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EXPLORING THE COMPLEXITY OF OCEAN ACIDIFICATION

An Ecosystem Comparison of Coastal pH Variability

by Lydia Kapsenberg, Amanda L. Kelley, Laura A. Francis, and Sarah B. Raskin

Humans' combustion of fossil fuels has increased atmospheric carbon dioxide (CO_2) concentrations and triggered measurable changes in climate. These effects are moderated by the ocean, which absorbs one-third of human CO_2 emissions—but at a cost (Rhein et al. 2013). Seawater uptake of CO_2 causes large shifts in the water's carbonate chemistry. Global mean ocean pH has declined from 8.2 to 8.1 (a 26% increase in acidity) since the Industrial Revolution and is predicted to decrease by an additional 0.2–0.4 pH units in the next century (Rhein et al. 2013).

The declining trend in ocean pH due to anthropogenic carbon emissions is known as *ocean acidification* and poses a global threat to marine species (Pörtner et al. 2014). Low seawater pH (e.g., pH 7.7) weakens the structural integrity of *calcium carbonate*, the material of many marine shells (e.g., oysters, mussels) and skeletons (e.g., corals, sea urchins), and can alter the physiology and growth of species, including shellfish and fish (Kroeker et al. 2013; Pörtner et al. 2014). However, not all species respond similarly to simulated ocean acidification scenarios (Kroeker et al. 2013). To better understand how sensitive marine plants, algae, and animals are to changing pH, scientists have started to measure pH in coastal ecosystems, where they have discovered that pH can vary drastically over hours to seasonal time scales (Hofmann et al. 2011). These pH data provide an opportunity for students to explore the complexities of ocean acidification research that are relevant in science today.

In this two-hour lesson, middle school students (grades 6–8) use *pH time-series data*, a sequence of successive measurements of ocean pH over a specified period of time, to explore pH variability in three different coastal marine ecosystems. Using what they have learned, students then interpret data from a Mystery Graph. The progression of activities in this lesson follows the inquiry-based Biological Sciences Curriculum Study 5E Instructional Model (Engage, Explore, Explain, Elaborate, and Evaluate), which has been shown to enhance student performance and understanding (Wilson et al. 2010). For advanced science classes and grade levels, this lesson can be extended and adapted by providing students with the original data (pH and temperature) and scientific publications associated with the data for critical reading (available with this article's online supplements at *www.nsta.org/middleschool/connections.aspx*). Scientific themes that students should be familiar with at the start of the lesson are described in Figure 1.

This lesson adheres to *Next Generation Science Standards* (*NGSS*) topic Matter and Energy in Organisms and Ecosystems (see sidebar on p. 53 for full standards alignment) (NGSS Lead States 2013). This topic is addressed through discussion and inquiry about the processes that drive ocean pH levels in different ecosystems. This lesson also aligns to *NGSS* science and engineering practices, such as Analyzing and Interpreting Data in the portion of the lesson where students learn to read and interpret pH time-series graphs from various ecosystems and the mystery graph. Students learn to identify Patterns in the data and learn Cause and Effect through discussion of different processes that cause the variation in ocean pH shown in the graphs (addressing *NGSS* crosscutting concepts). *NGSS* science and engineering practice Engaging in Argument from Evidence is addressed when students

LYDIA KAPSENBERG

Connecting to the *Next Generation Science Standards* (NGSS Lead States 2013)

<table>
<tr><td colspan="3">Standard
MS: Matter and Energy in Organisms and Ecosystems www.nextgenscience.org/msls-meoe-matter-energy-organisms-ecosystems</td></tr>
<tr><td colspan="3">Performance Expectations
The materials, lessons, and activities outlined in this article are just one step toward reaching the performance expectations listed below.

MS-LS1-6. Construct a scientific explanation based on evidence for the role of photosynthesis in the cycling of matter and flow of energy into and out of organisms.

MS-LS2-1. Organisms, and populations of organisms, are dependent on their environmental interactions both with other living things and with nonliving factors.

