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How Do Upwelling and El Niño Impact Coral Reef Growth? A GUIDED, INQUIRY-BASED LESSON

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PURPOSE OF ACTIVITY

This lesson uses real-world data to guide students toward understanding how climate and ocean variables impact coral reef growth. To begin this activity, students hypothesize how changes in environmental conditions could affect coral reef growth. They then compare metrics for reef growth (linear growth and percent coral cover) between two reefs in Pacific Panamá that are located in oceanographically and environmentally different embayments, or gulfs. A discussion following the first two activities allows the students to explore possible reasons for the observed differences between the reefs. Students then use their data to calculate a carbonate budget to estimate the rate of reef growth in each gulf. The purpose of calculating a carbonate budget is to provide students with an opportunity to estimate how variables such as coral growth rates, percent coral cover, and bioerosion contribute to the long-term potential for accretion or deterioration of coral reefs.

AUDIENCE

The lesson is designed for high school and undergraduate biology, marine biology, and oceanography courses.

BACKGROUND

Coral Reef Growth

Scientists can estimate the net rate of upward coral reef growth, known as vertical reef accretion, using three metrics: (1) the percentage of the reef composed of living corals, (2) the rate of linear extension of individual coral colonies (i.e., their vertical growth), and (3) the subtractive processes of reef erosion. The percent cover of living corals is the most common metric used to determine reef condition (Kuffner and Toth, 2016). Although percent coral cover and coral growth rates can be used to determine the potential for positive reef growth, net reef growth also takes into account the negative influence of erosive processes (Perry et al., 2012). Bioerosion, which occurs on all healthy reefs, is the removal of material by living organisms that physically or chemically degrade the coral skeleton (Glynn, 1997). Bioerosion is a natural process that breaks down dead coral and creates space for new corals to settle.

Scientists use these three metrics to determine how the additive and subtractive processes that control reef accretion—growth and erosion—may be impacted by future changes in climate. Environmental disturbances, including climate change, have already led to a reduction in live coral cover on a global scale (Gardner et al., 2003; Bruno and Selig, 2007), which has caused a reduction in reef accretion in some locations (Perry et al., 2013). Seawater temperature is a key environmental variable controlling reef accretion (Toth et al., 2018), and in some locations warming temperatures have caused declines in coral growth and coral cover (De'ath et al., 2009; Cantin et al., 2010; Hughes et al., 2018). Furthermore, some models suggest that reefs with lower coral cover will be more susceptible to bioerosion and ocean acidification, a process that reduces seawater pH and increases the dissolution of coral skeletons (Boleman et al. 2013; Kennedy et al., 2013; Enochs et al., 2015). Reefs that experience higher rates of bioerosion may become structurally weak, more susceptible to storm surge, and unable to grow at a rate that keeps up with sea level rise (Glynn, 1997; Perry et al., 2018). Together, the recent losses of coral cover, declines in coral growth rates, and the potential for increases in reef erosion suggest that the impacts of climate change on reef accretion may become more severe in the future.

Study Sites

Scientists have sought out coral reef ecosystems that can serve as natural laboratories for exploring the environmental conditions that may influence the response of reef accretion to climate change. Two research sites were selected on the Pacific coast of Panamá for this study based on their unique, natural oceanographic gradients, which influence the development of coral reefs in the region (Figure 1). One site is in the Gulf of Panamá and the other is in the Gulf of Chiriquí. Strong seasonal upwelling in the Gulf of Panamá results in cooler, more nutrient rich, and more turbid seawater conditions during three to four months each year. Upwelling does not occur in the adjacent Gulf of Chiriquí, so the waters are on average warmer and more nutrient-limited than in the Gulf of Panamá during the upwelling season (Figure 1; Glynn and Macintyre, 1977). The naturally occurring colder water in the Gulf of Panamá may, therefore, serve as a refuge for corals as sea surface temperatures (SSTs) continue to increase due to anthropogenic climate change (Glynn et al., 2001).

