A Classroom Activity Using Satellite Sea Surface Temperatures to Predict Coral Bleaching

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PURPOSE OF ACTIVITY

- Familiarize students with sea surface temperature (SST) and the use of satellites to remotely sense SST.
- Familiarize students with the effect of SST on coral health.

AUDIENCE

This activity illustrates how temperature influences coral bleaching and how remote sensing is used to monitor coral health. It can be presented with different levels of complexity to upper middle school through early college students. The target audience as written is eighth to tenth graders. Suggested extensions to the activity incorporate concepts of coral reef ecology and the impacts of climate change. If computers are available to students, consider using the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch online tutorial to prepare students for the activity (http://coralreefwatch.noaa.gov/satellite/education/tutorial/welcome.html). A background presentation on coral reefs and remote sensing is also available (http://coralreefwatch.noaa.gov/satellite/education/index.html). Following the activity, students can examine the current conditions on global coral reefs at the Coral Reef Watch Web site (http://coralreefwatch.noaa.gov/satellite/).

ACTIVITY DESCRIPTION

In 2005, scientists reported widespread coral bleaching affecting the entire Caribbean basin (Wilkinson and Souter, 2008). Using NOAA Coral Reef Watch (CRW) satellite products for the late summer of 2005, students will determine what the sea surface temperature and wind conditions were at sites in this region. They will then consider SST conditions over the course of the summer and use this information to predict the severity of bleaching at four specific sites. Class discussion will focus on reporting what they found and comparing results from the sites and across the region. The activity should take approximately 30 minutes, not including instruction time and time spent exploring the online tutorial.

BACKGROUND

Sea Surface Temperature and Coral Reefs

Coral reefs are some of the most diverse ecosystems on Earth. They provide coastal protection from storms, habitat for fish and other organisms, and they are sources of food, recreation, and components of medications. Coral reefs are also very sensitive to pollution from sediment and nutrient runoff from land, harmful fishing practices, and the impacts of climate change, including rising SSTs and increasingly acidic waters due to rising atmospheric carbon dioxide (CO_2) concentrations (Hoegh-Guldberg et al., 2007; Kleypas and Eakin, 2007). Though reefs are very important, over half of the world's reef

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NOAA CORAL REEF WATCH SATELLITE BLEACHING ACTIVITY

USING SATELLITE SEA SURFACE TEMPERATURE
TO PREDICT MASS CORAL BLEACHING

ANSWERS

NOAA CORAL REEF WATCH SATELLITE BLEACHING ACTIVITY

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The activity worksheet and answer sheet are available online at http://www.tos.org/hands-on

ecosystems have collapsed or are under threat resulting from a variety of human and natural influences (Wilkinson, 2008).

Corals are organisms that live in a symbiotic relationship with single-celled algae called zooxanthellae. Zooxanthellae are dinoflagellates, a group of microscopic algae that are usually found swimming or floating in the water column. But in this case, these microscopic organisms are living within the coral tissue. Both partners benefit from this relationship. By residing in the coral tissue, the zooxanthellae are provided with protection, shelter, nutrients (mostly waste material containing nitrogen and phosphorus), and a constant supply of CO_2 required for photosynthesis. Through photosynthesis, they produce carbohydrates that can account for as much as 95% of a coral's energy needs (Muscatine, 1990; Hoegh-Guldberg, 1999). These tiny algae also provide most or all of the characteristic color of the coral. When corals become stressed, one of their reactions is to expel these microscopic algae partners. Because coral tissue is clear, the white calcium carbonate skeleton beneath the coral tissue becomes visible, giving rise to the term "coral bleaching" (Glynn, 1996). On a small scale (i.e., an individual coral or a small area of reef), bleaching can be caused by many factors, such as freshwater from floods, pollution, disease, sediment settling on the corals, or cyanide fishing (Coral Disease Working Group, 2007). Widespread or "mass" coral bleaching of entire regions and even ocean basins has been linked to unusually high water temperatures (Glynn, 1996; Hoegh-Guldberg et al., 2007). If the thermal stress is mild and goes away within a few weeks, the coral can recover; if the stress is severe or lasts many weeks or even months, the corals can starve and die without their algae partners.

