Endeavor
STEM Teaching Certificate Project

Investigating Ocean Acidification

Grades 11 & 12
AP Environmental Science
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BIG IDEAS

- Human consumption of fossil fuels coupled with deforestation is releasing more CO_2 into the atmosphere than can be sequestered by photosynthesis, leading to an overall increase in atmospheric CO_2 levels.
- As the largest carbon sink in the world, the ocean exchanges CO_2 (and excess heat) with the atmosphere. As atmospheric CO_2 levels increase, more CO_2 is dissolved in the ocean. This is coupled with an increase in seawater temperatures as atmospheric temperatures increase due to global warming.
- When CO_2 dissolves in water, it undergoes the following reaction:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO^{3-} + H^+ \leftrightarrow CO_3^{2-} + H^+$$

Carbon dioxide + Water ↔ Carbonic acid ↔ Bicarbonate + Hydrogen ion ↔ Carbonate + Hydrogen ion

- The increase in hydrogen ions (H^+) in the ocean decreases the pH of the ocean, causing ocean acidification.
- For organisms with calcium carbonate shells (typically synthesized form calcite or aragonite) such as oysters, corals, and crustaceans, ocean acidification can affect their ability to grow their shells as calcium carbonate becomes less available in more acidic seawater.

EDUCATION STANDARDS

AP Environmental Science, Unit 9: Global Change (College Board, 2020)

- **Big Idea 2, Sustainability**: How can local human activities have a global impact
- **Enduring Understanding STB-4**: Local and regional human activities can have impacts at the global level.
- **Science Practice 1C, Concept Explanation**: Explain environmental concepts, processes, or models in applied contexts.
- **Learning Objective STB-4.H**: Explain the causes and effects of ocean acidification.
- **Essential Knowledge (EKs)**:

- **STB-4.H.1**: Ocean acidification is the decrease in pH of the oceans, primarily due to increased CO_2 concentrations in the atmosphere, and can be expressed as chemical equations.
- **STB-4.H.2**: As more CO_2 is released into the atmosphere, the oceans, which absorb a large part of that CO_2, become more acidic.
- **STB-4.H.3**: Anthropogenic activities that contribute to ocean acidification are those that lead to increased CO_2 concentrations in the atmosphere: burning fossil fuels, vehicle emissions, and deforestation.
- **STB-4.H.4**: Ocean acidification damages coral because acidification makes it difficult for them to form shells, due to the loss of calcium carbonate.

NGSS Performance Expectation(s)

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Constructing Explanations and Designing Solutions: • Make a quantitative and/or qualitative claim regarding the relationship between dependent and independent variables. • Design, evaluate, and refine a solution to a complex real-world problem, based on scientific knowledge, student-generated sources of evidence, prioritized criteria, and tradeoff considerations. **Developing and Using Models**: • Develop a model based on evidence to illustrate the relationships between systems or components of a system. • Develop and/or use a model (including mathematical and computational) to generate data to support explanations, predict phenomena, analyze systems, and/or solve problems. • Evaluate merits and	**HS-LS2-2**. Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales. • LS2.C: Ecosystem Dynamics, Functioning, and Resilience: A complex set of interactions within an ecosystem can keep its numbers and types of organisms relatively constant over long periods of time under stable conditions. If a modest biological or physical disturbance to an ecosystem occurs, it may return to its more or less original status (i.e., the ecosystem is resilient), as opposed to becoming a very different ecosystem. Extreme fluctuations in conditions or the size of any population, however, can challenge the functioning of ecosystems in terms of resources and habitat availability. **HS-LS2-5**. Develop a model to	**Stability and Change**: For both designed and natural systems, conditions that affect stability and factors that control rates of change are critical elements to consider and understand. • Much of science deals with constructing explanations of how things change and how they remain stable. Change and rates of change can be quantified and modeled over very short or very long periods of time. Some system changes are irreversible. **Systems and System Models**: A system is an organized group of related objects or components; models can be used for understanding and predicting the behavior of systems • Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions — including energy, matter and information flows — within and between systems at different scales.

- limitations of two different models of the same proposed tool, process, mechanism, or system in order to select or revise a model that best fits the evidence or design criteria. **Planning and Carrying Out Investigations**: - Plan an investigation or test a design individually and collaboratively to produce data to serve as the basis for evidence as part of building and revising models, supporting explanations for phenomena, or testing solutions to problems. - Make directional hypotheses that specify what happens to a dependent variable when an independent variable is manipulated. **Using Mathematics and Computational Thinking**: - Use mathematical representations of phenomena or design solutions to support and revise explanations. **Analyzing and Interpreting Data**: - Analyze data using tools, technologies, and/or models (e.g., computational, mathematical) in order to make valid and reliable scientific claims or determine an optimal design solution.	illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere. - LS2.B: Cycles of Matter and Energy Transfer in Ecosystems: Photosynthesis and cellular respiration are important components of the carbon cycle, in which carbon is exchanged among the biosphere, atmosphere, oceans, and geosphere through chemical, physical, geological, and biological processes. **HS-LS2-7**. Design, evaluate, and refine a solution for reducing the impacts of human activities on the environment and biodiversity. - LS2.C: Ecosystem Dynamics, Functioning, and Resilience: Moreover, anthropogenic changes (induced by human activity) in the environment — including habitat destruction, pollution, introduction of invasive species, overexploitation, and climate change — can disrupt an ecosystem and threaten the survival of some species. - ETS1.B: Developing Possible Solutions: When evaluating solutions it is important to take into account a range of constraints including cost, safety, reliability and aesthetics and to consider	**Cause and Effect: Mechanism and Prediction**: Events have causes, sometimes simple, sometimes multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science and engineering. Cause and effect relationships can be suggested and predicted for complex natural and human designed systems by examining what is known about smaller scale mechanisms within the system. Changes in systems may have various causes that may not have equal effects.

	social, cultural and environmental impacts.	