MS-LS2-4. Construct an argument supported by empirical evidence that changes to physical or biological components of an ecosystem affect populations.</td></tr>
<tr><td>Dimension</td><td>Name or NGSS code/citation</td><td>Matching student task or question taken directly from the activity</td></tr>
<tr><td>Science and Engineering Practices</td><td>Analyzing and Interpreting Data

Engaging in Argument from Evidence</td><td>What is the range of pH for each ecosystem?

For the Mystery Graph, hypothesize which ecosystem these pH data came from and describe the evidence behind your reasoning.</td></tr>
<tr><td>Disciplinary Core Ideas</td><td>LS1.C: Organization for Matter and Energy Flow in Organisms
• Plants, algae (including phytoplankton), and many microorganisms use the energy from light to make sugars (food) from carbon dioxide from the atmosphere and water through the process of photosynthesis, which also releases oxygen. These sugars can be used immediately or stored for growth or later use.</td><td>Draw and label a picture of photosynthesis in the ocean. Include the words carbon dioxide, sunlight, water, oxygen, and glucose.

How do you think a decrease in the pH of the ocean might affect the organisms that live in each of the three ecosystems we looked at (tropical, temperate, and polar)?</td></tr>
<tr><td>Crosscutting Concepts</td><td>Patterns

Cause and Effect</td><td>What ecosystem has the most regular, or repeatable, pH level?

The instructor facilitates a classroom discussion identifying how biotic and abiotic drivers of pH variability contribute to the pH observations in each ecosystem.</td></tr>
</table>

Connecting to the *Common Core State Standards* (NGAC and CCSSO 2010):

CCSS.ELA-LITERACY.RST.6-8.1

CCSS.ELA-LITERACY.RST.6-8.7

CCSS.ELA-LITERACY.RST.6-8.9

FIGURE 1 Educational scaffolding

Prior to presenting this lesson, students should be familiar with the concepts listed in this figure.

Topic	Concepts
Earth's systems: Climate zones	• Basic differences between tropical, temperate, and polar zones (e.g., location, temperature, sunlight)
Earth's systems: Ocean acidification	• How fossil fuel usage has altered the chemical characteristics of the world's atmosphere and ocean • How CO_2 is absorbed by seawater, reducing pH • The relationship between CO_2 in seawater and pH • *Example lesson:* Bruno et al. 2011
Earth's systems: Water movement	• Currents, tides, and upwelling events all move bodies of water • Upwelling delivers deep, cold, low-pH water to coastal regions
Chemistry: The pH scale	• What pH is and how it varies in nature (e.g., lemon juice is acidic and soapy water is basic) • How the concentration of protons (H^+) alters pH scale • How temperature influences pH • *Example lesson:* Kelley et al. 2015
Chemistry: Seawater carbonate chemistry	• The relationship between dissolved carbon dioxide (CO_2(aq)), carbonic acid (H_2CO_3), bicarbonate (HCO_3^-), and calcium carbonate ($CaCO_3$(s), i.e., marine shells) • Impact of low pH on marine organisms with CaCO3 body parts • *Example lesson:* Kelley et al. 2015
Biology: Abiotic vs. biotic	• The difference between abiotic and biotic processes in an environment
Biology: Photosynthesis vs. respiration	• When and what molecules (CO_2 vs. O_2) are used and released during photosynthesis and respiration • How light cycles relate to these biological processes

support their reasoning for choosing to which ecosystem the Mystery Graph data belong. In addition, *NGSS* disciplinary core ideas are addressed in activities where students draw a schematic of photosynthesis and discuss the impact of pH variability in the context of ocean acidification. This lesson also covers various Climate and Ocean Literacy Principles (U.S. Global Change Research Program 2009; Ocean Literacy Network 2013).

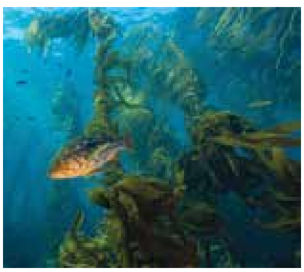
Engage: "See-Think-Wonder"

To engage students in ocean pH data analysis, the lesson starts with the "See-Think-Wonder" activity. The instructor asks students to look at representative photos from a tropical (coral reef), temperate (kelp forest), and polar (under sea ice in Antarctica) research site (Figure 2; additional photos and a worksheet are available with this article's online supplements). Using only what they can observe from the visuals, students describe what they see in each ecosystem. Next, the instructor guides students through the "think" and "wonder" portion of the activity, encouraging students to reflect on what these habitats make them think of or what they remind them of, as well as what questions ("wonder") they have about the habitats.