Laboratory studies show that only 1°C above the temperature a coral normally experiences in the warmest month can cause coral bleaching (reviewed in Hoegh-Guldberg, 1999; Glynn and D'Croz, 1990; Berkelmans, 2002); this is often referred to as the "bleaching threshold." Corals live very close to their thermal threshold and are, therefore, at risk of exceeding the threshold during unusually warm periods. Water temperatures at many coral sites have increased over the past century (Eakin et al., 2009) and are predicted to continue increasing (IPCC, 2007). Coral bleaching associated with warming ocean temperatures is considered one of the biggest threats to coral reefs (Hoegh-Guldberg et al., 2007; Kleypas and Eakin, 2007). Corals weakened by bleaching are also at increased risk of infectious diseases (Harvell et al., 2002; Bruno et al., 2007; Coral Disease Working Group, 2007) and may show reduced growth and reproduction (Hoegh-Guldberg, 1999; McClanahan et al., 2009). Fortunately, we can use satellites and remote-sensing tools to predict large-scale, thermal bleaching and advise resource managers and scientists of the impending threat of bleaching before it occurs.

Although local coral reef managers cannot stop climate change, there are things they can do to reduce its impacts (Marshall and Schuttenberg, 2006). The most important thing that managers can do is control other local stressors to coral reefs, such as protecting large predatory fish and herbivores (the algae eaters of the reef community) from unsustainable fishing practices. By protecting fish that do many different jobs on the reefs, the reef system will be healthier and more resilient. A second approach managers can take is to reduce land-based sources of pollution that flow onto a reef. Actions can include modifying land-use practices to avoid sediment runoff, implementing better standards for wastewater treatment and fertilizer use and application, and controlling industrial waste to improve water quality. Scientists are also working hard on new, cost-effective methods to "farm" corals, which may make large-scale reef restoration a possibility in the future. Any actions reef managers can take to boost coral health will help the reefs survive, but the only long-term solution is to reduce the amount of CO_2 going into the atmosphere.

Remote Sensing and Sea Surface Temperature

Remote sensing is the technique of measuring a property of an object without touching it. Each day, NOAA uses satellite remote sensing to monitor characteristics of Earth's surface from space. The Advanced Very High Resolution Radiometer (AVHRR) sensor on NOAA satellites measures SST by detecting the infrared radiation given off by the ocean surface. Infrared radiation is of lower energy than visible radiation on the electromagnetic spectrum and, although it cannot be seen, it can be felt as heat. For example, it is infrared radiation that you feel as heat coming off embers or a hot stove even when there is no visible glow. You feel infrared radiation on a sunny day. SST varies daily, seasonally, and among different locations. Measuring it is an important component of weather forecasting, climate prediction, and managing natural resources; we can also use it to observe and understand the conditions around coral reefs.