Math: **Tennessee Integrated Math Standards (Tennessee Department of Education, 2020)**

- **M1.N.Q.A.1** Use units as a way to understand real-world problems.
  a. Choose and interpret the scale and the origin in graphs and data displays.
  b. Use appropriate quantities in formulas, converting units as necessary.
  c. Define and justify appropriate quantities within a context for the purpose of modeling.
  d. Choose an appropriate level of accuracy when reporting quantities.
- **M1.A.CED.A.2** Create equations that describe numbers or relationships.
  a. Graph equations with two variables on coordinate axes with labels and scales, and use the graphs to make predictions.
- **M1.S.ID.A.1** Summarize, represent, and interpret data on two categorical and quantitative variables.
  a. Represent data from two quantitative variables on a scatter plot, and describe how the variables are related.
- **M1.S.ID.B.4** Interpret linear models.
  a. Explain the differences between correlation and causation. Recognize situations where an additional factor may be affecting correlated data.

ELA: **Tennessee English 11-12 Standards (Tennessee Department of Education, 2017)**

- **11-12.RI.KID.1** Analyze what a text says explicitly and draw inferences; support an interpretation of a text by citing and synthesizing relevant textual evidence from multiple sources.
- **11-12.RI.CS.4** Determine the meaning of words and phrases as they are used in a text, including figurative, connotative, and technical meanings; analyze how an author uses and refines the meaning of a key term or terms over the course of a text.
- **11-12.RI.IKI.8** Evaluate how an author incorporates evidence and reasoning to support the argument and specific claims in a text.

ITEEA Standards (International Technology and Engineering Teachers Association, 2020)

- **STEL-4P**. Evaluate ways that technology can impact individuals, society, and the environment.

MEASURABLE STUDENT LEARNING OBJECTIVES

Students will be able to:

- Analyze and interpret graphs/data to identify trends between atmospheric CO_2 levels, oceanic CO_2 levels, and pH
- Plan and carry out an investigation to collect data using probes correlating changes in CO_2 concentration with changes in pH and calcium concentration in seawater
- Construct an explanation regarding the chemical relationship and reaction between increasing CO_2, pH, and calcium availability in the ocean
- Obtain, evaluate, and communicate information from a scientific article to analyze the impact of ocean acidification on urchin growth and development
- Obtain, evaluate, and communicate information regarding current and/or future mitigation strategies to ocean acidification within a specific, local context

STEM INTEGRATION

Science (Environmental science, biology, chemistry)

In this unit, students are investigating the causes and effects of ocean acidification, an environmental challenge caused by climate change. This is an environmental, chemical, and biological problem. Students need to understand the environmental science behind the anthropogenic release and increase of CO_2 into the atmosphere, which enters the oceans; the set of chemical reactions that take place when CO_2 enters the oceans; and the biological use of calcium carbonate on the growth and development of shell-building organisms coupled with the impact a reduction in that material has for the fitness of the individual and species. To fully understand this global issue, students need to understand the different pieces of the puzzle that are provided by different scientific domains.

Additionally, students will be reading a published journal article, "Responses of sea urchin larvae to field and laboratory acidification" (Foo et al., 2020). This is intentionally included to develop students' scientific literacy skills as they read, analyze, and evaluate authentic research and scientific communication. This article, which is included with scaffolded questions, is intended to help expose students to, and prepare them for reading science as it is communicated within the scientific community to other scientists. Furthermore, this article highlights how scientific research is designed and conducted in the lab and the field, allowing students the opportunity to gain exposure to both and evaluate the purposes, affordances, and limitations of both avenues of research.

Math

In this unit, students need to have an awareness of building and analyzing graphs and graphical trends, logarithms (pH scale), and mathematical relationships between variables. During the first exploration, students need to dig through and make sense of data presented in a graph in order to analyze trends and make claims about CO_2 and pH. In the lab experience, students will collect their own data and make sense of relationships between variables on a graph. To truly understand the factors that play into this environmental issue and their relationships, students need to engage in mathematical analysis and reasoning.

Engineering

Environmental science is about understanding the human impact on the planet. But, it is moreover the understanding of how humans can design and implement strategies to mitigate environmental challenges and construct a more sustainable future. As such, engineering is key to designing solutions to problems, problems that oftentimes originate as questions that are asked and investigated by science. To conclude this unit, students will research current and/or proposed solutions/designs to ocean acidification and evaluate their effectiveness while proposing ways in which these solutions can be enhanced or expanded to protect the life that exists within our oceans and the individuals that rely on them. Environmental science is – and should be – hopeful. Humans can change and better the planet and engineering is the key to imagining and building that future.

NATURE OF STEM

Environmental science is both an incredibly interdisciplinary and human endeavor, perhaps even more so than other scientific domains. In this lesson, students are immersed in the nature of science (NGSS Release, 2013a) in a variety of ways, including:

- **using a variety of methods**: ocean acidification lab investigation, Woods Hole online simulation, Foo et al. (2020) research article, NASA data visualization studio
- **gathering and analyzing evidence-based empirical evidence**: generating hypotheses to gather qualitative and quantitative data from the lab/other data sources, identifying and analyzing trends from NASA and NOAA data
- **using models/mechanisms/theories to explain the natural world:** linking the hands-on modeling of the micro-level (CO_2 and pH levels) to understand and explain observations on the macro-level (global trends in ocean acidification and impact on organismal growth and development)

To fully understand the global environmental challenge of ocean acidification, students need to investigate the chemistry, biology, and environmental science behind the root cause and the effects of increasing CO_2 emissions, decreasing ocean pH, decreasing calcium carbonate availability for organisms, and change to food chains and ecosystems. Thus, students need to **gather and synthesize information from a wide variety of perspectives and sources** using a combination of observations and inferences (NSTA, 2024).