After students discuss their observations as a class, the instructor helps students categorize their observations as either abiotic or biotic, where *biotic* includes all living things (e.g., animals, algae) and *abiotic* includes physical characteristics (e.g., temperature, ocean currents). For example, coral reefs have little to no large algae and kelp (although corals contain microscopic algae that photosynthesize), but they do attract a high biodiversity in fish and invertebrates (biotic factors). Coral reefs are located in the tropics, where the water is warm and low in nutrients (abiotic factors).

In our class, students made associations between what they observed in the photos and their prior knowledge of these ecosystems from experiences either inside or outside of class. Some of their observations included, "It reminds me of an aquarium," and "It makes me think of a movie I saw." The "See-Think-Wonder" activity also allowed students to examine the different ecosystems with a more critical eye than they might normally use to look at photos. Because of this, students noticed the lack of life in the Antarctic ecosystem compared to the kelp forest or coral reef. Students also made observations about the amount of light present in each of the photos and made connections between the kelp forest and the organisms that live there. For example, one stu-

FIGURE 2 "See-Think-Wonder" discussion points and example ecosystem photos

Ecosystem	Biotic	Abiotic
Tropical: Coral reef  LYDIA KAPSENBERG	• Coral reefs are large structures of animals that have algae, which photosynthesize in their tissues. • Coral reefs create habitats for many invertebrates, fish, and sharks.	• The inner coral reef in a lagoon is protected from the open ocean. • Little daily water exchange with the open ocean occurs on inner coral reefs. • Warm and stable ocean temperatures
Temperate: Kelp forest  BRETT SEYMOUR, NATIONAL PARK SERVICE	• High species diversity and biomass (e.g., fishes, invertebrates, kelp, algae) • Kelp create a large biological infrastructure and habitat for other organisms.	• Upwelling events periodically bring deep, colder, dense water onshore. • Variable temperatures
Polar: Coastal Antarctica  STEVEN RUPP	• No large photosynthesizing macrophytes (no large kelp or algae) • Smaller biomass of marine invertebrates compared to kelp forests and coral reefs	• Southernmost ocean • Extremely stable and cold temperatures • Sea ice forms at the surface in winter and breaks up in summer. • No diurnal photoperiod; 24 hours of daylight in summer, 24 hours of darkness in winter

Additional photos and a worksheet are available with this article's online supplements.

dent said, "I think there is a lot of shelter for the animals because of the kelp."

After the "See-Think-Wonder" activity is completed (15–20 min.), the instructor shows students where the three ecosystems are located on a map to give them context for temperature influences based on locations. Alternatively, the instructor could ask students to predict where each ecosystem is from based on what they observed in the pictures.

The format of the "See-Think-Wonder" activity encourages student engagement in all levels of discussion. At the same time, this activity allows students to familiarize themselves with each ecosystem and identify potential processes that are different between each location. In our class, students engaged in lively discussions comparing the three ecosystems during the "See-Think-Wonder" portion. For example, prior to this lesson, our students had learned that, in the ocean, algae, kelp, and coral reefs photosynthesize just like plants on land. By observing sunlight in the kelp forest picture, students were able to draw their own conclusions about how sunlight and the presence of plant and algae life could affect the pH levels in a given ecosystem. The instructor guides this process by asking questions such as, "What happens when kelp photosynthesize? Does CO_2 increase or decrease? What does a decrease in CO_2 do to pH levels? Does that mean the ocean water pH is decreasing or increasing? What do you think happens at night to pH levels in the ocean? What makes you think that [have students explain their reasoning]?"

After students have had a chance to make their own connections between photosynthesis and pH levels, they complete a reading about the role of photosynthesis in the ocean and answer corresponding questions on the worksheet (see Figure 3; both available with this article's online supplements).