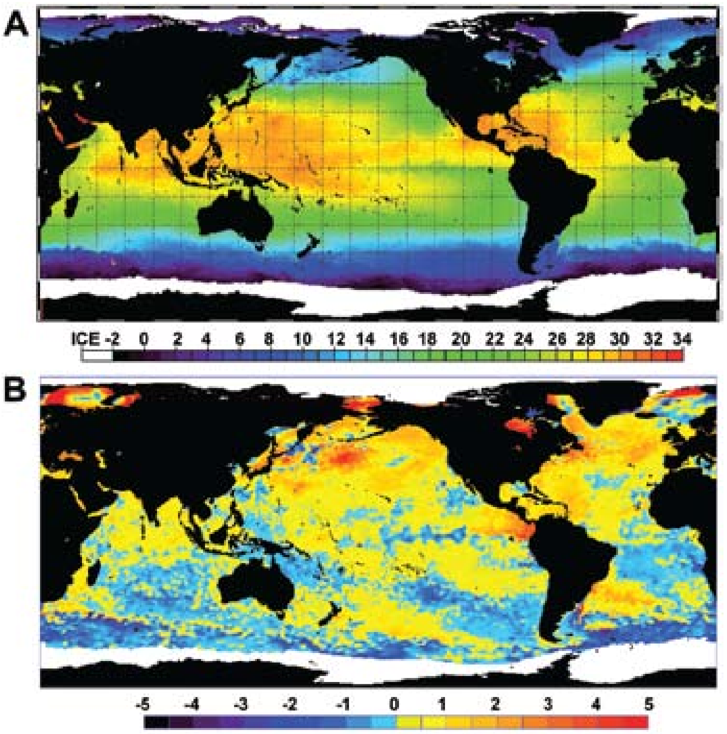

Figure 1. Global sea surface temperature (SST) and SST Anomaly for September 2, 2005. These two NOAA Coral Reef Watch products are released twice weekly. Global nighttime satellite SST (A) shows warmer waters near the equator and cooler waters near the poles; the global SST Anomaly product (B) indicates where temperatures are warmer or cooler than normal for the same time period.

NOAA Coral Reef Watch Products

NOAA Coral Reef Watch monitors satellite measurements of global-ocean SST to predict areas where coral bleaching might occur. SST data from NOAA polar-orbiting satellites are presented in 0.5-degree (~ 50 km) pixels, twice per week, and display nighttime temperature calibrated against patterns in buoy data at 1-m depth (Figure 1A). Thermal stress occurs when corals are exposed to temperatures warmer than their usual range. For each month and for each pixel, a seven-year mean SST or "climatology" was calculated from historical satellite data to provide the "usual" conditions for each location through the annual cycle. The SST anomaly is the difference between the measured SST and the climatology for that time of year (Figure 1B). Areas in purple and blue are cooler than normal, while areas in yellow and orange are warmer than normal. It is important to recognize that most corals do not live right at the ocean surface where satellites measures temperature. Although the corals often experience different temperatures from the sea

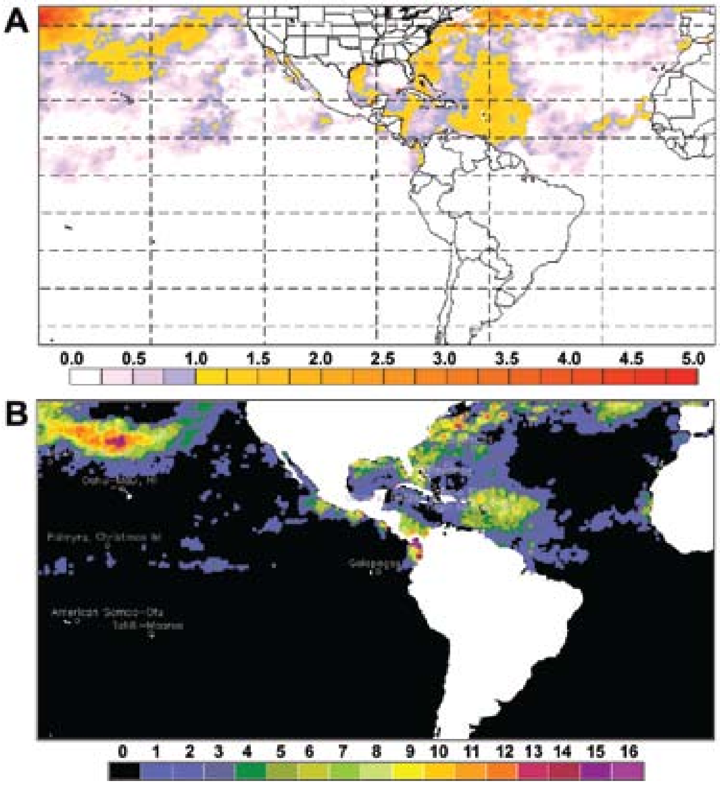

Figure 2. Western Hemisphere Coral Bleaching Hotspot and Degree Heating Weeks for September 2, 2005. Two NOAA Coral Reef Watch products are derived from SST to specifically pinpoint coral bleaching: the Coral Bleaching Hotspot product (A) indicates where SSTs are warmer than the warmest month climatology and if the bleaching threshold for each location is exceeded, while the Degree Heating Weeks product (B) accumulates bleaching-level thermal stress over the previous 12 weeks.

surface, the nighttime temperature anomaly is generally consistent from the surface through the range of depths in which coral reefs are found (to 100 m). As such, the night-time SST anomaly is an effective measure of whether the conditions experienced by corals are "normal" or not.

