

little as 2°C (3.6°F) of global warming could result in the loss of 20% of the forest by 2100. The most devastating drought in 100 years occurred in 2005, with forest fires penetrating deeply into the heart of the untouched forest. These fires released as much as 5 billion tonnes of CO₂ into the atmosphere—more than the combined annual greenhouse gas emissions of Japan and Europe. The loss of the Amazon would be an ecological, economic, social, and global environmental disaster (Figure 7.19).

CHECKPOINT 7.21 ▶ Why is the loss of the Amazon forests likely to accelerate the rate of global climate change?

7.2 PAUSE FOR... THOUGHT | *Is it true that the Amazon makes its own weather?*

Tropical forests are unique ecosystems. The Amazon experiences both dry and wet seasons associated with the annual migration of the ITCZ. During the dry season, NASA satellite photographs show that the forests are blanketed with myriad small clouds that form above the forest canopy. Up to 70% of the water that falls on the forests is lost from the canopy as transpiration that keeps the air humid, cools the forest during the day, warms the forest at night, and leads to the formation of clouds that can increase albedo. As much as 25% to 30% of the rain that falls in the forest is generated from water vapor that actually came from within the forest. Each tree in the canopy can release about 760 liters (200 gallons) of water into the atmosphere each year, leading some to refer to the Amazon as the “green ocean.”



▲ **Figure 7.19:** The current distribution of different ecosystem types in the Amazon Basin. The Amazonian forests area is so large and so important that even their partial loss would be an ecological disaster.

Case Study 3: Reef Systems

Barrier reef systems form part of a complex interconnected web of ecosystems that link near-shore with deep-water environments. Marine biologists believe that global warming could destroy many of these reefs by the end of the 21st century, affecting thousands of coastal communities and millions of people.

The Great Barrier Reef

The Great Barrier Reef system stretches for over 2,300 kilometers (1,429 square miles) off the northeast coast of Australia; it is the only biological structure that can be seen from space. The reef system is the largest of the maritime World Heritage areas and is composed of over 3,000 reefs and 940 islands. Together with the surrounding waters, the reef encompasses a diverse and complex range of communities. The barrier reef itself protects the Australian coastline, forming sheltered lagoons with abundant patch reefs and broad areas of seagrass, salt marsh, and mangrove swamp communities (Figure 7.20).

The Great Barrier Reef, like the Amazon forest, has evolved to cope with the natural pace of change associated with the waxing and waning of continental ice sheets. Borehole samples recovered from the base of the reef suggest that it is at least 600,000 years old, but other estimates extend the reef’s age as far back as 18 to 20 million years.

