How Do Upwelling and El Niño Impact Coral Reef Growth?

ANSWER KEY

PRE-LAB ACTIVITY AND DISCUSSION

TABLE S1A. Answer key comparing conditions in the Gulf of Chiriquí and the Gulf of Panamá during normal and El Niño climatic regimes. This information should be used to guide students toward identifying how the environment might change as a result of climate change.

Condition	Environmental Parameter	Gulf of Chiriquí	Gulf of Panamá
Normal	Upwelling	• No upwelling	• Upwelling
	Temperature	• Water temperatures up to ~10°C warmer	• Water temperatures up to ~10°C cooler
	Nutrients	• Lower nutrient levels	• Higher nutrient levels
	Turbidity	• Lower turbidity	• Higher turbidity
	Tidal range	• Smaller tidal range (max = 5 m)	• Larger tidal range (max = 6 m)
El Niño	Upwelling	• No upwelling	• Reduced upwelling
	Temperature	• Water temperature up to 4°C above normal	• Water temperatures up to 2°C below Chiriquí
	Nutrients	• Lower nutrient levels than normal years	• Lower nutrient levels than normal years
	Turbidity	• Less turbid than normal years	• Less turbid than normal years
	Tidal range	• Tidal ranges are similar to normal conditions	• Tidal ranges are similar to normal conditions

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ACTIVITY 1

TABLE S2A. Answer key for linear extension measurements on corals in each gulf during 2016 and 2017.

Replicate	Gulf	Coral ID	2016 Height (cm)	2017 Height (cm)	Change in Height from 2016 to 2017 (cm)	Mean Annual Growth Rate (cm yr^{-1})	Standard Deviation	Standard Error
1	Panamá	1L	5.6	9.8	4.1			
2	Panamá	4L	9.7	13.7	3.9			
3	Panamá	6L	7.4	11.2	3.7			
4	Panamá	10D	7.6	10.3	2.6			
5	Panamá	26L	5.5	10.0	4.4			
					Summary Statistics:	3.8	0.7	0.3
1	Chiriquí	36D	6.0	8.6	2.6			
2	Chiriquí	37L	7.4	10.4	3.0			
3	Chiriquí	38D	5.3	8.6	3.2			
4	Chiriquí	43D	5.6	8.9	3.3			
5	Chiriquí	44L	4.6	7.5	2.8			
					Summary Statistics:	3.0	0.2	0.1

Discussion Questions for Activity 1

1. What differences did you observe in the average linear extension between the two gulfs?
Answer provided in Table S2A.

2. Did one gulf have more coral variable growth than the other?
The Gulf of Panamá was more variable. Answer provided in Table S2A.

3. What might be some reasons for the differences in linear extension? What evidence from the pre-lab activity supports your hypothesis?
There was a strong El Niño event that affected reefs in Pacific Panamá in 2015–16 when the corals were growing. The cooler temperatures in the Gulf of Panamá mean that the corals in this gulf would have experienced less high-temperature stress during El Niño. Table S1A indicates that temperatures are 2° cooler, likely allowing the corals to grow more quickly than the more stressed corals in the Gulf of Chiriquí.

5. How do you think sea surface temperature impacts coral linear extension?
Anomalously warm temperatures reduce coral growth. Note that extreme cool temperatures can also reduce coral growth.

6. Hypothesize how other factors like increased turbidity might impact coral linear extension. Explain.
Turbidity could limit the availability of light needed by coral symbionts to produce sugars to photosynthesize, thus decreasing growth. Nutrients can have both positive and negative impacts on coral growth. It is possible that the elevated nutrients in the Gulf of Panamá also contributed to the relatively higher growth rates; however, elevated nutrients can also increase the rates of bioerosion. This is probably the reason why bioerosion rates are higher in the Gulf of Panamá compared with the Gulf of Chiriquí.

ACTIVITY 2

Note that the values in Table S5A will vary depending on which grid cells the students randomly selected.

TABLE S5A. Answer key for percent coral cover. Depending on the random sampling by the students, coral cover may vary among student pairs; however, the data should be fairly similar to what is presented in this table.