The Coral Bleaching Hotspot and Degree Heating Weeks (DHW) products are derived from SST to specifically pinpoint coral bleaching. The Hotspot product shows areas where the current SST is above the average temperature of the warmest month for each pixel (Figure 2A). When the Hotspot reaches the bleaching threshold value of 1°C, the temperatures in that region are high enough to cause coral bleaching (Hoegh-Guldberg, 1999; Berkelmans, 2002), shown as yellows and oranges in the Hotspot image. Widespread bleaching occurs when temperatures get hot and stay hot. The DHW product (Figure 2B) measures accumulating thermal stress over the past 12 weeks by summing any Hotspots at or above 1°C and expressing them in units of °C-weeks. A DHW of 4°C-weeks represents enough accumulated thermal stress to cause ecologically significant bleaching, and a DHW of 8°C-weeks indicates that widespread bleaching and mortality are likely.

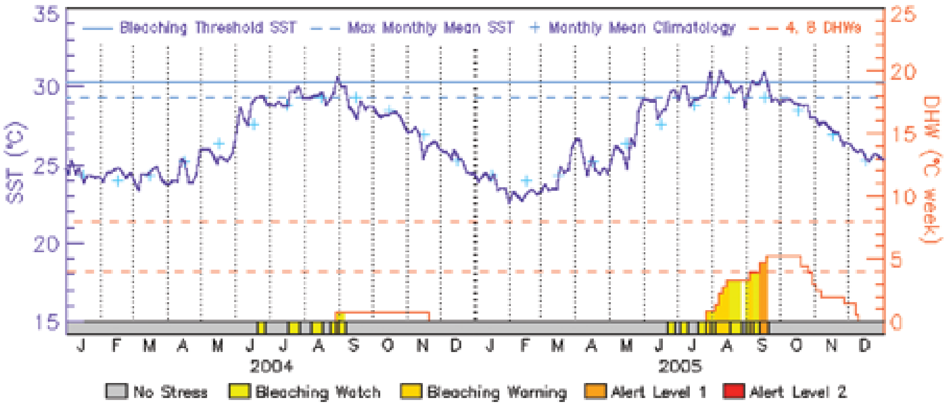

Figure 3. Time Series Graph for Lee Stocking Island in the Bahamas. One of 190 "Virtual Stations" available globally, this graph displays the current SST (purple line), the monthly average temperature or "climatology" (blue plus signs), the maximum monthly mean (blue dotted line), and the bleaching threshold (blue solid line). When temperatures reach or exceed the bleaching threshold, thermal stress is accumulated as degree heating weeks (DHWs) and displayed using the right-hand axis (red solid line) with 4°C- and 8°C-weeks marked for reference (red dotted line). A Bleaching Watch is issued when the Hotspot is greater than 0°C but less than 1°C, and a Bleaching Warning is issued when the Hotspot is greater than 1°C- and the DHW less than 4°C-weeks. An Alert Level 1 is declared when DHWs are between 4°C- and 8°C-weeks, and an Alert Level 2 when DHWs are at or above 8°C-weeks.

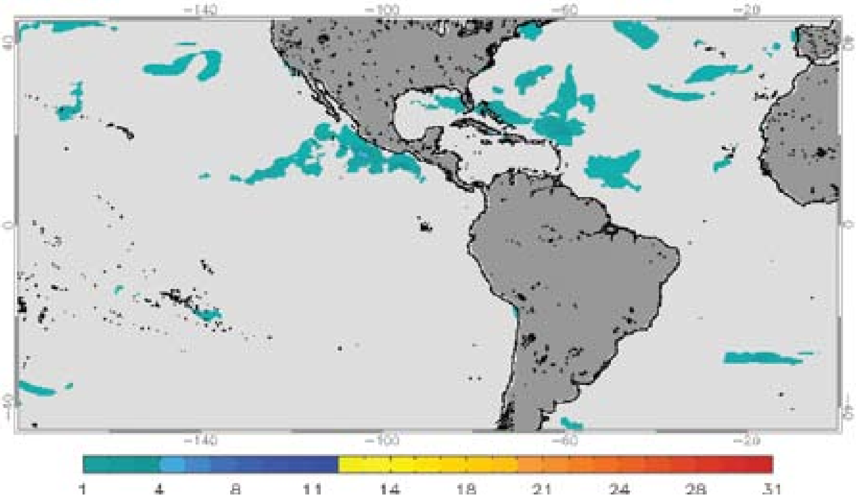

Figure 4. Western Hemisphere Doldrums for September 2, 2005. Using satellite wind data from several satellites, the Coral Reef Watch Doldrums product indicates for how long the daily average wind speed was less than 3 m s^{-1} (about 7 mph). Turquoise indicates doldrums-condition persistence for the past four days, blues for between four and 12 days, and yellow to orange colors for the most recent two weeks to a month.

