Ease into Climate Change Instruction through Ocean Acidification

Abstract

Although climate change garners the bulk of headlines, ocean acidification is an equally important issue that also results from our increasing consumption of fossil fuels. As atmospheric CO$_2$ dissolves in the ocean, the ocean’s pH decreases, making it increasingly difficult for organisms that build calcium carbonate skeletons to grow and thrive. Given that these marine calcifiers—such as corals, snails, shellfish, crustaceans, and plankton—often form the base of oceanic food webs and are habitat and food resources for larger oceanic plants and animals (including humans), ocean acidification poses a serious threat. In this article, we present a series of investigations that provide evidence that increases in anthropogenic sources of CO$_2$ contribute to the acidification of the ocean, and that an increasingly acidic ocean can negatively impact marine calcifiers.

Key Words: ocean acidification; climate change; carbon dioxide; pH; marine calcifiers.

Introduction

The term ocean acidification refers to the ongoing decrease in the pH of the Earth’s oceans, which results from increasing amounts of atmospheric CO$_2$ dissolving in the ocean, forming carbonic acid and making hydrogen ions (H$^+$) more available. This increased availability of hydrogen ions has a negative effect on marine calcifiers (e.g., corals, oysters, sea snails, and some plankton) — organisms that build their shells and skeletons from calcium (Ca$^{2+}$) and carbonate ions (CO$_3^{2−}$) — because those hydrogen ions bind to available carbonate to create bicarbonate (HCO$_3^{−}$), which is unusable by calcifiers. This results in slower growth rates of shells or skeletons in these organisms.

Additionally, the shells and skeletons that marine calcifiers have been able to construct are more readily dissolved as water becomes more acidic. As a result, these organisms are less competitive and more susceptible to predation. Because marine calcifiers serve as habitat and food resources for larger oceanic animals and plants and form the base of oceanic food webs (Woods Hole Oceanographic Institution, 2021), their removal could result in a trophic cascade, spelling disaster for those organisms at the top, including fish that rely on marine calcifiers for food and habitat, as well as organisms that depend on fish, such as seabirds, whales, and even humans.

According to Jane Lubchenko, past president of the American Association for the Advancement of Science and former National Oceanic and Atmospheric Administration chief, ocean acidification is climate change’s “equally evil twin” (Associated Press, 2012) – an issue that is just as important, addresses many of the same NGSS standards, and results from the same anthropogenic sources as does climate change (the rapid increase of atmospheric CO$_2$ due to human burning of fossil fuels). In this article, we provide two investigations that provide concrete evidence in real time that (1) increases in anthropogenic sources of CO$_2$ contribute to the acidification of the ocean; and (2) a more acidic ocean environment is expected to negatively impact marine calcifiers, which form the base of oceanic food webs.

Three-Dimensional Science Learning

We bundled the following performance expectations, practices, and crosscutting concepts from the Next Generation Science Standards (Table 1; NGSS Lead States, 2013) into learning targets to guide the lesson:

1. Model human alteration of the biosphere by developing a model-based explanation for the observed pattern of atmospheric CO$_2$ increase, oceanic CO$_3^{2−}$, and decreased pH of ocean waters and identify any cause-and-effect relationships.

2. Investigate the effect of oceanic acidification on organisms with calcium carbonate shells and use the findings to revise your models to include CaCO$_3$.

The activities described below and the outputs that result from students’ engagement in them are expected to aid the students in meeting these performance expectations. Given the modeling focus of the article, it is important to highlight what models are and how they contribute to science learning. Models are representations of...
Table 1. NGSS performance expectations, practices, and crosscutting concepts that guided the lesson.

| Performance Expectations | Practices | Crosscutting Concepts | Nature of Science |
|--------------------------|-----------|-----------------------|------------------|
| HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity. | Developing and using models | Patterns | Science knowledge is based on empirical evidence |
| HS-PS1-6. Refine the design of a chemical system by specifying a change in conditions that would produce increased amounts of products at equilibrium. | Planning and carrying out investigations | Cause and effect | |
| HS-LS4-5. Evaluate the evidence supporting claims that changes in environmental conditions may result in (1) increases in the number of individuals of some species, (2) the emergence of new species over time, and (3) the extinction of other species. | Analyzing and interpreting data | | |

real-world phenomena, such as ocean acidification, but not exact copies. They provide an opportunity for students to reduce the background noise and to focus on the key aspects of the phenomenon under study. Modeling is considered an essential science practice (NGSS Lead States, 2013), which involves students’ development of models in response to a question, problem, or phenomenon through use of their existing knowledge, use of models to make sense of the phenomenon, evaluation of models through experimentation, and revision of models to reflect new understandings and increase the model’s explanatory power, or better account for all facets of the phenomenon under study (Zangori et al., 2017). In this manner, models can aid student understanding and communication of systems, and allow for making predictions and revising the models (and, thus, their understanding of the system) as insights are gained through experimental testing of the models.