	Average % Cover					
Gulf	**Replicate 1**	**Replicate 2**	**Replicate 3**	**Average**	**Standard Deviation**	**Standard Error**
Chiriquí	40	48	48	45.33	4.62	2.67
Panamá	100	98	98	98.67	1.15	0.67

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?
   The average percent cover was lower and variability was higher in the Gulf of Chiriquí. See Table S5A.

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?
   Changes in sea surface temperature (warmer in the Gulf of Chiriquí) due to El Niño events. The Gulf of Chiriquí experiences more extreme effects of El Niño compared with the Gulf of Panamá.

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?
   Error could be due to some students misidentifying substrates. Sources of variability include using different quadrats in the analyses and the randomization process.

4. How could you minimize those errors if you were conducting the study for real?
   Answers will vary.

6. If Panamanian reefs are 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.
   We would expect coral cover in the Gulf of Chiriquí to decrease significantly. The Gulf of Panamá may not experience the full effects of an El Niño (because of upwelling) and may not see a significant decline in coral relative to the Gulf of Chiriquí. More frequent and intense El Niño events could serve as a tipping point that would drive the shutdown of reef accretion in the region.

ACTIVITY 3

TABLE S6A. Data table to record the average net carbonate production in each gulf. The table can be used for the additional analyses below. The sensitivity analyses should use the present-day rate of net carbonate production for the Gulf of Chiriquí.

	Net carbonate production (kg CaCO^{-3} m^{-2} yr^{-1})	Percent Decrease in Net Carbonate Production
Gulf of Panamá (present day)	48.9	N/A
Gulf of Chiriquí (present day)	13.6	N/A
10% decrease in coral cover in Chiriquí	7.6	44.1
20% decrease in coral cover in Chiriquí	1.6	88.2
30% decrease in coral cover in Chiriquí	−4.4	132.4
10% decrease in linear growth in Chiriquí	10.9	19.9
20% decrease in linear growth in Chiriquí	8.1	40.4
30% decrease in linear growth in Chiriquí	5.4	60.3
10% decrease in both coral cover and linear growth in Chiriquí	5.5	59.6
10% increase in bioerosion in Chiriquí	12.2	10.3
20% increase in bioerosion in Chiriquí	10.9	19.9
30% increase in bioerosion in Chiriquí	9.5	30.1

Calculations

Present-day carbonate production in the Gulf of Panamá:

$$TCP_{year} = \left[\frac{98.7}{100} \times [(2.0 \times 3.8 \times 10{,}000) \div 1000]\right] = 75.0 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$$

$$NCP_{year} = 75.0 - 26.1 = 48.9 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}.$$

Present-day carbonate production in the Gulf of Chiriquí:

$$TCP_{year} = \left[\frac{45.3}{100} \times [(2.0 \times 3.0 \times 10{,}000) \div 1000]\right] = 27.2 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$$

$$NCP_{year} = 27.2 - 13.6 = 13.6 \text{ g CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}.$$

Additional Analyses

Calculations for a decrease in percent coral cover in the Gulf of Chiriquí:

10% decrease in coral cover

$TCP_{year} = \left[\frac{35.3}{100} \times [(2.0 \times 3.0 \times 10{,}000) \div 1000]\right]$ = 21.2 kg $CaCO_3$ m^{-2} yr^{-1}

$NCP_{year} = 21.3 - 13.6 = 7.6$ g $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 44.1% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

20% decrease in coral cover

$TCP_{year} = \left[\frac{25.3}{100} \times [(2.0 \times 3.0 \times 10{,}000) \div 1000]\right]$ = 15.2 kg $CaCO_3$ m^{-2} yr^{-1}

$NCP_{year} = 15.2 - 13.6 = 1.6$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of an 88.2% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

30% decrease in coral cover

$TCP_{year} = \left[\frac{15.3}{100} \times [(2.0 \times 3.0 \times 10{,}000) \div 1000]\right]$ = 9.2 kg $CaCO_3$ m^{-2} yr^{-1}

$NCP_{year} = 9.2 - 13.6 = -4.4$ kg $CaCO_3$ m^{-2} yr^{-1}. When coral cover is this low, the reefs in the Gulf of Chiriquí would shift from accreting reefs to eroding reefs.