Yet, students cannot forget that as science address questions about the natural world, it is – at its core – a human endeavor. The process of **doing science is driven by people** and the **results of doing science are communicated to and impact the lives of people** (NSTA, 2024). This unit examines the impacts of ocean acidification, a process that affects the organisms of the sea just as much as it impacts those who rely on the ocean – the people who have historical and cultural ties to it, the people who live on/around it, the people who make their living relying on the organisms within it, and the people who are tied to it from hundreds or thousands of miles away. As students do this, it is my hope that they understand that science does not always provide answers; instead, **science provides directions and considerations that must also incorporate ethics and societal values** to understand impacts and resolve issues (NGSS Release, 2013a). Thus, this unit is designed to conclude with people in mind, by having students evaluate local contexts and the actions that are being taken in those contexts to help mitigate the environmental challenge of ocean acidification. This final component also ties in the engineering practices and the nature of engineering, the ideas that **designs provide tentative solutions for problems of global and human significance** (Deniz et al., 2020) – designs that must rely on and work with and work for people, organisms, and local contexts.

MATERIALS NEEDED

Access to a technology (computer, tablet, phone)

Copies of handouts:

- **Link at all handouts**: https://docs.google.com/document/d/1VySSI02-imu91koH6DP0hUEBsUhk2OnSlmxgMKA8p2s/edit?usp=sharing

- Handout A: Global Oceanic Data
- Handout B: Ocean Acidification Lab
- Handout C: Ocean Chemistry Click and Learn
- Handout D: Sea Urchin Article (Foo et al., 2020)
- Handout E: Local Oceanic Data Presentation and Rubric

Ocean Acidification Lab materials (per group):

- ~3.5 g of yeast
- ~1 g of sugar
- 150 mL of water, heated to 38 - 43°C
- 150 mL ocean water (https://algaeresearchsupply.com/products/artificial-sea-water-kit-500ml)
- Biochamber set up
    - Plastic bottle
    - Biochamber
    - Aquarium tubing
    - 2 rubber stoppers
- LabQuest with pH, calcium, and salinity probes, and carbon dioxide sensor

ENGAGING CONTEXT/PHENOMENON

The engaging phenomenon for this learning sequence is a combination of two images and two graphs (available here: **Handout A: Global Oceanic Data**) . The first component to the phenomenon shows a pencil sea urchin and an American lobster's development under present ocean conditions and under projected ocean conditions. Students are asked to follow the ***See-Think-Wonder*** (Project Zero, 2022) protocol as they make observations of the urchin and the lobster. Although both organisms were allowed to grow and develop under the same ocean conditions (i.e., same level of CO_2 for both current and predicted oceanic levels between the two species), the patterns of growth and development are different – the urchin gets smaller whereas the lobster grows larger. This is intended to "trouble" the phenomenon a bit, as it is not a straightforward observation that organisms will/are getting smaller in size. Ultimately, the effects of ocean acidification will be different in different locations and with different organisms – a key nuance to highlight as students explore the overall environmental challenge of ocean acidification. Additionally, the conditions in which these images have been taken have been intentionally left slightly vague for the student as the background does not outline what is different between the current and predicted oceanic conditions. Thus, it is expected that students generate questions as to why organisms have different responses, what is causing changes in growth patterns, what is different about the current and predicted oceanic conditions, etc.

The next set of data students will explore are graphs from NOAA data showing the trends between atmospheric and oceanic CO_2 concentrations and the trend between oceanic CO_2 concentration and pH levels. This is intended to help provide some context to the oceanic conditions from the first set of qualitative data and observations they will generate from the images. Although this set of data allows students to begin to understand that there is a direct relationship between atmospheric and oceanic CO_2 concentrations and an inverse relationship between oceanic CO_2 concentration and pH level, students will not understand why or how that relationship exists. Thus, this data will set up and move student inquiry into the next phase where they will model, investigate, and quantify that relationship in the lab.

DATA INTEGRATION

The specific data sources are presented in underlined hyperlinks after each description.

Data Presented to Students

Engage

In this phase, students will be making observations from qualitative and quantitative data to generate questions about the phenomenon (growth patterns of organisms) and identify trends seen in oceanic conditions (CO_2

levels and pH). Data includes:

- Sea urchin and lobster growth patterns (qualitative): Woods Hole Oceanographic Institute
- Atmospheric and oceanic CO_2 levels (quantitative): NOAA
- Oceanic CO_2 and pH levels (quantitative): NOAA

Explain

At this point, students will understand that increasing CO_2 leads to a decrease in ocean pH and the chemical reactions by which the process of ocean acidification occurs. Connecting back to the initial phenomenon (the contrast in growth patterns observed between the urchin and lobster), students will explore NASA surface pH level data to understand that pH levels change at different rates in different locations across the globe. Data includes:

- Oceanic surface pH levels (quantitative/qualitative): NASA

Elaborate

Students will read a primary literature source to understand how ocean acidification is predicted to affect a specific organism, the sea urchin. This data is intended to help students answer their questions about the phenomenon from the opening sequence, particularly how does increasing CO_2 impact organisms' growth and development. Students understand a general idea from the "Explain" click and learn, but this grounds that understanding in a specific context, examining a particular species. Data includes:

- Sea urchin growth and development (quantitative/qualitative): Foo et al. (2020)

Evaluate

In this final phase of the lesson, students will apply and extend their understanding to specific contexts. Students will engage in gathering data about the conditions of a local area as they investigate the impacts of ocean acidification on a particular organism in that region. This is intended to summarize students' understanding about the general trend of ocean acidification, while giving them the opportunity to understand that the impacts of ocean acidification will be different in particular regions across the globe. Data includes:

- Oceanic CO_2 and pH levels from coastal moorings (quantitative): NOAA

Data Collected by Students

Explore

In the lab, students will collect their own data from pH and CO_2 probes to understand and quantify the relationship between those two variables. They will be collecting quantitative data as they observe an increase in CO_2 concentration and a decrease in pH levels. This will help them further quantify the trends they observe in the previous NOAA data and help prepare them to further investigate the chemical reasons why these trends exist.

TEACHER BACKGROUND KNOWLEDGE

The ocean is the largest carbon sink on the planet as upwards of 31% of the CO_2 on Earth exists in the ocean (Gruber et al., 2019). Once CO_2 enters the ocean, it can either dissolve in the water, or eventually through the process of sedimentation, sink to the bottom of the ocean as a physical precipitate. However, as more CO_2 is released to the atmosphere via anthropogenic sources such as the burning of fossil fuels, more CO_2 enters the oceans, thereby reducing the amount of CO_2 in the atmosphere. But, that's not a good thing.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO^{3-} + H^+ \leftrightarrow CO_3^{2-} + H^+$$

Carbon dioxide + Water ↔ Carbonic acid ↔ Bicarbonate + Hydrogen ion ↔ Carbonate + Hydrogen ion

Examine the series of chemical reactions above. When CO_2 enters the ocean and reacts with water molecules, it forms carbonic acid. Carbonic acid then releases a free hydrogen (H^+) ion into the water, becoming bicarbonate. Bicarbonate donates another free H^+ ion, further leading to a decrease in pH (as pH is a measure of the H^+ concentration in a solution). This causes the ocean to become more acidic. Because the reactions are in equilibrium, an increase in CO_2 on the left side of the equation shifts the overall reaction to the right, causing the ocean pH to continually decrease.

Free carbonate in the ocean combines with calcium to form calcium carbonate. Calcium carbonate, which exists in more soluble forms, such as calcite and aragonite, is used to build the shells of organisms such as urchins, clams, and mussels. However, as carbonate levels in the ocean rise (due to the decomposition of CO_2), the reaction shifts back to the left and the carbonate becomes bicarbonate, a form of organic carbon that shell-building organisms cannot use. Thus, calcium carbonate concentration overall becomes limiting to those organisms, impeding their ability to build shells. Furthermore, excess H^+ ions can enter the tissues of these organisms, forcing them to expend energy to return their internal pH back within their range of tolerance. Yet, this overall trend is different for various organisms such as the lobster, which has been shown to grow thicker shells and larger bodies which is hypothesized to help protect them from the effects of increasing H^+ concentration. Overall, changes in ocean chemistry at the levels of producers and primary consumers due to a reduction in free carbonate can have significant impacts on the trophic pyramid, leading to trophic collapse.

Suggested sources:

- https://earth.jpl.nasa.gov/news/28/how-is-climate-change-impacting-shellfish-in-the-ocean/
- https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification
- https://www.nature.com/scitable/knowledge/library/ocean-acidification-25822734/
- https://www.epa.gov/ocean-acidification/understanding-science-ocean-and-coastal-acidification
- https://www.whoi.edu/oceanus/feature/ocean-acidification-a-risky-shell-game/

DIFFERENTIATION OF INSTRUCTION

- Students will have access to technology (laptops, tablets, phones) during the lesson. Students will have access to both physical and digital copies of all handouts and graphic organizers allowing them choice in either writing or typing notes, responses, etc.
- The NOAA data presented to students links out to Plotly (https://chart-studio.plotly.com/create/?fid=dvignoles:12#/) which allows students to manipulate the presentation of data using a multitude of accessibility tools (e.g., changing font size, changing background color/contrast, etc.).
- For the lab, directions will be provided, projected on the board in shorter and more succinct steps, and the sample procedure will be modeled for all students before beginning. Students are encouraged to ask questions of their peers and teacher if they need any assistance with setting up and or using the equipment.
- For the research article, the text has been chunked into sections, each containing questions to guide students through their analysis. Reading strategies, such as highlighting or circling new vocabulary, will be modeled for students before they begin analyzing the text. Furthermore, it is suggested that the teacher model how to breakdown the text with students in an example before students begin.
- In their final design project, students have a choice in the medium of expression, allowing all students to

differentiate their individual voice and creativity. For students who may need assistance in laying out their project, a sample template is provided.

- Students will be working in groups throughout the process, with built in times for individual and peer collaboration.

REAL-WORLD CONNECTIONS FOR STUDENTS

Oceanic acidification is both a present and forthcoming environmental challenge. To that end, this lesson is rooted in a real-life issue: students are investigating historical trends in ocean conditions and chemistry, current conditions, and projected impacts on the health of the ocean and the organisms that rely on it. Most students have a connection to or an idea of the ocean or a body of water. Oceans are consistently being talked about in conversation or in media, from coral bleaching, to hurricanes, to organisms that live in the ocean. President John F. Kennedy once remarked that we are all tied to the sea. And, that remark is especially salient as people are still connected to the sea, even if they do not live near it or visit it. Our food comes from the sea, our weather is shaped by the ocean, our global climate – and climate change – is impacted by the ocean (the very phenomenon investigated in this lesson).