In the activities described below, students engage in considering and developing a variety of types of models. For example, students are tasked with

a) developing conceptual models of what they think happens to CO$_2$ as it is released into the atmosphere and absorbed by the ocean, and then revising those models as the activities progress and more information becomes available;

b) making sense of graphical models that represent the relationship between atmospheric CO$_2$, CO$_2$ dissolved in seawater, and the pH of seawater, based on data collected at sites in the Pacific Ocean, and developing graphical models through the collection and analysis of data through experimentation;

c) devising experimental models of CO$_2$ interacting with water and of acidic water interacting with calciferous shells to represent components of ocean acidification by blowing CO$_2$ into solution and by soaking eggshells in solutions of different acidities, and

d) making use of and developing analytical models when considering pH as a logarithmic function and developing chemical equations to account for ocean acidification using symbols.

We encourage educators making use of these activities to consistently point out the different types of models represented herein and emphasize their usefulness in the context of each of the activities.

○ Introductory Instruction

Elicit Initial Student Ideas

Pose the following question to your students: “How does burning of fossil fuels affect the biosphere?” Have them write their answers on slips of paper.

Introduce the Lesson

Introduce the lesson by asking the students, “What patterns do you see in the graph?” (Figure 1). After providing the students with the opportunity to consider the question on their own, allow them to discuss their answers in small groups before soliciting a response. Guiding questions might include “What are the variables being compared?,” “What trends do you notice?,” and “What predictions can you make from the graph?” Students should observe that as atmospheric CO$_2$ increases, so does the CO$_2$ dissolved in seawater, which decreases the pH of the seawater.

Figure 1. Atmospheric CO$_2$, seawater pCO$_2$, and seawater pH as measured at the Mauna Loa and Aloha stations in Hawaii, North Pacific (Dore et al., 2009).
Review pH

The pH scale ranges from 0 to 14 and is used to indicate the acidity (pH < 7) or alkalinity (pH > 7) of a solution. The pH is equivalent to the negative decadic logarithm of the H⁺ concentration (mol/l): pH = −log₁₀ [c(H⁺)]. Review pH by discussing Table 2 when interpreting Figure 1.

Explain that reducing the pH of a solution by only 0.3 means to double the number of H⁺ in this solution. Explain that even small pH changes, such as those indicated in the graph, can be significant for biological systems. An illustrative example might be human blood, which has to be in the pH range 7.35–7.45. Increasing or decreasing the blood pH by >0.05 has negative effects on one’s health, such as reducing the blood’s ability to get rid of wastes like ammonia or even damaging the kidneys. The blood pH example can aid students in considering the sensitivity of oceanic ecosystems to small changes in pH.

Model & Predict

To address the first learning target, pose the following question: “How would you expect the increasing amount of CO₂ that humans are producing to affect the chemical nature of the ocean?” Have students model what they think happens to CO₂ as it is released into the atmosphere and absorbed by the ocean, and predict how humans’ increasing the production of CO₂ will affect the chemistry of the ocean (Figure 2).

Teacher Explanation

Inform your students that ~25% of the atmospheric CO₂ from fossil fuel burning, cement manufacture, and land-use changes is sequestered by the ocean (Le Quéré et al., 2012). Explain that developing initial models of understanding and making predictions offers an opportunity for formative assessment – and will give them a reference point as to what they knew, or thought they knew, at the start of the lesson (National Research Council, 2014). Additionally, indicate to students that scientists test and enhance their models through experimentation (as in Experiment 1).

○ Experiment 1

Pose the following question: “How would you expect the increasing amount of CO₂ that humans are producing to affect the chemical nature of the ocean?” Provide students the following materials and challenge them with planning an investigation that would test the models they created on their whiteboards. With a little prompting, they ought to be able to come up with methods similar to those described below.