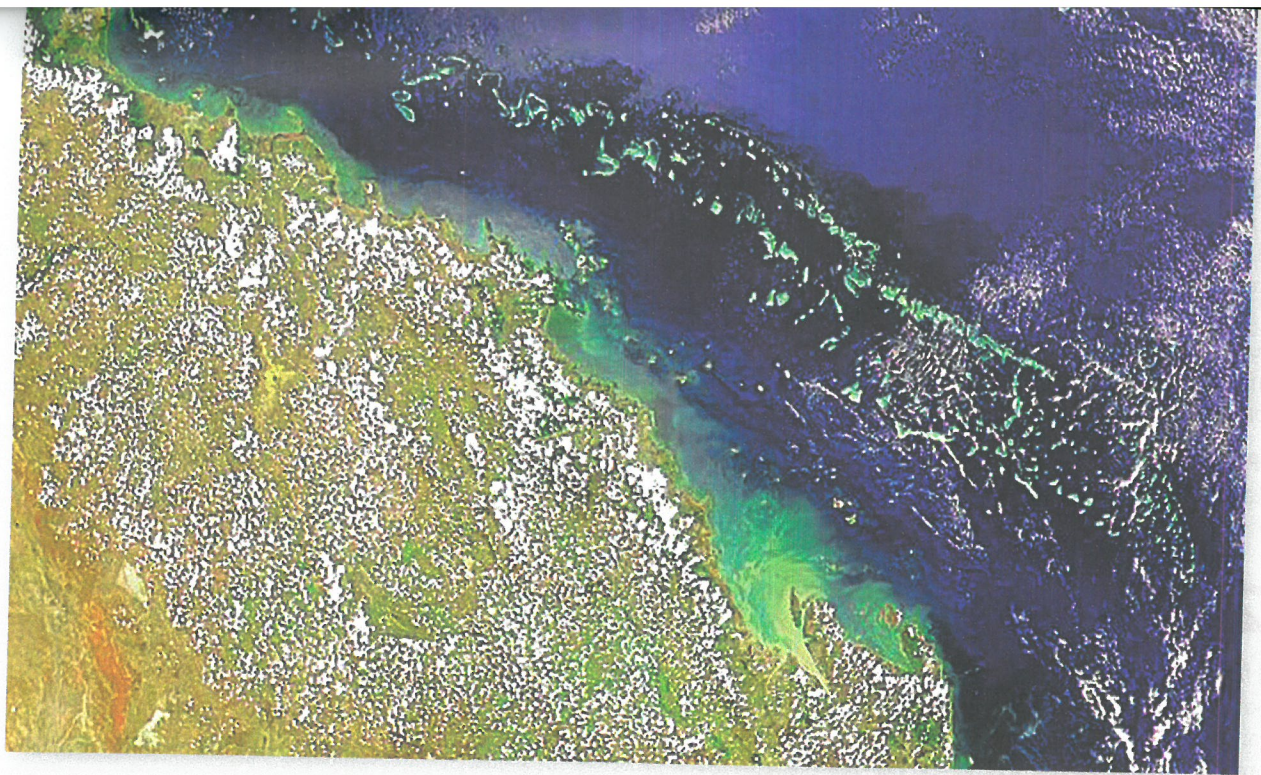
This ancient reef has had time to evolve into a rich and complex ecosystem that includes more than 400 species of corals, 500 species of marine algae, 1,500 species of fish, more than 5,000 species of mollusks, and more than 40 species of whales, dolphins, porpoises, turtles, and (rare) dugongs. All these populations are interconnected, and any imbalance between species can have a dramatic impact on the overall health of the entire reef system.

CHECKPOINT 7.22 ▶ In what ways are reef systems similar to tropical forests?

Coral Bleaching

Scleractinian (stony, reef-building) corals live in a symbiotic relationship with **zooxanthellae**, a variety of dinoflagellate algae that provide nutrition to the coral through photosynthesis. Many of these algae are particularly sensitive to heat stress, suffer cell damage, and are expelled by the coral when the temperature rises above a critical threshold. It is the algae that give corals their unique and varied color, so when the algae are expelled, the coral appears white and **bleached** because all that remains is the natural white color of the calcium carbonate that forms the substance of the reef (Figure 7.21).

CHECKPOINT 7.23 ▶ In your own words, describe how and why coral bleaching occurs.



▲ **Figure 7.20:** The Great Barrier Reef off the coast of Australia appears to be thriving, but it is under threat from a combination of climate change, pollution, and exploitation. In this satellite photograph, the coral reef appears as light green patches in the blue ocean to the top right-hand side. The coast of Australia to the bottom left is dotted with small white cumulus clouds.

Coral bleaching occurs when the reef is exposed to a sudden large rise in temperature or more prolonged exposure at slightly elevated temperatures. NOAA defines the sensitivity of corals to bleaching in terms of “degree heating weeks” (DHW). One DHW is equivalent to one week of sea surface temperatures 1°C (1.8°F) greater than the expected summertime maximum. Two DHWs are equivalent to two weeks at 1°C (1.8°F) above the expected summertime maximum *or* one week of 2°C (3.6°F) above the expected summertime maximum.

▼ **Figure 7.21:** Symbiotic zooxanthellae add all the color we associate with healthy corals. Corals like the example in this photograph turn white and cannot live for long after rising temperature forces the coral to expel the colored zooxanthellae.



Bleaching is likely to occur when $\text{DHW} > 4$, and severe bleaching when $\text{DHW} > 8$ (Figure 7.22).

CHECKPOINT 7.24 ▶ What are degree-heating weeks, and how do scientists use them to monitor the health of reef systems?