While this lesson is designed to investigate the science behind ocean acidification, it would be remiss to not address the connections various groups of people have and continue to hold and form with the ocean. Science is not neutral and nor is it removed from place. This lesson – like all lessons – must first tap into students' funds of knowledge, by focusing on the relationships and responsibilities between people and place –where are students engaged in science, how are they engaged in science, and to what end and with what considerations are they engaged with science (Bang, Marin, & Medin, 2018). To that end, it is my recommendation that before any component of this lesson be placed in front of students, that students engage in a conversation about what they know about the ocean and what their connections are to it. This is intended to help all students come to understand that, even if they have not been to the ocean or, as is the case with my students who do not live near the ocean, all individuals are connected to and impacted by the ocean in some way. Additionally, in this conversation, values and norms can be addressed reminding students that science is a human endeavor, science has impacts on individuals and their livelihoods, and that even if they themselves do not see an issue such as ocean acidification as significant to them, it may be significant to others in the room. Ultimately, students should be encouraged to think about and find the ways in which the (changing) ocean has a connection to them – from recreation and travel, to food sources, to weather we experience, etc.

INTEGRATION POSSIBLE MISCONCEPTIONS

Ocean acidification is a slightly misleading name. Many students are aware of everyday acids (vinegar, lemon juice, etc.) and may have a conception of the pH scale. The ocean is naturally basic (~8.1) and ocean acidification implies that the ocean will become an acid (drop below pH 7), although in the immediate future this is unlikely to occur. Care should be taken to help students understand that although the pH is dropping, therefore moving towards the acidic end of the pH scale, the ocean is not becoming an acid – it is still basic, just becoming less basic.

Many students may think that as ocean acidification takes place, it will dissolve the shells of organisms, such as clams and oysters. This has been **experimentally shown to be true** under extremely high levels of carbon dioxide (2,850 ppm vs. 425 ppm, current) (Woods Hole Oceanographic Institution, 2024). **In the field**, scientists have observed the shells of pteropods, microscopic organisms that grow to be less than 1 cm in diameter begin to dissolve in seawater (Kennedy, 2014). However, both cases are two extremes of a spectrum of environmental conditions. Thus, the instructional focus should primarily emphasize the difficulty in most organisms to build shells over the dissolution of organisms' shells.

Ocean acidification is not uniform and will not impact all organisms and locations equally. Cooler, deeper waters are currently more affected than warmer, shallower waters (Barker & Ridgwell, 2012) due to water chemistry and differing saturation levels of aragonite. Additionally, not all organisms respond the same. In the lab, it has been demonstrated that ocean acidification caused clams, oysters, and scallops to decrease in size whereas the blue crab, American lobster, and a large prawn grew larger, more robust shells (Woods Hole Oceanographic Institution, 2024). Therefore, it is imperative that students understand both the general global trend and the nuances and specific impacts that trend will have in particular contexts.

LESSON PROCEDURE

5E	Details of 5E Lesson Implementation
Engage SWBAT: Analyze and interpret graphs/data to identify trends between atmospheric CO_2 levels, oceanic CO_2 levels, and pH	**Procedure:** Students will begin the lesson by exploring pictures of sea urchins and lobsters grown in present-day ocean conditions and projected ocean conditions. Students will use a *See-Think-Wonder* protocol (Project Zero, 2022) to guide their analysis. For each image, students will ***individually*** observe what similarities or differences they see between each growth condition (What do you see?) and reflect on those observations (What do you think about that?). Then, they will share with their ***group*** and identify some questions they have or avenues they might need to investigate (What does it make you wonder?). Next, students will examine NOAA data to first examine the trends in atmospheric and ocean CO_2 levels. Students will identify the rise in atmospheric and ocean CO_2 levels and understand the reason for seasonal oscillations in measured levels, due to changes in global photosynthetic activity. Once students interpret the atmospheric and oceanic CO_2 data, they will then think about another layer of data by examining the change in oceanic CO_2 levels and pH levels. Students will be asked to identify the correlation between dissolved CO_2 levels and pH levels, again analyzing the oscillation in levels. This data will lead students to identify the correlation between increasing oceanic CO_2 levels and decreasing pH levels. **Modifications** This introductory lesson engages students in the *See-Think-Wonder* thinking protocol. If students are not familiar with this resource, teachers should model a sample protocol to help students work through the following questions: What do you see? What do you think about that? What does it make you wonder? In the second component of this lesson, students will be analyzing two graphs with NOAA data. Each of these graphs is accessible online and it is encouraged that all students utilize the online platform as they can expand the graph to look at specific time periods (years, months, and days), highlight specific data points, and manipulate the format of the graphs. For some students, a quick refresher of the overall processes of photosynthesis (which captures carbon dioxide) and cellular respiration (which releases carbon dioxide) might clarify the oscillating patterns observed in the data on the graph. **Standards Addressed**