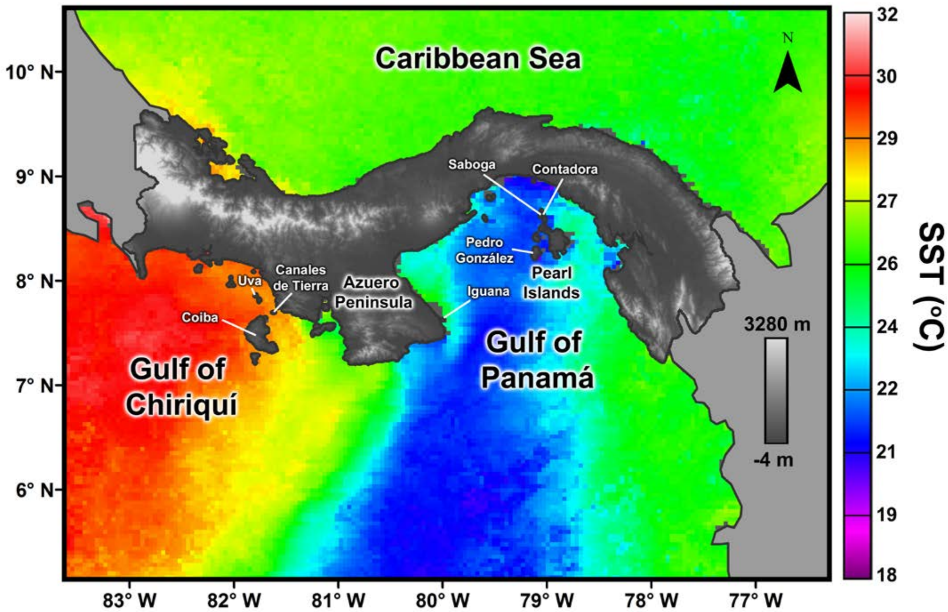

FIGURE 1. Map of Pacific Panamá showing the island locations of study reefs in relation to upwelling regimes. The coloration of the ocean shows sea-surface temperature (SST) at the peak of the 2009 upwelling season in March. Created from MODIS Aqua/SST data (http://poet.jpl.nasa.gov). Gray-scale on the isthmus indicates elevation.

The El Niño–Southern Oscillation

The reefs along the Pacific coast of Panamá are ideal for studying the interaction between temperature and upwelling on coral reef development because they are strongly affected by changes associated with the El Niño–Southern Oscillation (ENSO). Warming that occurs during the warm phase of ENSO, known as El Niño, is similar to what is expected under anthropogenic climate change (Collins et al., 2010). Thus, scientists have used the response of these reefs to El Niño events to gain insights into how reef ecosystems might respond to future climate change. During "non-El Niño" years, the trade winds in the Pacific Ocean move from east to west, isolating warmer water in the western Pacific. During El Niño, in contrast, the trade winds weaken. Warm water flows eastward, resulting in warmer SSTs in the eastern tropical Pacific, including in Pacific Panamá. These anomalously warm SSTs can lead to coral bleaching, which occurs when high temperatures cause a breakdown in the symbiotic relationship between the corals and the algae that live within their tissues and nourish the coral animals. Because corals rely on photosynthesis by their symbiotic algae for up to 90% of their energetic needs, prolonged or intensive coral bleaching often leads to coral mortality (e.g., Glynn, 1993; Aronson et al., 2000; Lesser and Farrell, 2004; Anthony et al., 2007). Repeated El Niño events over the last several decades have had significant, negative impacts on the growth and abundance of corals throughout the eastern Pacific (Manzello, 2010; Glynn et al., 2017). El Niño effects have been less extreme where seasonal upwelling can keep temperatures from getting too high (Glynn et al., 2001). Scientists have suggested that an increase in the frequency and/or intensity of ENSO events caused Panamanian reefs to stop accreting for a period of ~2,500 years, beginning around 4,200 years ago (Toth et al., 2012, 2015). The 2,500-year hiatus in reef growth highlights the fact that climate has been a primary control on coral reef development for thousands of years or more (Toth et al., 2017).