Materials

• Three safety glasses per group
• Six straws per group (for students to blow air with CO₂ into solution)
• Three 300 mL Erlenmeyer flasks (or clean, empty cola bottles) per group (to house the solution)
• Water: 200 mL
• Sodium hydroxide (NaOH, c = 1 mol/L): 1 mL per flask (to make the starting solution basic)
• Thymolphthalein: 4–6 drops per flask (an acid-base indicator that indicates when the basic solution has become less basic) (Nota: Using phenolphthalein instead of thymolphthalein would be more reasonable, because the color changes from pink to clear when the pH is <8.2. A solution including thymolphthalein turns clear if the pH decreases to <9.4. In the European Union, solid phenolphthalein and solutions with a concentration >1% are classified as carcinogenic, and potentially mutagenic and toxic for reproduction. Thymolphthalein might be a safer alternative.)
• A stopwatch or timing device

Methods

1. Assign students to groups of four.
2. Refer to safety precautions: Sodium hydroxide is caustic. The students must not touch or inhale the chemicals and must wash their hands immediately after direct contact.
3. Give each group three Erlenmeyer flasks. Each flask should be filled with 200 mL water. To each, 1 mL of sodium hydroxide (NaOH) and 4–6 drops of thymolphthalein

Table 2. Relationship between pH, number of H⁺ ions, and H⁺ ion concentration.

| Factor | Value |
|--------|-------|
| pH     | 1     | 7    | 8    | 8.03 | 8.33 | 9    |
| c(H⁺) [mol/L] | 10⁻¹  | 10⁻⁷ | 10⁻⁸ | 10⁻⁸.03 | 10⁻⁸.33 | 10⁻⁹ |
| Number of H⁺ | 6*10²² | 6*10¹⁶ | 6*10¹⁵ | 5.60*10¹⁵ | 2.81*10¹⁵ | 6*10¹⁴ |

Figure 2. Initial student model of ocean acidification.
should be added, which turns the solution from clear to blue. This solution reflects the slightly alkaline nature of the ocean.

4. One of the students should serve as the timer. The others wear safety glasses.

5. Using two straws (put together to get more distance from the bubbling solution), one student blows into the blue solution of the first flask until it turns clear while another student times. The student records the time for one blower. Remind students to be careful, when blowing into the straw, not to suck the solution into the straw or blow so forcefully that the solution splashes out of the flask.

6. Next, the activity is repeated with two blowers. One student records the time while two students, each using two straws, blow into the solution of the second flask until it turns clear. The student records the time for the blowers.

7. Finally, the activity is repeated with three blowers. One student times while three students, each using two straws, blow into the solution until it turns clear. The student records the time for the blowers.

8. Each group adds to an Excel document time required for one, two, and three student blowers to turn the solution from blue to clear.

9. Students are tasked with creating a table of the average time for one, two, and three blowers to change the acidity of the solution by adding CO$_2$. 

10. Finally, students are tasked with determining an appropriate means by which to graph the data (e.g., Figure 3; using a bar chart, including 95% confidence intervals, to indicate significant differences in acidification rate with different numbers of blowers).

**Teacher Explanation**

Ask the students what conclusions they can draw from their observations. Students should be able to report that (1) adding CO$_2$ to the ocean makes the ocean more acidic; and (2) as the rate of CO$_2$ entering the ocean increases, so does the rate at which the ocean becomes more acidic.

As that CO$_2$ dissolves in the ocean and forms carbonic acid (H$_2$CO$_3$), it dissociates into bicarbonate (HCO$_3^-$), leaving an H$^+$ ion behind, which increases the acidity of the ocean (Kleypas et al., 1999):

\[
\begin{align*}
\text{CO}_2 + \text{H}_2\text{O} & \leftrightarrow \text{H}_2\text{CO}_3 \\
(1.1) \quad \text{CO}_2(g) & \leftrightarrow \text{CO}_2(aq) \\
(1.2) \quad \text{CO}_2(aq) & \leftrightarrow \text{H}_2\text{CO}_3 \\
(1.3) \quad \text{H}_2\text{CO}_3 & \leftrightarrow \text{HCO}_3^- + \text{H}^+ \\
(1.4) \quad \text{HCO}_3^- & \leftrightarrow \text{CO}_3^{2-} + \text{H}^+ 
\end{align*}
\]

Explain that this experiment is very simple compared to the investigations that scientists are conducting in the oceans; however, it models the ocean’s buffer system and offers them an opportunity to refine their initial models.

**Student Takeaway**

Adding CO$_2$ to the solution made it more acidic, and as the rate of CO$_2$ introduced to the solution increased with each additional blower, so did the rate at which the solution became acidic.

