksheet (Figure 6) where they record, graph, and interpret their data as well as data collected by the Hawaii Ocean Time-series program. Lesson 2 concludes with students completing the postsurvey (Figure 1).

If electronic probes are not available, students can measure the decrease in pH using low-tech alternatives such as pH strips or bromothymol-blue or red-cabbage-juice indicator solutions.

Safety

The two experiments included in this paper pose no particular hazards. Only ordinary household materials (yeast, water, sugar, vinegar) and beach sand are used. However, it is always important to enforce proper labo-

FIGURE 4 **Lesson 1 student worksheet to accompany press release or summary of press release (*answers provided in italics*)**

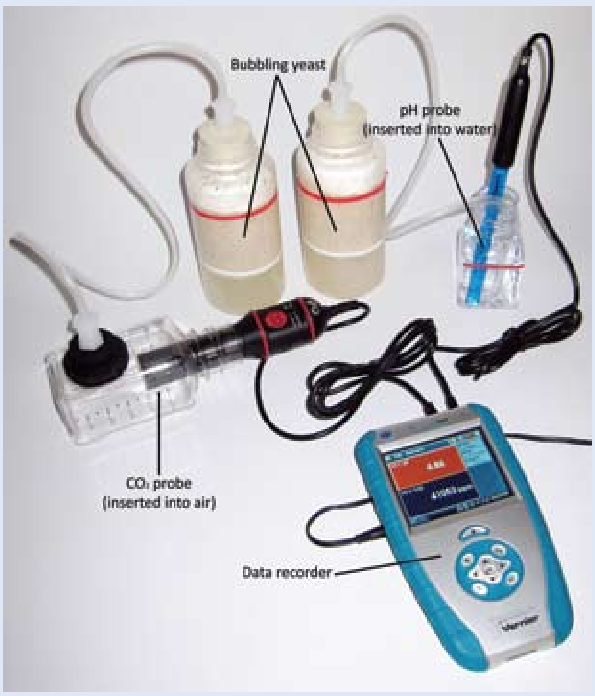
1. What do many scientists consider to be the biggest threat that oceans face today? *Many scientists consider ocean acidification to be the largest and most significant threat.*
2. In your own words, what does the “Honolulu Declaration” hope to accomplish? *The declaration hopes to prevent further ocean acidification and to protect coral reefs.*
3. What are two major strategies supported by the declaration? *(1) Reducing the amount of carbon dioxide we produce. (2) Creating healthier coral reef ecosystems so that they are better able to resist climate change.*
4. What are two actions you could take to help support these strategies? *(1) Students could support these strategies by limiting their own fossil fuel emissions. Some ways to do this are to encourage their parents to drive less and walk or ride a bike more, buy local food to reduce “plate mileage,” use less air conditioning or heat, turn off the lights when leaving a room, etc. (2) Students could help create healthier coral reefs by supporting the development of marine reserves, not allowing pollutants to enter the ocean, not touching corals, etc.*
5. If coral reefs are unable to survive due to ocean acidification, what effects would this have on your life? List three examples. *Coral reefs provide humans many benefits. For example, reefs are good for the economy and provide jobs because they support ecotourism. Reefs are the rainforests of the ocean and support a wide variety of marine life, some of which are eaten as food. Reefs also help protect the land from the impacts of waves and storms. Coral reefs are also a source of compounds used in medicines. If coral reefs disappear, our economy may weaken, there may be less seafood to eat, there will be fewer marine creatures to observe, and coastal erosion might increase.*

ratory safety procedures, such as those outlined by the National Science Teachers Association: *www.nsta.org/pdfs/SafetyInTheScienceClassroom.pdf*. As with all laboratory experiments, students should wear close-toed shoes and chemical splash goggles. Students should never put any laboratory supplies or equipment into their mouths, and eating, drinking, and gum chewing should not be permitted. Instruct students to report all accidents and injuries immediately, no matter how trivial. Backpacks and books should not be brought into the laboratory area. Work areas should be kept clean and neat at all times, and work surfaces should be cleaned at the end of each laboratory or activity. If aides or special equipment are needed to accommodate students with special needs, the needs should be established in advance by a team of appropriate experts.