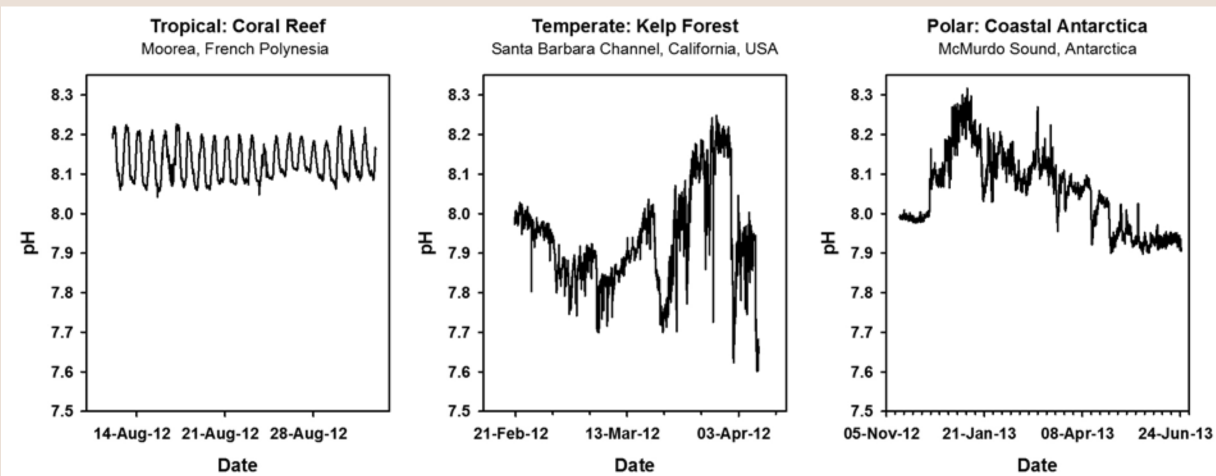
FIGURE 3 Students participate in the classroom discussion and fill out their worksheets

PHOTO COURTESY OF THE AUTHORS

Explore: Ecosystem comparison of ocean pH

For each ecosystem, students explore time-series pH data collected by scientists in coastal tropical, temperate, and polar oceans (Figure 4). Students

FIGURE 4 Marine ecosystem comparison of variable ocean pH levels over different timescales



work with partners or in small groups to identify graph characteristics, such as axis names and unit intervals, and describe what the differences in the *x*-axes of the three graphs mean. Students then identify the ranges and lengths of the pH time-series and compare patterns between all three graphs. Using a ruler, students can estimate the length of the data time-series, the minimum and maximum pH values, and approximate mean value. They should describe what ecosystems exhibit the largest or fastest changes in pH and which have regular and repeatable patterns of pH variability. When this activity was done in our classroom, conversations emerged among students as to why the kelp-forest ecosystem might have short, dramatic changes in pH levels compared to the other ecosystems.

Note: Instructors can provide advanced learners the raw time-series pH and temperature data for each site so they can generate their own graphs and compute basic, descriptive statistics (e.g., min, max, range, mean, standard deviation) for pH and temperature (see the online supplements for the data file).

Explain: Drivers of pH variability

After exploring pH data from different ecosystems, students discuss in small groups (four or five students) how differences in the ecosystems they identified in the "See-Think-Wonder" activity might explain the differences in pH variability observed at each site (Figure 4). During this activity, our students drew connections between the quantity of photosynthesizing organisms (kelp, marine plants) and the greater changes in pH levels. When looking at the stable portion of the pH graph for coastal Antarctica at the start of the time-series, one student commented, "I think the pH levels in Antarctica don't change as much because there [aren't as many] living things there." The instructor facilitates a discussion identifying the biotic and abiotic drivers of pH variability in each ecosys-