Calculations for a decrease in coral growth in the Gulf of Chiriquí:

10% decrease in coral growth

$TCP_{year} = \left[\frac{45.3}{100} \times [(2.0 \times 2.7 \times 10{,}000) \div 1000]\right]$ = 24.5 kg $CaCO_3$ m^{-2} yr^{-1}

$NCP_{year} = 24.5 - 13.6 = 10.9$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 19.9% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

20% decrease in coral growth

$TCP_{year} = \left[\frac{45.3}{100} \times [(2.0 \times 2.4 \times 10{,}000) \div 1000]\right]$ = 21.7 kg $CaCO_3$ m^{-2} yr^{-1}

$NCP_{year} = 21.7 - 13.6 = 8.1$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 40.4% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

30% decrease in coral growth

$TCP_{year} = \left[\frac{45.3}{100} \times [(2.0 \times 2.1 \times 10{,}000) \div 1000]\right]$ = 19.0 kg $CaCO_3$ m^{-2} yr^{-1}

$NCP_{year} = 19.0 - 13.6 = 5.4$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 60.3% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

Calculations for a 10% decrease in both coral cover and growth in the Gulf of Chiriquí:

$$TCP_{year} = \left[\frac{35.3}{100} \times [(2.0 \times 2.7 \times 10{,}000) \div 1000]\right] = 19.0 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$$

$NCP_{year} = 19.0 - 13.6 = 5.5$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 59.6% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

Calculations for an increase in bioerosion in the Gulf of Chiriquí:

10% increase in bioerosion

$$TCP_{year} = \left[\frac{45.3}{100} \times [(2.0 \times 3.0 \times 10{,}000) \div 1000]\right] = 27.2 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$$

$NCP_{year} = 27.2 - 15.0 = 12.2$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 10.3% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

20% increase in bioerosion

$$TCP_{year} = \left[\frac{45.3}{100} \times [(2.0 \times 3.0 \times 10{,}000) \div 1000]\right] = 27.2 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$$

$NCP_{year} = 27.2 - 16.3 = 10.9$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 19.9% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

30% increase in bioerosion

$$TCP_{year} = \left[\frac{45.3}{100} \times [(2.0 \times 3.0 \times 10{,}000) \div 1000]\right] = 27.2 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$$

$NCP_{year} = 27.2 - 17.7 = 9.5$ kg $CaCO_3$ m^{-2} yr^{-1}, which is representative of a 30.1% decrease in net carbonate production in the Gulf of Chiriquí relative to the present day.

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? 10% change in coral growth? Both?
   44.1%, 19.9%, 59.6%

2. Which factor, percent cover or linear growth, appears to have the greater impact on net carbonate production in the Gulf of Chiriquí? Explain.
   Change in percent cover of coral has a larger proportional impact on net carbonate production. Percent cover is representative of a two-dimensional space, whereas linear growth is one-dimensional.

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.
   More intense and frequent El Niño events are likely to decrease coral growth and cover, which in turn will reduce carbonate production and reef accretion. Based on the reef accretion data collected, the Gulf of Chiriquí, which experiences more frequent El Niño events, has a significantly lower rate of net carbonate production than the Gulf of Panamá. If coral cover decreases by 30% in the Gulf of Chiriquí, then net carbonate production will be negative and the reef will start eroding.

4. How do increases in bioerosion compare to decreases in percent coral cover or linear growth?
   Increases in bioerosion have a smaller proportional impact on net carbonate production.

OPTIONAL STATISTICAL ANALYSIS

Activity 1

Comparison of change in height between gulfs. Independent t-test: $t = 2.2$, $p = 0.02$.

Activity 2

Comparison of percent coral cover between gulfs. Independent t-test: $t = 19.4$, $p < 0.001$.

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