Extensions

If time permits, we encourage your class to conduct one or more extension activities. What would happen to pH if seawater were used in lieu of fresh water? Can students develop an experimental procedure to safely measure the CO_2 emissions from vehicles? What else (besides coral sand) in the marine environment dissolves in acid? These are just some ideas to get stu-

FIGURE 5 **Equipment setup for ocean acidification simulation (Lesson 2)**

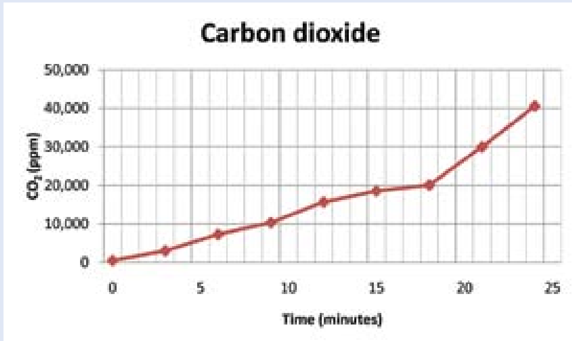


JIM FOLEY

FIGURE 6 Lesson 2 student worksheet to accompany yeast experiment (*answers provided in italics*)

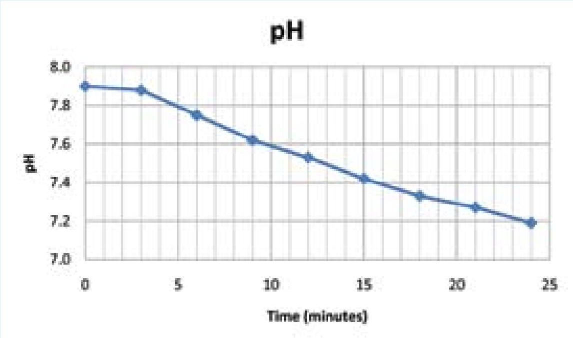
1. Make a prediction. After the yeast is activated, what will happen to the pH and CO_2 levels over time? Record your prediction here: *The yeast will create CO_2, so CO_2 levels are predicted to increase over time. Because carbonic acid is formed when CO_2 dissolves in water, the pH would be expected to decrease over time.*
2. After learning how to safely use all laboratory equipment, set up your experiment and decide when to record the readings from your sensor(s) in the following table. Also record any observations. *Measurements will vary. The initial CO_2 concentration is typically about 300–600 ppm and may even exceed 1,000 ppm if the ventilation is poor. The pH of the water should be between 6 and 8. Distilled water has a pH of 7, but tap water can contain harmless, dissolved minerals that can affect its pH. The changes in CO_2 concentration and pH will vary among groups. A few minutes after the start of the experiment, students should observe the yeast foaming, and CO_2 bubbles should be seen entering the water sample being measured by the pH group. Generally, CO_2 will increase slowly for the first several readings, and then will rapidly begin increasing. The pH value should decrease by about 1 pH unit over the course of the experiment. Remember that pH is measured on a logarithmic scale, so a decrease of just 1 pH unit represents a tenfold change in hydrogen ion concentration (i.e., becomes 10 times more acidic). The following table shows sample data and observations:*
3. What gas is the yeast producing? *Carbon dioxide (CO_2).*
4. Create a graph of the change in pH or CO_2 concentration (depending on which data you collected) over time using the grid below. Label your axes and include units. Time (in minutes) will be on the *x*-axis. *Below are sample graphs of the CO_2 and pH data. Student graphs should show similar trends. In order to make the change in pH evident in a graph of the pH data, make sure students scale the y-axis appropriately. The scale should not run from 0 to 14; it should just cover the range of pH observed in the experiment (see example below).*

a.