In 2016–2017, the authors and colleagues completed an expedition to evaluate coral reefs in the two Panamanian gulfs. Their objectives were to determine if there were differences in (1) coral growth over a one-year interval, and (2) percent coral cover between the Gulf of Chiriquí (non-upwelling) and the Gulf of Panamá (upwelling).

RESEARCH QUESTIONS AND HYPOTHESES

For this lab, students will answer the following research questions: (1) How do upwelling and El Niño impact coral growth (Activity 1)? and (2) how do they impact percent coral cover (Activity 2)? Students will formulate hypotheses about how coral growth and percent coral cover might differ between gulfs and over time, and what environmental variables might be responsible for those differences. Students will test their predictions by measuring the growth of experimental corals using before-and-after images taken one year apart in each gulf, and by comparing percent coral cover between the two gulfs using photographs taken of permanent quadrats.

Students will then use their data to calculate a carbonate budget (Activity 3) for each reef to answer the following research question: How might upwelling and El Niño impact the potential for long-term reef accretion in Pacific Panamá? Students should use their data from the first two activities to hypothesize how changes in environmental factors may affect reef accretion. To ensure that students have a general understanding of the biology and ecology of coral reefs, we encourage teachers to provide additional information prior to completing the lesson, through discussion or a student-led, online scavenger hunt (e.g., https://oceanservice.noaa.gov/education/tutorial_corals/). A glossary of the terms students will need to know is included at the end of the online Activity Sheet.

MATERIALS

Materials for each pair of students:

Activity 1

- Online Handout S1 and Handout S2 (see online Notes for the Instructor)
- Online Activity Sheet Table S2
- Metric ruler
- Calculator

Activity 2

- Online Handout S3 and Handout S4 (see online Notes for the Instructor)
- Online Activity Sheet Tables S4 and S5
- Envelope with random numbers 1–36
- Two dry-erase pens and one dry eraser
- Calculator

ACTIVITIES

Pre-Lab Activity

The instructor should provide students with an opportunity to compare the environmental conditions between the two gulfs in Pacific Panamá to help guide them toward formulating explanations for the differences they may observe in coral growth and percent cover between the gulfs in Activities 1 and 2. This pre-lab activity can be completed as a homework assignment or as an introduction to the lesson at the beginning of class. Table S1 in the online Activity Sheet can be used for this pre-lab activity and also includes discussion questions.

Pre-Lab Discussion Questions

1. What are some similarities and differences in the environmental conditions between the two gulfs?
2. What environmental changes occur in each gulf during an El Niño event?

Activity 1. Determining Coral Growth in Upwelling and Non-Upwelling Environments

Suggested Class Time: Approximately 45 Minutes

During this activity, pairs of students will measure the lengths of five independent experimental colonies of the cauliflower coral, *Pocillopora damicornis* (Handout S1 and Handout S2). The paired images were taken one-year apart, in 2016 and 2017, during a non-El Niño period. The difference in the lengths of the coral colonies between these two time points will provide students with an annual linear extension rate.

1. Measure each coral from the point of attachment at the base (lower dashed line in Figure 2) to the furthest branch tip (upper based line in Figure 2) using string, rulers, or calipers. Do not include the epoxy base (purple in Figure 2) in the measurement. The furthest branch for each coral may not be perpendicular to the base.
2. Measure the initial length of each of the corals (2016) and record their data in the online Activity Sheet Table S2. Then measure the final lengths of the same corals (2017) and record the data. The photographs are labeled to identify the individual corals.
3. After measuring each coral, calculate total linear extension over a one-year period by subtracting the initial length from the final length.
4. Calculate the average yearly growth rate for all corals (cm yr^{-1}) from each gulf. Also calculate the standard deviation and standard error.
5. Create a bar graph with standard error bars to compare the average annual growth rate for each gulf.