	AP Environmental Science • STB-4.H.2: As more CO_2 is released into the atmosphere, the oceans, which absorb a large part of that CO_2, become more acidic. • STB-4.H.3: Anthropogenic activities that contribute to ocean acidification are those that lead to increased CO_2 concentrations in the atmosphere: burning fossil fuels, vehicle emissions, and deforestation. **NGSS** • LS2.C: Ecosystem Dynamics, Functioning, and Resilience: Moreover, anthropogenic changes (induced by human activity) in the environment — including habitat destruction, pollution, introduction of invasive species, overexploitation, and climate change — can disrupt an ecosystem and threaten the survival of some species. • LS2.B: Cycles of Matter and Energy Transfer in Ecosystems: Photosynthesis and cellular respiration are important components of the carbon cycle, in which carbon is exchanged among the biosphere, atmosphere, oceans, and geosphere through chemical, physical, geological, and biological processes. **Formative/Summative Assessments** Students will be provided with a graphic organizer to help organize their observations and questions regarding the phenomenon. These questions will help guide student investigations throughout the unit as they uncover various pieces to the puzzle and continue building/modeling their understanding of ocean acidification. These initial questions are formative in nature, as they will launch student progression through each learning segment. **Resources** • **Handout A Global Ocean Data:** https://docs.google.com/document/d/1VySSI02-imu91koH6DP0hUEBsUhk2OnSlmxgMKA8p2s/edit#bookmark=id.lpcze86vxcef

Explore SWBAT: Plan and carry out an investigation to collect data using probes correlating changes in CO_2 concentration with changes in pH and calcium concentration in seawater	**Procedure:** Students will conduct an investigation during an ocean acidification lab. During this lab, students will model the effects of increasing CO_2 concentrations on the pH and calcium concentrations of ocean water, observed via a closed system of ocean water and respiring yeast (a model for increasing CO_2 emissions from anthropogenic sources). In lab groups of 3-4, students will set up, run, and collect data from the ocean acidification lab. This lab captures the CO_2 from respiring yeast in one container and injects it in seawater in a biochamber via aquarium tubing. During the lab, students will use pH and CO_2 probes to observe the relationship that as CO_2 increases, the pH of seawater (which is naturally basic) becomes slightly more acidic. Students will model the above following the below procedure (abbreviated): • Connect the bottles/beakers, biochamber, and seawater with aquarium tubing • Set up the LabQuest with pH probes, carbon dioxide sensor • Take initial calcium readings • Begin yeast respiration by combining yeast, warm water, and sugar • Collect data for 20 minutes • Take final readings At the end of the lab, students should observe a decrease in pH as carbon dioxide concentrations increase. Students may also be able to observe a small decrease in calcium concentration. Students should be reminded that this is just a model for real-life biological processes and should reflect on the use of microscale models to analyze and predict macroscale processes. Students will then graph their data using graphing software and answer analysis questions relating to their data. **Modifications** Students may need assistance with the experimental design and procedure aspects of this lab. The procedure and sample apparatus setup should be read aloud, modeled for students, and projected for students. Additionally, it may be helpful to shorten/highlight critical elements of the procedure to help students progress through the experiment. Students will likely need help setting up the probeware and LabQuest collection device. Special care should be given to help students set up and use these tools, especially as the procedure is modeled for students before the lab begins. Graphing assistance will be provided via graphing software, although based on levels of familiarity, students may need assistance with formatting/inputting data into such programs. For some students, the analysis questions may need to be shortened/read aloud to them or given to them in smaller chunks (one at a time). **Standards Addressed** **AP Environmental Science** • STB-4.H.2: As more CO_2 is released into the atmosphere, the oceans, which absorb a large part of that CO_2, become more acidic. **NGSS**

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- LS2.B: Cycles of Matter and Energy Transfer in Ecosystems: Photosynthesis and cellular respiration are important components of the carbon cycle, in which carbon is exchanged among the biosphere, atmosphere, oceans, and geosphere through chemical, physical, geological, and biological processes.

Formative/Summative Assessments

Before beginning the lab, students will formatively explore the experimental design of the lab by identifying the independent, dependent, and control variables; formulating a testable hypothesis; and analyzing why yeast is being used as a model.

At the conclusion of the lab, students will organize and visualize their data via a graph made using graphing technology of the students' choice. Then, they will answer a series of analysis questions. Sample questions include:

- Looking at your data and your graph, what is the relationship between pH and CO_2?
- Why do you think that relationship exists?
- What molecule are you measuring with the pH probe? What do your data from the pH probe indicate about the relative abundance of this molecule over time?
- How did calcium concentrations change throughout the course of this experiment? What might this mean for organisms such as molluscs that require calcium carbonate to form their shells?

Resources

- **Handout B Ocean Acidification Lab**: https://docs.google.com/document/d/1VySSI02-imu91koH6DP0hUEBsUhk2OnSlmxgMKA8p2s/edit#bookmark=id.naqp2omv37o2

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Explain

SWBAT: Construct an explanation regarding the chemical relationship and reaction between increasing CO_2, pH, and calcium availability in the ocean

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Procedure: In this phase, students will explore a click and learn from Woods Hole to explore the chemical reactions that take place when CO_2 dissolves in seawater. During this click and learn, students will explore the chemical reaction, below, and how it impacts organisms' abilities to build shells.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO^{3-} + H^+ \leftrightarrow CO_3^{2-} + H^+$$

Carbon dioxide + Water ↔ Carbonic acid ↔ Bicarbonate + Hydrogen ion ↔ Carbonate + Hydrogen ion

For organisms with calcium carbonate shells (typically in the form of calcite or aragonite) such as oysters, corals, and crustaceans, ocean acidification can affect their ability to grow their shells as calcium carbonate becomes less available in more acidic seawater.

One additional component to the click and learn asks students to consider global patterns in ocean acidification, as change is not equal in all locations – a trend consistent with most impacts of climate change. To begin to think about that idea and to identify patterns, students will view the ocean acidification surface pH provided by NASA's Scientific Visualization Studio (https://svs.gsfc.nasa.gov/30794/).