**Refine Models**

Have students enhance their initial models on the background of their experimentation (Figure 4). Pose the following question: “How do you explain the chemical reactions observed in the experiment on a macroscopic, submicroscopic, and/or symbolic level?” Give the students an opportunity to consider the question on their own before they discuss their answers in small groups. Guiding questions could include “Which reactants are involved?”, “How are the electrons spread in the molecules involved?”, “Can you think of acids resulting from CO$_2$?”, and “With respect to Le Chatelier’s principle, how would a change in concentration and temperature affect the system?” Ask the students to add the chemical equations to their models.

**Model & Predict**

To address the second learning target, pose the following question: “How would you expect an increasingly acidic ocean to affect ocean organisms’ construction of calcium carbonate shells?” Have students predict how they foresee an increasingly acidic ocean affecting organisms in the ocean (+ and − effects). Ask students to add to the previously refined model a marine food web, including organisms
with calcium carbonate shells. Have students discuss the manner in which those organisms use and create calcium carbonate shells from the calcium and carbonate that is in solution in the ocean. Ask students to consider, and model, the effect that an increasingly acidified ocean would have on the shell building of the organisms and, thus, on organisms that depend on those shelled organisms for food.

Experiment 2

Pose the following question: “How would you expect an increasingly acidic ocean to affect ocean organisms’ calcium carbonate shells?” Then provide your students the materials below and a few minutes to consider how they would go about using them to answer the question.

Materials

- Eggshells (before the day of the activity, have students collect eggshell halves and bring them, washed and dried, to class)
- Scales (digital scales with resolution to the hundredths is recommended; a scale that measures mass only to 0.1 g can hide differences in lost mass of eggshells between seltzer concentration conditions, especially the lower-concentration conditions)
- Seltzer water (i.e., water that has CO$_2$ dissolved in it): 1000 mL for each group
- Five airtight containers for each group (~500 mL volume, with airtight lids help to keep the CO$_2$ from degassing)
- Five coffee filters for each group
- 1000 mL H$_2$O for each group
- pH strips

Methods

Allow students to share and critique the different approaches they came up with for determining how an increasingly acidic ocean would be expected to affect marine calcifiers. Then introduce the following methods for carrying out Experiment 2:

1. Student groups design a data sheet to record the different measurements associated with the experiment (e.g., filter number and mass, initial weights of eggshells placed into each of solution concentrations, post-soaking eggshell weights).
2. Students mark and weigh each of the five filters.
3. Students put two eggshell halves in each of their five filters and weigh them.
4. Students enter on an Excel spreadsheet the weights of the filter, the eggshells, and the combined weight of the filter with eggshells.
5. Students mark one container 0% seltzer, one 25%, one 50%, one 75%, and one 100% seltzer.
6. Students should put the appropriate combination of water and seltzer in each container (see Table 3) and test each with a pH strip.
7. Students place eggshells in each of the five containers and put the lid on. Be sure to note which eggshells are placed in each seltzer treatment to account for their specific weights.
8. Leave the eggshells soaking in solution for at least 72 hours (a longer soak should increase the significance of the results).
9. After 72 hours, test the solution again with a pH strip.
10. Remove eggshells from the solution by pouring the entire contents of each container into a matching filter and allow to dry. The gentle breeze from a fan could expedite the process.
11. Once dried, weigh each filter with eggshells.
12. Enter the “post” weight of eggshells for each concentration of seltzer water.
13. If multiple replications of the experiment are being conducted, create a table of the average “pre” and “post” shell mass for each of the five seltzer concentrations.
14. Students are tasked with determining an appropriate means for modeling the data (e.g., Figure 5; calculate, graph, and interpret the percent change in mass of the shells for each of the five seltzer concentrations and include 95% confidence intervals).

Tips for Increasing the Dissolution of the Eggshells

- Make sure eggshells are completely dry before weighing “pre” and “post.”
- Use airtight containers to keep the CO$_2$ from degassing, perhaps using jars with a rubber seal. Checking the pH before and after would provide some indication as to whether the different solutions maintained their different acidities from start to finish.

Table 3. Appropriate combination of water and seltzer for each container.

| Seltzer | 0% Seltzer | 25% Seltzer | 50% Seltzer | 75% Seltzer | 100% Seltzer |
|---------|------------|------------|------------|------------|-------------|
| Water   | 400 mL     | 300 mL     | 200 mL     | 100 mL     | 0 mL        |
| Seltzer | 0 mL       | 100 mL     | 200 mL     | 300 mL     | 400 mL      |

Figure 5. Percent change in eggshell mass in different concentrations of seltzer water.
• Refrigerate the carbonated water prior to and during the experiment to help keep the \( \text{CO}_2 \) in solution.
• Gently crush the eggshells to provide more surface area for dissolution, rather than using two half shells (however, note that crushed eggshells are harder to get out of the container and into the filter for weighing, and the loss of even the smallest pieces of shell can impact the outcome of the investigation). Perhaps put crushed shells into a teabag and then into solution.
• Regular swirling/agitation of the jars should aid in the erosion/dissolution of the shells and mimics the natural movement of ocean water.