Discussion Questions for Activity 1

1. What differences did you observe in the average linear extension between the two gulfs?
2. Did one gulf have more variable growth than the other?
3. What might be some reasons for the differences in linear extension? What evidence from the pre-lab activity supports your hypothesis?
4. How do you think sea surface temperature affects coral linear extension?
5. Hypothesize how other factors like increased turbidity might impact coral linear extension. Explain.

Activity 2. Determining Percent Coral Cover in Each Gulf

Suggested Class Time: Approximately 1–1.5 Hours

1. Familiarize yourselves with the benthic-cover key (Handout S3) and the practice quadrat (Activity Sheet Table S3), which classify the different types of seafloor components you may encounter, including the identification of live coral (which can have white tips) and coral overgrown with algae.

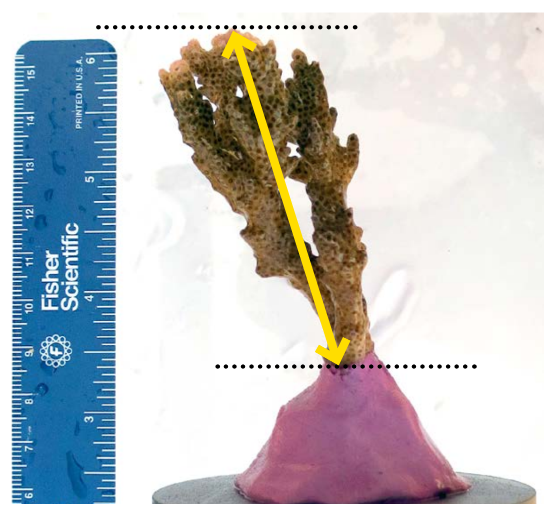

FIGURE 2. An example of an individual coral colony. Linear measurements should be taken from the base to the furthest tip. The ruler is to provide scale.

2. Each reef image is gridded to randomize the areas that each student pair will quantify. Use dry erase pens and number the grids on each image 1–36 (Handout S4).
3. Number pieces of paper 1–36 and place in envelope. Use the numbered papers to randomly select fifteen grid cells per image. Estimate and record the percent coral cover that makes up each randomly selected grid cell in Activity Sheet Table S4.
4. After estimating the total percent coral cover for all 15 selected grid cells, convert your measurements into percentages of coral cover for each image. For example, if image 1 resulted in 4 grid cells with 100% live coral, 1 grid cell with 50% live coral, and 10 grids with 0% live coral, then you would calculate and record coral cover as:

$$\frac{4.5}{15} \times 100 = 30\% \text{ coral cover},$$

   Repeat this procedure for each gulf. If time is limited, the instructor can use her/his discretion to reduce the number of randomly selected grid cells per image.
5. Upon completing your analyses, calculate the average percent coral cover in each gulf during each time period by averaging the measurements from the three images per gulf. Also, calculate the standard deviation and standard error for each gulf.
6. Create a bar graph of the average percent coral cover with standard error bars to compare the two gulfs. Data tables are provided in the supplementary materials (Activity Sheet Table S5).

Discussion Questions for Activity 2

1. What differences did you observe in the average percent coral cover between the two gulfs? Did both gulfs show the same level of variability among quadrats?
2. What might be some reasons for the difference in percent cover in each gulf? What evidence from the pre-lab activity supports your hypotheses?
3. What are some sources of error and variability in the data that might have caused differences in the measurements among student pairs? How might those differences have been caused?
4. How could you minimize those errors if you were conducting the study for real?
5. If Panamanian reefs were hit by a strong El Niño in the future, how would you expect coral cover to change in each gulf? Discuss what this may mean for the future of coral reefs.