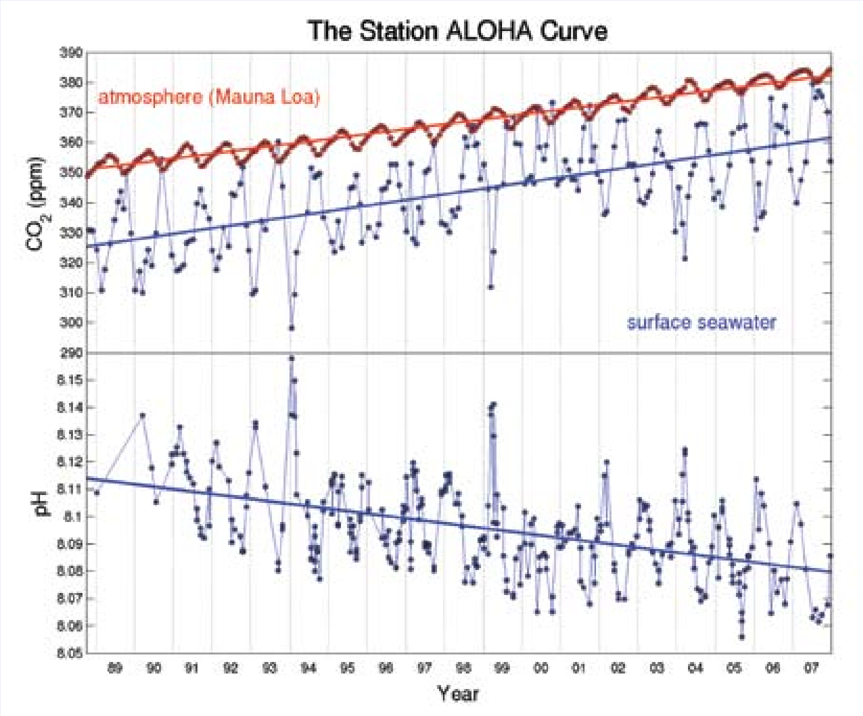
Time (minutes)	pH	CO_2 (ppm)	Observations
0	7.90	507	Before starting this experiment, we waited 5 minutes until pH reached an equilibrium value.
3	7.88	3,035	Bubbles are coming out of the tube into the water.
6	7.75	7,300	A bubble comes out of the tube about every second. The yeast is starting to foam.
9	7.62	10,300	Foam is about ½ way to the top.
12	7.53	15,690	CO_2 is starting to get really high!
15	7.42	18,567	
18	7.33	20,100	Foam is about ¾ of the way to the top.
21	7.27	30,002	
24	7.19	40,560	Foam is just below the red line. Stopped the experiment.

b.



5. What does your graph show? Did the CO_2 concentration increase or decrease? What about the pH? *Carbon dioxide increased with time, whereas pH decreased with time.*
6. What is the relationship between CO_2 and pH? Explain. *Carbon dioxide dissolves in the water and causes carbonic acid to form. This decreases the pH of the water.*
7. The graph below shows how carbon dioxide and pH have changed over the past 20 years. The *x*-axis measures time in years. The *y*-axis of the top graph measures CO_2 concentration. This top graph shows how the CO_2 concentration in both the atmosphere (red dots) and ocean (blue dots) change with time. The *y*-axis of the bottom graph measures pH of the ocean. Best-fit lines to the data are shown for all graphs. Note that (1) CO_2 concentrations have increased in both the atmosphere and ocean since the HOT program began collecting data in October 1988; and (2) as a result, the pH of the ocean has decreased during this same timeframe. Use the graph to answer the following questions:
   a. How much CO_2 was in the atmosphere in 1988? *350 ppm* In 2007? *~380 ppm*
   b. How much CO_2 was in the ocean in 1988? *330 ppm* In 2007? *~350–380 ppm*

c.



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   c. What was the pH of the ocean in 1988? *8.11* In 2007? *~8.06-8.09*

Teacher note: *The pH and CO_2 readings vary throughout the year because they are affected by the Northern Hemisphere growing season.*

8. How do the data in these graphs compare to the data you collected? *As the CO_2 concentration in the atmosphere increases, the CO_2 concentration in the ocean increases (top graph), and there is a subsequent decrease in the ocean's pH (bottom graph). These results should be very similar to what students found.*
9. According to these data and the data you collected, how will increasing atmospheric CO_2 affect marine organisms? *Because CO_2 increases the acidity of the water, increasing CO_2 will cause marine organisms that have calcium carbonate shells to have difficulty growing. Some of the organisms affected are corals and calcifying plankton. Lots of organisms depend on coral reefs for shelter and plankton for food, so the effects of ocean acidification on marine ecosystems could be devastating.*

dents started on designing and implementing new experiments with the supplies provided. Alternatively or additionally, an extension lesson can be dedicated to brainstorming ways to mitigate ocean acidification. Students can propose ways of limiting fossil fuel emissions that are relevant to their local communities (e.g., setting up a website to facilitate carpooling) and share these solutions with their local press or local officials.

Assessment

Student learning can be assessed by comparing the results of pre- and postsurveys (Figure 1). Statistical significance of any gains can be determined through the use of probability values (p-values). Teachers can also assess student learning through the worksheets provided with each lesson. Teacher answer keys to both worksheets are provided in Figures 4 and 6. For teachers who wish to use these lessons at the high school level, higher-level assessment instruments (such as more advanced readings and worksheets) and alignment with high school science and mathematics standards can be found at *http://cmore.soest.hawaii.edu/education/teachers/science_kits/ocean_acid_kit.htm.* ■

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