Teacher Explanation
Gather the students and let them explain what they have just demonstrated. Summarize that in an ocean that is increasingly acidic from anthropogenic inputs of \( \text{CO}_2 \), excess \( \text{H}^+ \) ions sequester free carbonate ions out of solution and erode the calcium carbonate skeletons and shells of existing organisms. Thus, as the acidity of each solution increases (i.e., concentration of seltzer water), the percent eggshell mass lost should also increase.

Refine Models
Have students enhance their models on the background of their experimentation (Figure 6). Ask them: “Which reactants are involved? How are the electrons across the molecules involved?” Ask the students to include their chemical equations in their model. Allow them to consider, first alone and then in groups, how the ocean becomes more acidic, and how an increasingly acidic ocean erodes the calcium carbonate skeletons and shells of existing organisms. Ask them to discuss the following question with their classmates: “How does an increasingly acidic ocean impact calcifiers’ way of life and ultimately their survival?”

Teacher Explanation
The increasing number of \( \text{H}^+ \) ions that results from the reaction \( \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+ \) will bind with existing carbonate ions \( \text{CO}_3^{2-} \) that are already in solution in the ocean, thus sequestering those carbonate ions as bicarbonate as well. The result is an increase in bicarbonate (\( \text{HCO}_3^- \)) and a decrease in the availability of carbonate (\( \text{CO}_3^{2-} \)) ions in solution. This process has a negative effect on marine calcifiers — those organisms that build their shells and skeletons using carbonate, including corals, oysters, sea snails, and plankton — because the building blocks required to do so (\( \text{CO}_3^{2-} \)) are less available. Not only does more acidic water reduce the amount of carbonate in the water column available for calcifiers, thus making it more difficult for them to produce their skeletons and shells, it also dissolves their skeletons, as well as the shells right off these organisms’ backs (Orr et al., 2005; Bednarek et al., 2012)!

\[
(2.1) \text{CaCO}_3(s) \leftrightarrow \text{Ca}^{2+}(aq) + \text{CO}_3^{2-}(aq) \\
(2.2) \text{Ca}^{2+} + \text{CO}_3^{2-} + \text{H}^+ \leftrightarrow \text{Ca}^{2+} + \text{HCO}_3^- 
\]

Student Takeaway
As oceans become increasingly acidic from anthropogenic inputs of \( \text{CO}_2 \), excess \( \text{H}^+ \) ions sequester free carbonate ions out of solution and erode the calcium carbonate skeletons and shells of existing organisms, making them less competitive and more susceptible to predation, thus reducing their immediate survivability.

Implications of Ocean Acidification
Have the students predict the effect that a reduction of marine calcifiers due to ocean acidification would have on the oceanic food web specifically and on humankind in general and discuss. Then randomly pass out students’ anonymous responses to the initial question: “How does burning of fossil fuels affect the biosphere?”

As students read their anonymous peers’ responses aloud, tally the different ways they mention that burning of fossil fuels affects the biosphere, and note how many mention ocean acidification. This would be a great spot to talk about ocean acidification as a “twin” phenomenon to climate change, with similar antecedents. Point out that, at first blush, people may not consider that fossil fuel consumption can impact the acidity of the ocean. It may be even less readily apparent that a more acidic ocean will likely decrease the abundance of marine calcifiers and, thus, threaten the health of oceanic ecosystems and even the students’ own way of life.

○ Conclusion
The scientific inquiry described here engages students in understanding the effects of anthropogenic \( \text{CO}_2 \) on the acidification of the ocean and the oceanic food web. These activities align with NGSS standards, and aid students in making connections between human activity and environmental degradation. Engaging students in scientific inquiry regarding ocean acidification should facilitate an easier transition into teaching about climate change. The issue of ocean acidification can be an interesting starting point to a discussion of chemical phenomena like acids and bases, energy/enthalpy, and chemical equilibrium, making them more tangible.

○ Acknowledgments
We thank the following individuals for their contributions to the article: Tiger Gordon for sharing insight on chemistry in the classroom, Laura Zangori for stimulating discussions about modeling, and Pat Friedrichsen for inspiring us to share these ideas with the biology education community at large.

Figure 6. A formal model for the chemical process of ocean acidification and effects on organisms with calcium carbonate shells.
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