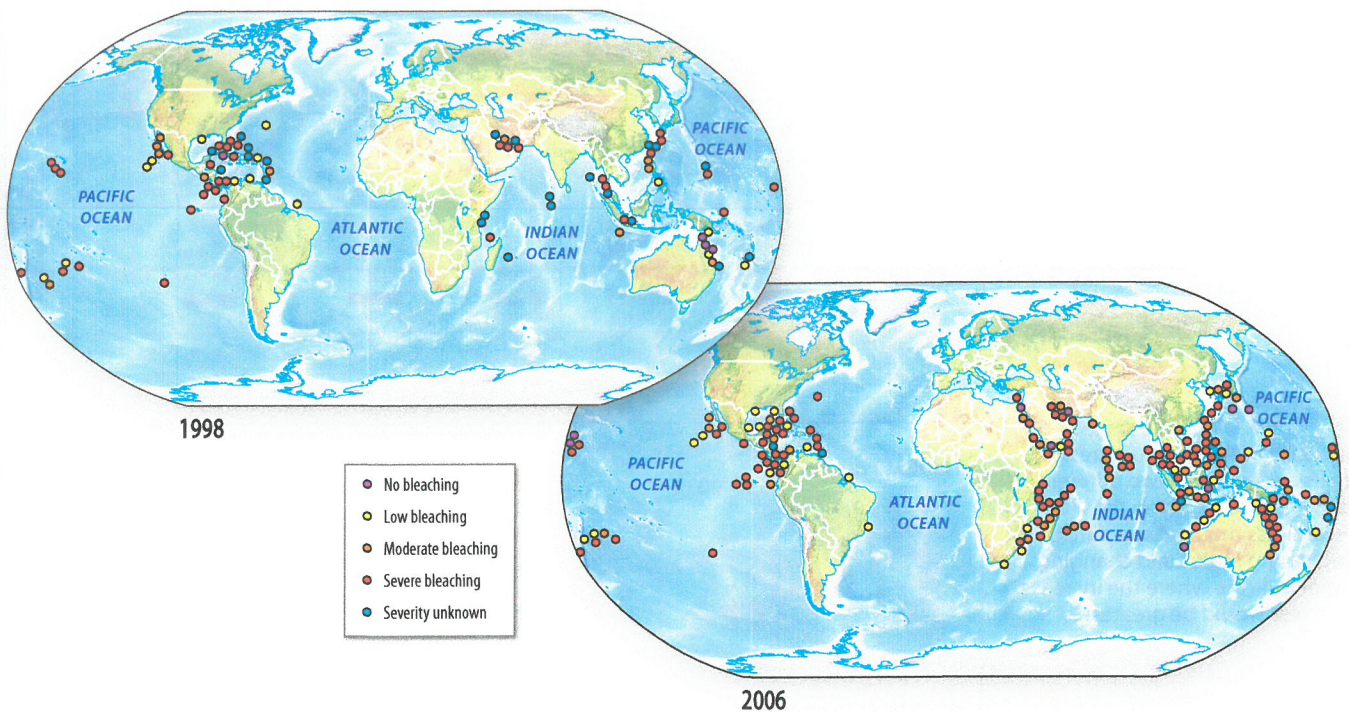
Lessons from El Niño

Severe bleaching occurred in the Great Barrier Reef in 1998 and 2002 and in the Caribbean in 2005. These events were closely associated with natural El Niño events. However, as ocean temperatures gradually warm around the world, more extensive bleaching will take place globally. There is evidence that some corals can adapt to higher water temperatures by hosting a different variety of symbiotic **dinoflagellate** known as “clade D,” but scientists do not know whether this can offset the impact of annual to biannual bleaching events that are likely to occur within the next 30 to 50 years (Figure 7.23).