Satellite data are summarized at 190 "Virtual Stations" around the world (http://coral-reefwatch.noaa.gov/satellite/current/experimental_products.html) that simulate data-collecting buoys in the water. For each station (such as the one pictured in Figure 3), the purple line shows SST time series, the blue plus signs (+) are the monthly climatology values (the historical monthly means), the dotted blue line represents the warmest monthly mean temperature found in the climatology for that pixel, and the solid blue line is the bleaching threshold temperature. The DHW data are shown by a solid red line, relative to the right-hand axis, with the key values of 4°C weeks and 8°C weeks indicated with dashed red lines. Yellow-to-red colors along the x-axis indicate periods when bleaching alerts were issued.

NOAA Coral Reef Watch is developing additional satellite products to monitor other conditions related to a coral bleaching event, such as an extended period of low wind (Doldrums) product that uses data from several satellites to indicate how long the average wind speed was below a critical threshold (3 m s^{-1}, or about 7 mph; Figure 4). This information is important because wind can cause mixing of the water column, bringing cooler water up from deeper in the ocean. When the wind is light, more heating of surface waters near coral reefs can occur.

MATERIALS

The activity worksheet and answer sheet are available as Portable Document Format files (PDF) to download from The Oceanography Society Hands-On Oceanography Web site at http://www.tos.org/hands-on. An online tutorial giving more-detailed descriptions of the satellite products can be found at http://coralreefwatch.noaa.gov/satellite/education/tutorial/welcome.html.

ACTIVITY

After instruction and/or exploration of the online tutorial, students should be split into four groups to complete worksheets. Each group is assigned to one of the following pixel locations: Bermuda (32.0°N, 64.5°W), Lee Stocking Island (Bahamas) (23.5°N, 76.5°W), the west coast of Puerto Rico (18.0°N, 67.5°W), or the US Virgin Islands (USVI; 18.0°N, 65.0°W). Using satellite SST maps and time series, students examine the maps to determine temperature and wind conditions at their assigned locations during the 2005 Caribbean bleaching event. Students then interpret the thermal stress observations to predict the likelihood of coral bleaching at their sites and, finally, they compare the severity of thermal stress with the other sites throughout the Caribbean. After the activity is complete, a spokesperson from each group should report back to the class about his or her group's location. The post-activity discussion compares field data acquired during the 2005 bleaching event with the students' predictions. Students can also be asked for suggestions as to what can be done to help save the coral reefs (see the *What can be done?* section of the online tutorial). Some modifications to the activity are also suggested below; their use depends on the backgrounds of the students, the broader objectives of the class, and the teacher's areas of knowledge.

POST-ACTIVITY DISCUSSION

During the 2005 bleaching season, much of the Caribbean region experienced temperatures above the bleaching threshold. DHWs rose above 8°C-weeks in some areas, indicating widespread bleaching and mortality. Over 1500 on-site surveys were conducted during the 2005 bleaching event by scientists and managers across the basin. Each dot in Figure 5A represents the average percentage of the coral colonies bleached at that location.