Caution! Students should be reminded that pH is a logarithmic scale, so small changes in free H^+ concentration will translate to larger changes in the reported pH value, indicating acidity. However, be cautious as many students may think the oceans are becoming so

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	acidic (down to the pH of vinegar ~2–3) that all shells will immediately dissolve as if they were placed in acid. Instead, the focus should be on the relationship of the loss of calcium in the form of calcite or aragonite that organisms such as urchins, corals, and crustaceans rely on to build their shells. Organisms will have a harder time building shells first, *before* the immediate dissolution of those shells. **Modifications** This click and learn engages students with some advanced chemical reactions and ideas about evolution. For students without a strong chemistry background, additional attention should be provided as they write out chemical reactions, understanding how compounds split apart, and different components of those compounds can combine and rearrange into new molecules. Drawing this step out in simple diagrams (such as consisting of connected circles for each compound, OO → O + O) may help students visualize the processes occurring as CO_2 dissolves in water. For students without a strong background in the processes of evolution, care should be taken to understand that natural selection is a process by which environmental factors select for or against the survival of organisms and those organisms that survive tend to reproduce more, leading to an increase in organisms with that specific phenotype (in this case the ability to build shells). This causes the population or species to change; organisms cannot evolve individually. Furthermore, take care to explore the idea of a tradeoff – the idea that all organisms are always balancing many (often conflicting) forces. In this case, organisms are balancing survival: building shells vs. expelling H^+ ions entering their tissues, which damages shells and uses energy. Everyday examples can be provided for students first: e.g., should I go bowling with friends after school (and potentially not get homework done) or should I go to the library and study (and potentially not get to socialize). **Standards Addressed** **AP Environmental Science** • STB-4.H.1: Ocean acidification is the decrease in pH of the oceans, primarily due to increased CO_2 concentrations in the atmosphere, and can be expressed as chemical equations. • STB-4.H.4: Ocean acidification damages coral because acidification makes it difficult for them to form shells, due to the loss of calcium carbonate. **NGSS** • LS2.C: Ecosystem Dynamics, Functioning, and Resilience: A complex set of interactions within an ecosystem can keep its numbers and types of organisms relatively constant over long periods of time under stable conditions. If a modest biological or physical disturbance to an ecosystem occurs, it may return to its more or less original status (i.e., the ecosystem is resilient), as opposed to becoming a very different ecosystem. Extreme fluctuations in conditions or the size of any population, however, can challenge the functioning of ecosystems in terms of resources and habitat availability. • LS2.C: Ecosystem Dynamics, Functioning, and Resilience: Moreover, anthropogenic changes (induced by human activity) in the environment — including habitat

	destruction, pollution, introduction of invasive species, overexploitation, and climate change — can disrupt an ecosystem and threaten the survival of some species. **Formative/Summative Assessments** For this segment, students will be formatively assessed using scaffolded questions that accompany the click and learn interactive. Accompanying questions include the following sample questions: • Write out the chemical reaction that occurs when CO_2 dissolves in seawater below • What two molecules do organisms such as claims, urchins, and oysters need to build shells? • How do H^+ ions interfere with shell building? • Why must organisms expend energy to get rid of H^+ ions? What is the tradeoff? **Resources** • **Handout C Ocean Chemistry:** https://docs.google.com/document/d/1VySSI02-imu91koH6DP0hUEBsUhk2OnSlmxgMKA8p2s/edit#bookmark=id.hyhjobep5txx • **Woods Hole Click and Learn:** https://www.whoi.edu/interactives/calcification/index.html • **NASA Scientific Visualization Studio Ocean Acidification Surface pH video**: https://svs.gsfc.nasa.gov/30794/
Elaborate SWBAT: Obtain, evaluate, and communicate information from a scientific article to analyze the impact of ocean acidification on urchin growth and development.	**Procedure:** In this segment, students will use their knowledge of ocean acidification chemistry from the previous activity combined with the engaging phenomena sea urchin growth as they investigate how the two are connected. Students will be reading, analyzing, and answering questions from Foo et al. (2020). This article examines the effect of elevated CO_2 levels/decreased pH on the growth and development of sea urchins, both in the lab and in the field. As students read the article, they are prompted with embedded questions that are designed to help them in their understanding of the article and their findings, as well as the overall impacts of ocean acidification. **Modifications** Reading research articles is difficult for many students. The format, syntax and structure of scientific writing, and the vocabulary used is different from many of the ways students naturally read and write. Thus, it may be helpful to model reading the first few sections with students, focusing particularly on the main ideas of those paragraphs while questioning the purpose of the authors in the context of their research. Furthermore, reading strategies such as circling new or unfamiliar vocabulary should be expressed to students to remind them of tools to help them while going through the research paper. For all students, the article has been chunked into sections with embedded questions which are intended to help guide students' engagement with and understanding of the research. Ultimately, the focus of the article should be on the experimental design and the data presented in the figures. To that end, modeling how to read figures (identifying independent/dependent variables, identifying trends, etc.) could be presented to students before and/or as they are reading the article.

Standards Addressed

AP Environmental Science

- STB-4.H.4: Ocean acidification damages coral because acidification makes it difficult for them to form shells, due to the loss of calcium carbonate.

NGSS

- LS2.C: Ecosystem Dynamics, Functioning, and Resilience: Moreover, anthropogenic changes (induced by human activity) in the environment — including habitat destruction, pollution, introduction of invasive species, overexploitation, and climate change — can disrupt an ecosystem and threaten the survival of some species.
- LS2.C: Ecosystem Dynamics, Functioning, and Resilience: A complex set of interactions within an ecosystem can keep its numbers and types of organisms relatively constant over long periods of time under stable conditions. If a modest biological or physical disturbance to an ecosystem occurs, it may return to its more or less original status (i.e., the ecosystem is resilient), as opposed to becoming a very different ecosystem. Extreme fluctuations in conditions or the size of any population, however, can challenge the functioning of ecosystems in terms of resources and habitat availability.