FIGURE 5 Biotic and abiotic sources of pH variability for each ecosystem

Ecosystem	Biotic	Abiotic
Tropical: Coral reef	• Coral reefs photosynthesize during the day due to the algae in their tissue. This generates a daily cycle in pH. • Without continuous water exchange, the daily pH cycles due to biological processes are amplified compared to kelp forests.	• Little daily water movement between the lagoon and the open ocean at this site reduces the influence of oceanographic processes on pH (e.g., tides, upwelling). • Stable temperatures reduce thermal effects on pH.
Temperate: Kelp forest	• Daily cycles in pH occur due to photosynthesis of kelp and algae by day, which removes CO_2 from the water. • Nighttime respiration by the kelp-forest community adds CO_2 back into the seawater, reducing the pH at night, similar to coral reefs.	• Cold, deep water has lower pH than warmer surface waters. • Upwelling events reduce pH on an order of days by bringing deep water to the surface. • Tides can influence pH on a semidiurnal timescale by moving different water masses.
Polar: Coastal Antarctica	• Summertime increase in phytoplankton (removes CO_2 from seawater) increases pH rapidly in December and January during 24-hour daylight. • Death of phytoplankton and respiration of zooplankton and bacteria at the end of summer cause a decline in pH after January. • No daily fluctuations in pH (unlike kelp forest or coral reefs), as daylight changes seasonally.	• The warming that occurs during summer (< 2°C) has a very small influence on pH variability (< 0.03 pH units). • After summer, increased mixing of deeper water reduces pH by bringing lower-pH water back to the surface.

tem and corrects any misconceptions (Figure 5). The instructor may ask questions to guide this discussion, such as, "What did you notice about the pH of the kelp-forest ecosystem compared to the other ecosystems? When we looked at the photo of the kelp-forest ecosystem [display all photos of all three ecosystems again if possible], what differences did you notice between the kelp forest and the other two ecosystems? [Students will make observations about the presence of the kelp.] How do you think the kelp affects the pH in this ecosystem?"

Note: Advanced learners can generate hypotheses about the sources of pH variability driving the observed patterns and explain how they could test their hypotheses (e.g., upwelling events could be investigated by looking at temperature data).

Elaborate

Mystery Graph

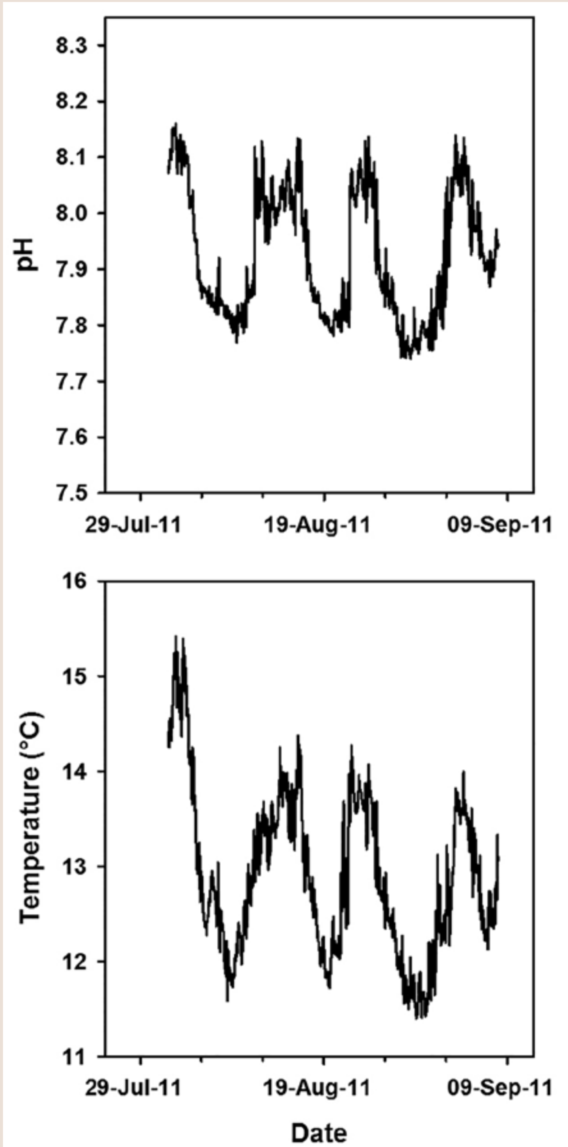
Once students form a basic understanding of pH variability, they use their knowledge to elaborate on the concepts covered during the discussion on drivers of pH variability by interpreting "mystery data" and assigning it to a marine ecosystem (Figure 6). First, students describe the pH variability of the Mystery Graph (e.g., min, max, range, approximate mean). Then, individually, students develop a hypothesis about which ecosystem these pH data came from and defend their answer using evidence from the Mystery Graph compared to the three ecosystem-comparison graphs (Figure 4). Students need to describe the sources of pH variability (abiotic and biotic) that might yield the pH observations in the Mystery Graph and how those drivers could be different between their mystery site and the matching ecosystem site from Figure 4 (e.g., differences in the duration of an upwelling event can change the duration of low pH). The instructor may also encourage students to incorporate what they have learned in the "Photosynthesis and the Ocean" reading in their answers.