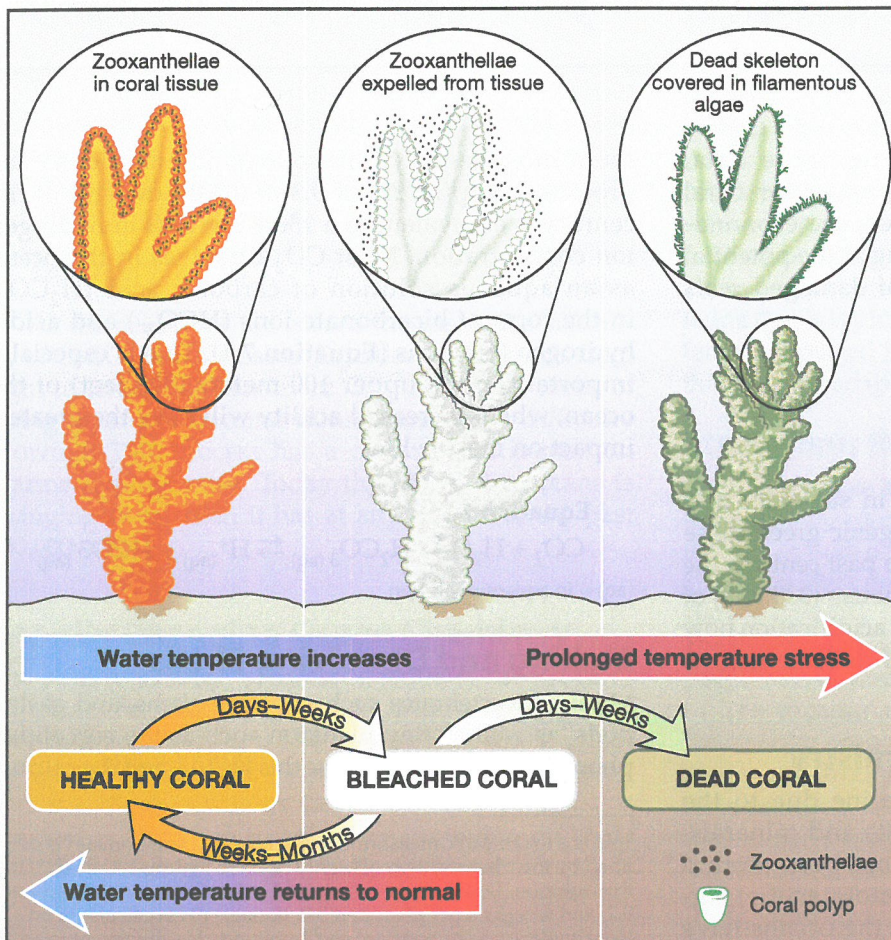
CHECKPOINT 7.25 ▶ What impact does El Niño have on coral bleaching?

An Eye in the Sky

In the United States, NOAA established a satellite tracking system for sea surface temperature (SST) data and launched a new coral reef watch that generates automatic alerts for coral bleaching. NOAA also set up a special Coral Reef Task Force and a new coral reef conservation program for the United States. The aim of these programs is to provide effective

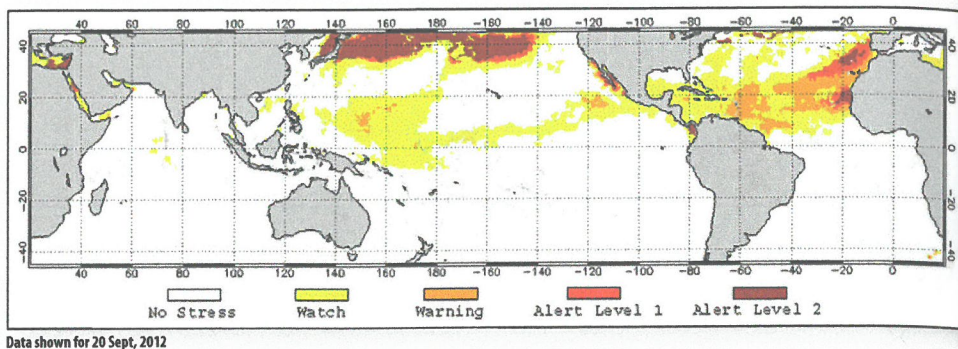


▲ **Figure 7.22:** The number of bleaching events around the globe in 1998 and 2006. Note an increase in the frequency of bleaching events across the world, especially in the western Pacific and Indian Ocean.