Activity 3. Estimating a Carbonate Budget for Panamanian Reefs

Suggested Class Time: Approximately 1–1.5 Hours

Estimating carbonate budgets for coral reefs gives researchers a measure of the potential for long-term reef growth and identifies where a particular reef falls on the spectrum from net accretion to net erosion. The carbonate production of a reef can be estimated using percent coral cover and linear growth rates (in cm yr^{-1}) of corals on a reef. Perry et al. (2012) developed an equation that students can use in simplified form to estimate yearly production (in kg m^{-2} yr^{-1}) of calcium carbonate, or $CaCO_3$, for each reef explored in this lesson. The formula below has been modified to assume that rugosity, a measure of the topographical complexity of the reef, is similar between the two reefs. Total carbonate production (TCP) can be estimated as:

$$TCP_{year} = \left[\frac{x}{100} \times [(D \times G \times 10{,}000) \div 1{,}000]\right],$$

where x is the average percent cover estimated from the images (Activity 2), D is a skeletal density constant, assumed to be 2.0 g $CaCO_3$ cm^{-3} for both reefs (from Manzello, 2010), and G is the annual linear growth rate (in cm yr^{-1}) of *Pocillopora damicornis* (Activity 1). In this activity, the students should:

1. Calculate the total annual $CaCO_3$ production (TCP) for both gulfs.
2. Subtract an assumed rate of bioerosion (B) for each gulf to calculate the "net" carbonate production (NCP):

$$NCP_{year} = TCP_{year} - B.$$

Manzello et al. (2008) estimated the rate of bioerosion (B) as 26.1 kg $CaCO_3$ m^{-2} yr^{-1} for the Gulf of Panamá and 13.6 kg $CaCO_3$ m^{-2} yr^{-1} for the Gulf of Chiriquí. A positive value for net carbonate production indicates net accretion, whereas negative values indicate net erosion. Students should record the values for NCP in Activity Sheet Table S6.

Additional Analyses

1. Assume a 10% decline in coral growth and/or coral cover in only the Gulf of Chiriquí to see how bleaching during an El Niño event might influence carbonate production and reef accretion. Calculate the percent difference from the average annual accretion rate and record your data in Activity Sheet Table S6. Note that this lesson does not account for horizontal, or "lateral," coral growth, which is also an important component of reef accretion.
2. Attempt a sensitivity analysis by comparing how a decline of 20% or 30% in coral growth or percent cover and/or a 10%, 20%, or 30% increase in bioerosion in the Gulf of Chiriquí might affect the reef's overall carbonate production. Note that the calculations for varying levels of bioerosion do not include physical processes, such as wave energy, that contribute to reef erosion. Calculate the percent difference from the original annual accretion rate that you calculated for the Gulf of Chiriquí and record your data in Activity Sheet Table S6.

Discussion Questions for Activity 3

1. What is the percent change in net carbonate production in the Gulf of Chiriquí due to a 10% change in coral cover? A 10% change in coral growth? Both?
2. Which factor, linear growth or percent cover, has a greater impact on net carbonate production in the Gulf of Chiriquí? Explain.

3. How might more intense and frequent El Niño events impact net carbonate production (and therefore reef accretion) in the Gulf of Chiriquí? Compare your sensitivity analyses to the estimates of net carbonate production for the Gulf of Panamá.
4. How do increases in bioerosion compare with decreases in percent coral cover or linear growth?

INTERNET RESOURCES

- **Marine Paleoecology Laboratory**
  http://research.fit.edu/marine-paleolab/
  Summarizes research in the eastern tropical Pacific being conducted by investigators at the Florida Institute of Technology.
- **NOAA — El Niño & La Niña (El Niño–Southern Oscillation)**
  https://www.climate.gov/enso
  US government website describing the climatic changes that occur during El Niño events.
- **University of Exeter — ReefBudget**
  http://geography.exeter.ac.uk/reefbudget/
  Reef budget website provides additional resources and description of methods used to calculate carbonate production in coral reefs.
- **NOAA — What is Coral Bleaching?**
  https://oceanservice.noaa.gov/facts/coral_bleach.html
  US government website explaining coral bleaching.

SUPPLEMENTARY MATERIALS

The handouts, student activity sheet, answer key, and notes for the instructor are available online at https://doi.org/10.5670/oceanog.2018.424.

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