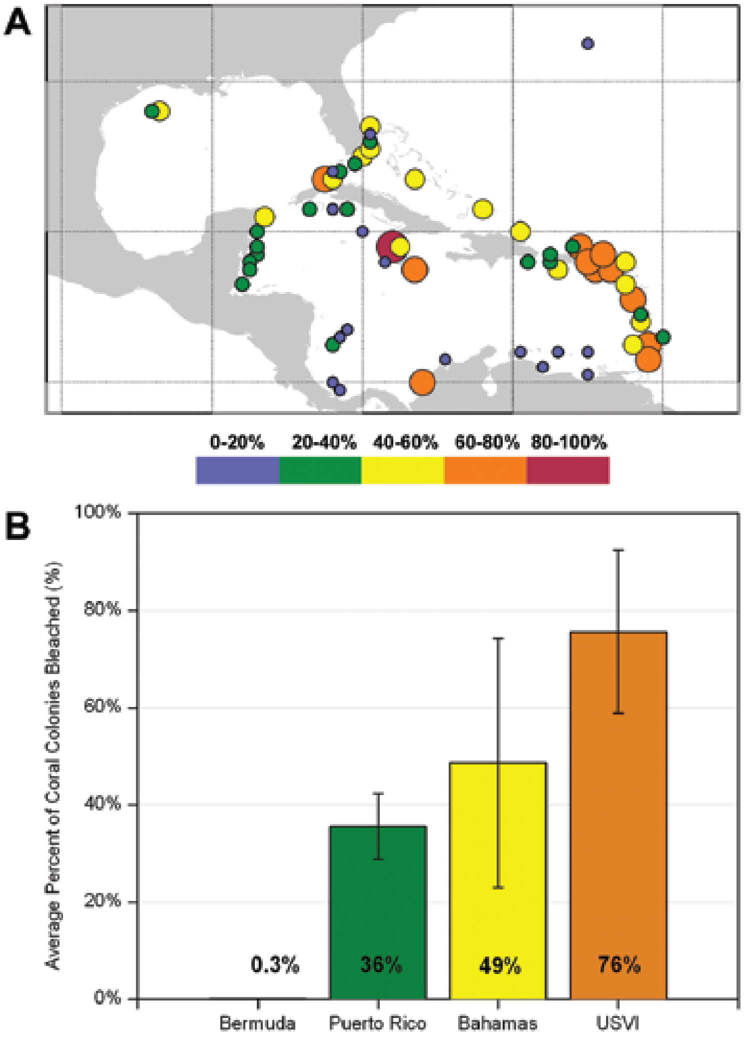

Figure 5. The 2005 Caribbean Bleaching Event. The average percent of coral colonies that bleached at reef sites across the region (A), based on data collected during the 2005 Caribbean Bleaching Event. Bleaching data from within 50 km of the four sites in this exercise were averaged (standard deviation shown) for comparison with the satellite products (B). The US Virgin Islands (USVI) had the worst bleaching, Puerto Rico and the Bahamas had moderate bleaching, and there was very little bleaching at Bermuda.

Bleaching surveys within 50 km of each of the four sites in this exercise were grouped for comparison with the satellite products (Figure 5B). Bleaching was worst in the US Virgin Islands, where about 76% of the coral colonies were affected. Puerto Rico and Lee Stocking Island (Bahamas) witnessed moderate bleaching (36% and 49% of colonies bleached, respectively). In Bermuda, less than 0.3% of coral colonies bleached. Note that variability in the data (shown by the error bars) is due to localized effects within each 50-km pixel; individual observations are influenced by small-scale factors such as species composition, upwelling, currents, and reef depth.

POSSIBLE MODIFICATIONS TO ACTIVITY

- Explore further details of the components of the electromagnetic spectrum beyond infrared radiation.
- Determine what other characteristics of the ocean surface can be measured by satellites and how scientists might use this information (e.g., ocean color, sea surface height, and roughness of the water surface).
- For more advanced students, explore remote-sensing image analysis with Coral Reef Watch Data using the free UNESCO Bilko software, available at http://coralreefwatch.noaa.gov/satellite/education/bilko_lesson.html.
- Talk about "bleaching weather"—low cloud cover, little to no wind, and weak currents—that is associated with warm SST. Also, consider some of the associated physical processes: waves, turbulence, mixing, and stratification.
- Introduce concepts of climate change and how CO_2 emissions can affect both ocean temperature and pH. Present the concept of ocean acidification and how that might affect organisms that build calcium carbonate shells or skeletons (see Coral Reef Watch Ocean Acidification Web page http://coralreefwatch.noaa.gov/satellite/oa/description/oaps_intro_oa.html for products and a discussion of this issue).
- Explore more details about coral physiology and ecology with students; for example, consider what happens to a coral reef ecosystem (corals, plants, fish, and other animals) after a mass bleaching event.
- Discuss climate change impacts on organisms, such as corals, that live near their limits of thermal tolerance or other physiological optima. This discussion could include sea-level rise, saltwater intrusion, and changing precipitation patterns.
- Discuss with students how their everyday actions contribute to climate change, and what actions they can take to help coral reefs (suggestions can be found at http://coralreef.noaa.gov/outreach/thingsyoucando.html).