Linking to ocean acidification

The final discussion activity allows students to apply what they have learned about coastal pH variability to the process of ocean acidification. To start, students draw straight lines on their pH graphs (Figure 4) representing past global ocean mean pH (8.2), present-day mean pH (8.1), and future mean pH (7.7). Students should identify which ecosystems best match average global ocean conditions of pH 8.1 and whether species alive today experience the pH level predicted for the end of the century. The instructor guides a discussion by asking questions such as, "If an animal experiences a pH of 7.7, what ecosystem does it come from? If an animal can only tolerate a pH range from 8.0–8.2, which environment is best for that species? How do you think

FIGURE 6 Mystery Graph

These pH and temperature data were collected at a temperate coastal site that experiences upwelling. Upwelling occurs for a few days at a time and can be identified by periods of simultaneous low pH (~7.8) and cold temperatures (~12°C).



a decrease in the pH of the ocean might affect the organisms that live in each of the three ecosystems we looked at (tropical, temperate, and polar)?" The discussion should focus on what environmental exposure and tolerance mean in terms of tolerance of future ocean acidification. What do students think pH levels will be like in a kelp forest if mean ocean pH declines by 0.4 pH units? Is this a large departure from current pH levels? Which ecosystems do students think will fare best under future conditions? For example, are animals that already experience pH 7.8 better equipped to experience pH 7.6 compared to species that experience pH > 8.0? Why? These are questions that scientists are currently trying to answer.

Note: Advanced students can individually write answers to discussion questions or read part of the discussion section of a scientific paper that addresses concepts intended to be covered in classroom discussion (see Ecosystem Data in this article's online supplements for suggested references).

Evaluate

Throughout the lesson, the instructor checks for understanding during small-group work and discussions. For example, during the "See-Think-Wonder" activity, the instructor may need to address misconceptions that arise about the various ecosystems. Student learning can be assessed based on reasoning and use of scientific evidence to justify their conclusions about their ecosystem choice for the Mystery Graph.

Opportunity for place-based learning

While global processes, such as ocean acidification, can be challenging to communicate, connecting students to their local environment leads to increased engagement and enthusiasm (Athman and Monroe 2004; PEEC 2008). Place-based learning using real scientific data enables students to see that their learning is relevant to their world, helps them connect with similar issues around the globe, and develops their curiosity about and interest in science. As an example, this lesson was implemented in the Oxnard Unified School District and adapted based on feedback from instructors and students. The pH data from the temperate kelp-forest site described in this lesson was collected in the local marine ecosystem. The nearby Channel Islands National Marine Sanctuary and National Park enable students to visit a kelp-forest ecosystem directly or participate in a Channel Islands Live Program, which transmits a real-time interaction with scuba divers in a kelp forest to the local and remote schools. The Channel Islands National Marine Sanctuary and National Park location is relevant and meaningful to students and instructors, as it is found just offshore of the southern California coast near where students live. These specially protected areas are focal points that encourage partnerships in science, education, technology, management, and the community.

For other school districts, this lesson can be adapted by connecting schools with the nearest marine scientists and pH datasets through online portals (e.g., *www.sanctuaries.noaa.gov*, *www.ioos.noaa.gov*, *www.pmel.noaa.gov*). This lesson presents a unique opportunity to teach ocean science in the context of the local environment and encourages place-based learning. One of the ultimate goals of bringing relevant, local ocean-science data into the classroom is to catalyze the energy and skills of students toward conservation of natural resources. A strong connection to place has been shown to be an important prerequisite to taking an active role in stewardship in one's community (Clark 2008). As participants in place-based learning, students become actively engaged in studying and responsibly addressing relevant local issues, and results have included stronger community support for

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conservation and education, higher levels of learning engagement, and a renewed sense of value for the spirit of place (Clark 2008). ■

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