Formative/Summative Assessments

Students will be answering embedded questions within the article, which has been chunked into sections to help students access the information presented. Questions are arranged at different DOKs, for example:

- What were the independent and dependent variables of this study?
- Why did the researchers prepare three separate fertilizations of urchins for each condition and then test 6 different replicates of each fertilization?
- An important element of this study was the deliberate choice to study the effects of ocean acidification in a laboratory and field setting simultaneously. What are some affordances and limitations to each of these settings, i.e., what pros/cons are there to a laboratory experiment vs. a field setting and vice versa?

Students will answer these questions and then discuss them together. It is up to the teacher's discretion to go section-by-section or to review at the end, depending on classes' and students' individual needs.

Resources

- **Handout D Sea Urchin Article (Foo et al., 2020):** https://docs.google.com/document/d/1VySSI02-imu91koH6DP0hUEBsUhk2OnSlmxgMKA8p2s/edit#bookmark=id.ffg9eq5gqzwn
- **Foo et al. (2020) Full Article**: https://pubmed.ncbi.nlm.nih.gov/32217382/

Evaluate SWBAT: Obtain, evaluate, and communicate information regarding current and/or future mitigation strategies to ocean acidification in a specific, local context.	**Procedure:** To finish this learning sequence, students will examine the environmental challenge of ocean acidification and its current/future impacts in a specific location. Students will explore live NOAA coastal mooring data (https://www.pmel.noaa.gov/co2/story/Coastal+Moorings) to investigate factors that impact ocean acidification in a specific location of their choosing. This will allow students to synthesize what they've learned in a specific context, as ocean acidification will impact different local ecosystems in different ways. Then, students will research and analyze potential mitigation solutions, tying in engineering design practices. Students will: 1. Identify the location of the coastal mooring 2. Explain ocean acidification: what is it, how does it happen, etc. 3. Identify/describe current (within the current year) oceanic CO_2 and pH data 4. Create a graphic describing historical trends in CO_2 and pH at their location 5. Identify a specific organism that will be impacted by ocean acidification in their location 6. Describe how ocean acidification currently affects or will impact that organism if trends continue 7. Research and explain a mitigation plan/design/strategy that is currently in place, or is proposed for future use to counteract the impacts of ocean acidification 8. Describe 2 strengths/benefits to that plan/design/strategy 9. Describe 1 limitation/drawback to that plan/design/strategy 10. Identify a consideration that should be taken into account to consider the impact, effectiveness, and/or expansion to this plan Finally, students will produce and present their final design product in a gallery walk/public share out. **Modifications** Students may need additional help exporting historical data from the NOAA coastal moorings in order to create a graphic analyzing trends. Assistive graphing technology (such as that provided by NOAA in the program or HHMI's Data Explorer) can be used to help students with graphing. Students may require assistance with finding mitigation plans, reading through them, and analyzing their use. Additionally, students may need help identifying high-quality and reliable sources. Students may additionally need a template to help them organize their information and communicate it in their final design product. Use of the sample template is encouraged. **Standards Addressed** **AP Environmental Science** • STB-4.H.1: Ocean acidification is the decrease in pH of the oceans, primarily due to increased CO_2 concentrations in the atmosphere, and can be expressed as chemical equations. • STB-4.H.2: As more CO_2 is released into the atmosphere, the oceans, which absorb a large part of that CO_2, become more acidic.

- STB-4.H.3: Anthropogenic activities that contribute to ocean acidification are those that lead to increased CO_2 concentrations in the atmosphere: burning fossil fuels, vehicle emissions, and deforestation.
- STB-4.H.4: Ocean acidification damages coral because acidification makes it difficult for them to form shells, due to the loss of calcium carbonate.

NGSS

- LS2.C: Ecosystem Dynamics, Functioning, and Resilience: A complex set of interactions within an ecosystem can keep its numbers and types of organisms relatively constant over long periods of time under stable conditions. If a modest biological or physical disturbance to an ecosystem occurs, it may return to its more or less original status (i.e., the ecosystem is resilient), as opposed to becoming a very different ecosystem. Extreme fluctuations in conditions or the size of any population, however, can challenge the functioning of ecosystems in terms of resources and habitat availability.
- LS2.C: Ecosystem Dynamics, Functioning, and Resilience: Moreover, anthropogenic changes (induced by human activity) in the environment — including habitat destruction, pollution, introduction of invasive species, overexploitation, and climate change — can disrupt an ecosystem and threaten the survival of some species.
- ETS1.B: Developing Possible Solutions: When evaluating solutions, it is important to take into account a range of constraints including cost, safety, reliability and aesthetics and to consider social, cultural and environmental impacts.

Formative/Summative Assessments

For students' final assessment, they will be creating some form of a product design/presentation product containing the 10 elements described above. The format of this product will be open to allow for student choice and creativity. Students will publicly display their products in a gallery walk format so students can learn of the various (and different) impacts of ocean acidification on communities and organisms across the globe. Students will score each other's products using a rubric (linked below), emulating a process of peer review.

Resources

- **Handout E: Local Oceanic Data Presentation:** https://docs.google.com/document/d/1VySSI02-imu91koH6DP0hUEBsUhk2OnSlmxgMKA8p2s/edit#bookmark=id.oe68r9eda4hi
- **Final Product Rubric:** https://docs.google.com/document/d/1VySSI02-imu91koH6DP0hUEBsUhk2OnSlmxgMKA8p2s/edit#bookmark=id.qznj6vd8n39j

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