SATELLITE IMAGERY RESOURCES ONLINE

- QuikScat Winds images from the NOAA Marine Observing Systems Team: http://manati.orbit.nesdis.noaa.gov/hires/
- Current and archived Sea Surface Temperature, SST Anomaly, Coral Bleaching Hotspot, and Degree Heating Week data and time series: http://coralreefwatch.noaa.gov/satellite/
- Background presentation for this activity: http://coralreefwatch.noaa.gov/satellite/education/

REFERENCES

Berkelmans, R. 2002. Time-integrated thermal bleaching thresholds of reefs and their variation on the Great Barrier Reef. *Marine Ecological Progress Series* 229:73–82.

Bruno, J.F., E.R. Selig, K.S. Casey, C.A. Page, B.L. Willis, C.D. Harvell, H. Sweatmand, and A.M. Melendy. 2007. Thermal stress and coral cover as drivers of coral disease outbreaks. *Public Library of Science: Biology* 5(6):e124.

Coral Disease Working Group of the Global Environmental Facility Coral Reef Targeted Research Program. 2007. Coral disease, environmental drivers, and the balance between coral and microbial associates. *Oceanography* 20(1):172–195. Available online at: http://www.tos.org/oceanography/issues/issue_archive/issue_pdfs/20_1/20.1_breaking_waves.pdf (accessed April 24, 2009).

Eakin, C.M., J.M. Lough, and S.F. Heron. 2009. Climate variability and change: Monitoring data and evidence for increased coral bleaching stress. Pp. 41–62 in *Coral Bleaching: Patterns, Processes, Causes and Consequences*. M.H. Van Oppen and J.M. Lough, eds, Ecological Studies 205, Springer, Berlin.

Glynn, P.W., and L. D'Croz. 1990. Experimental evidence for high temperature stress as the cause of El Niño-coincident coral mortality. *Coral Reefs* 8:181–191.

Glynn, P.W. 1996. Coral reef bleaching: Facts, hypotheses and implications. *Global Change Biology* 2:495–509.

Harvell, C.D., C.E. Mitchell, J.R. Ward, S. Altizer, A.P. Dobson, R.S. Ostfeld, and M.D. Samuel. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science* 296:2,158–2,162.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching, and the future of the world's reefs. *Marine and Freshwater Research* 50(8):839–866.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, and others. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318:1,737–1,742.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller Jr., eds, Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Kleypas, J.A., and C.M. Eakin. 2007. Scientists' perceptions of threats to coral reefs: Results of a survey of coral reef researchers. *Bulletin of Marine Science* 80(2):419–436.

Marshall, P., and H. Schuttenberg. 2006. *A Reef Manager's Guide to Coral Bleaching*. Great Barrier Reef Marine Park Authority, Townsville, Australia, 163 pp.

McClanahan, T.R., E. Weil, J. Cortes, A.H. Baird, and M. Ateweberhan. 2009. Consequences of Coral Bleaching for Sessile Reef Organisms. Pp. 121–134 in *Coral Bleaching: Patterns, Processes, Causes and Consequences*. M.H. Van Oppen and J.M. Lough, eds, Ecological Studies 205, Springer, Berlin.

Muscatine, L. 1990. The role of symbiotic algae in carbon and energy flux in reef corals. *Coral Reefs* 25:1–29.

Wilkinson, C., and D. Souter, eds. 2008. *Status of Caribbean Coral Reefs after Bleaching and Hurricanes in 2005*. Global Coral Reef Monitoring Network, and Reef and Rainforest Research Centre, Townsville, Australia, 148 pp.

Wilkinson, C., ed. 2008. *Status of Coral Reefs of the World: 2008*. Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, Townsville, Australia, 296 pp. http://www.gcrmn.org/publications.aspx.

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