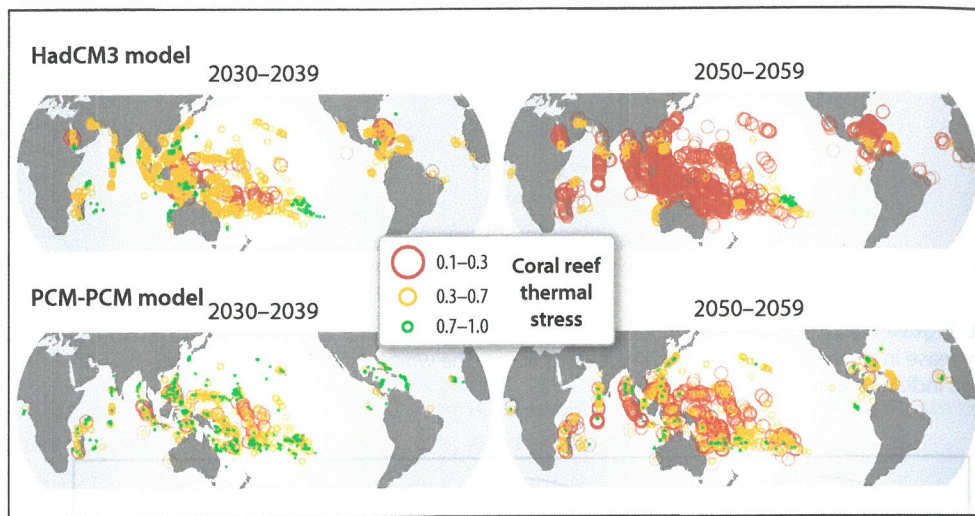


◀ **Figure 7.23:** The bleaching and recovery processes. The loss of Zooxanthellae from corals happens suddenly, and unless the temperature of the water falls dramatically, many corals are unable to recover and die.

► **Figure 7.24:** The NOAA coral bleaching alert system gives advanced warning of bleaching events, based on satellite observations of ocean temperature that are plotted on maps such as this one showing global data shown for September 20, 2012. Where is the greatest threat of bleaching?



► **Figure 7.25:** The projected increase in the thermal stress of reefs according to two different climate models, using the IPCC A2a-emissions scenario. Circles of increasing radius and changing color indicate where the increase in stress would be greatest.



satellite coverage, onsite monitoring, more data, better modeling, and continued support for coral reef conservation. Because coral reefs are economically important, NOAA is also looking at the potential social and economic implications of damaged reefs (Figures 7.24 and 7.25).

Case Study 4: Ocean Acidification

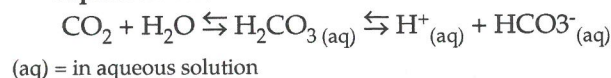
Carbon dioxide is slightly soluble in seawater and increases ocean acidity. As anthropogenic greenhouse gas emissions have increased over the past century, the concentration of CO_2 in the top 100 meters (328 feet) of the ocean has also increased, and **ocean acidification** now poses a major threat to a number of delicate marine ecosystems (Figure 7.26).

Understanding Ocean Chemistry

Seawater is normally slightly alkaline due to the high concentration of dissolved salts and minerals. The historical pH^1 of ocean water has been around 8.2, but it has decreased (become more acidic) significantly over the past century, as the oceans have absorbed as much as 50% of the CO_2 added to

the atmosphere by anthropogenic emissions. The projected drop in pH of 0.3 to 0.5 by the end of the century is equivalent to a 150% increase in hydrogen ion concentration. Most CO_2 dissolves in the ocean as an aqueous solution of carbonic acid (H_2CO_3) in the form of bicarbonate ions (HCO_3^-) and acidic hydrogen (H^+) ions (Equation 7.1). This is especially important in the upper 100 meters (328 feet) of the ocean, where increased acidity will have the greatest impact on marine life.

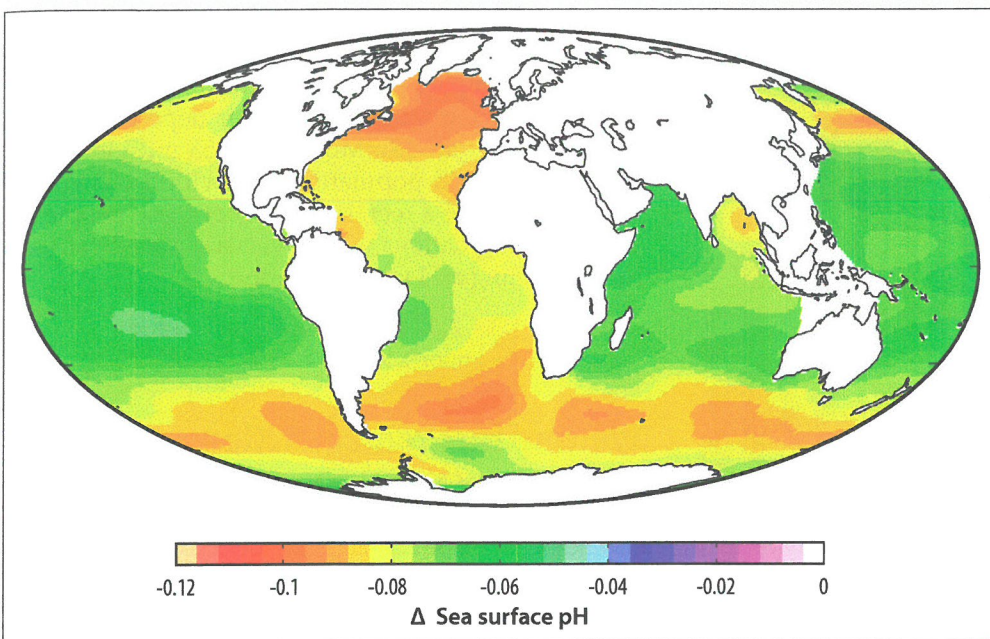
Equation 7.1:



Making and Dissolving Shells

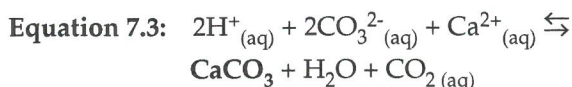
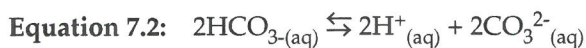
Marine invertebrates such as corals, clams, and gastropods, as well as tiny plankton such as the coccolithophores and foraminifera, use this HCO_3^- and the calcium

¹pH is a logarithmic measure of the acidity of a solution and is defined by the concentration of highly reactive hydrogen ions (H^+) in that solution. Distilled water has a pH of 7.0, seawater a pH around 8.2, and vinegar a pH of around 3.0. Because pH is calculated on a logarithmic scale, a change of just 1 unit of pH is equivalent to an increase of 10 times the actual concentration of hydrogen ions.

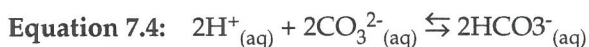


◀ **Figure 7.26:** Estimated change in annual mean sea surface pH between the preindustrial period (1700s) and the end of the 20th century. The more negative the change, the greater the relative increase in acidity, as shown on this map by increasing color intensity from green through yellow to orange and red.

ion Ca^{2+} in seawater to produce the calcium carbonate they need to build their shells (**Equations 7.2 and 7.3**).



The addition of H^+ to the oceans upsets the balance of Equation 7.3 and as acidity increases, the ocean adjusts to regain balance (equilibrium) by “mopping up” excess H^+ , using carbonate ions (CO_3^{2-}) to form more HCO_3^- (**Equation 7.4**).



As the acidity of the oceans increases, the solubility of CaCO_3 also increases (Equation 7.3 proceeds from right to left to produce more CO_3^{2-}), and the shells of living creatures become thinner and have difficulty growing. This process has a catastrophic impact on marine invertebrates. Today the pH of the oceans is changing faster than it has at any time over the past 100,000 years.

Rapidly Changing Ocean Chemistry

The rate of change of ocean chemistry is critically important for species that might otherwise survive if they had time to adapt. The level of CO_2 in the atmosphere has been much higher in the past (Chapter 6), and marine ecosystems have survived intact, but the oceans had time to adjust by removing much of the additional gas from the surface and mixing it into deep-ocean currents. The problem is greatest for common species that build their shells from **aragonite**, a common soluble form of calcium carbonate. Some

studies suggest that parts of the oceans could become so acidic by 2100 that some marine invertebrates will no longer be able to make shells of aragonite.

Endangering Shallow Marine Ecosystems

Marine biologists have studied how shallow marine ecosystems are affected by ocean acidity by looking at places around the world where CO_2 from volcanic activity seeps naturally to the surface. Where this happens, seagrass communities flourish, but corals and coralline red algae, echinoderms (sea urchins), calcareous foraminifera, coccolithophores, oysters, and other mollusks are rare or absent. In essence, the high abundance and diversity of fauna that is typical of shallow marine carbonate ecosystems is replaced by a much lower-diversity ecosystem that is better adapted to high ocean acidity (**Figure 7.27**).

Struggling Reef Systems

Coral reefs have been carefully monitored to assess the impact of increasing ocean acidity. Studies have shown that the growth of some corals has slowed by as much as 13% since 1990, and corals could cease to grow and even start to dissolve if atmospheric CO_2 reaches 560 ppm. The disappearance of keystone species could push many major reefs toward a critical tipping point (**Figure 7.28**).

The broader reef ecosystem is also at risk. Many fish that are economically important spend part of their life in and around coral reefs. In addition, reef structures protect coast ecosystems from the impact of major storms. Reefs weakened by increasing ocean acidity may not withstand the increasing intensity of tropical storms.

CHECKPOINT 7.26 ▶ What impact will ocean acidification have on reef systems?

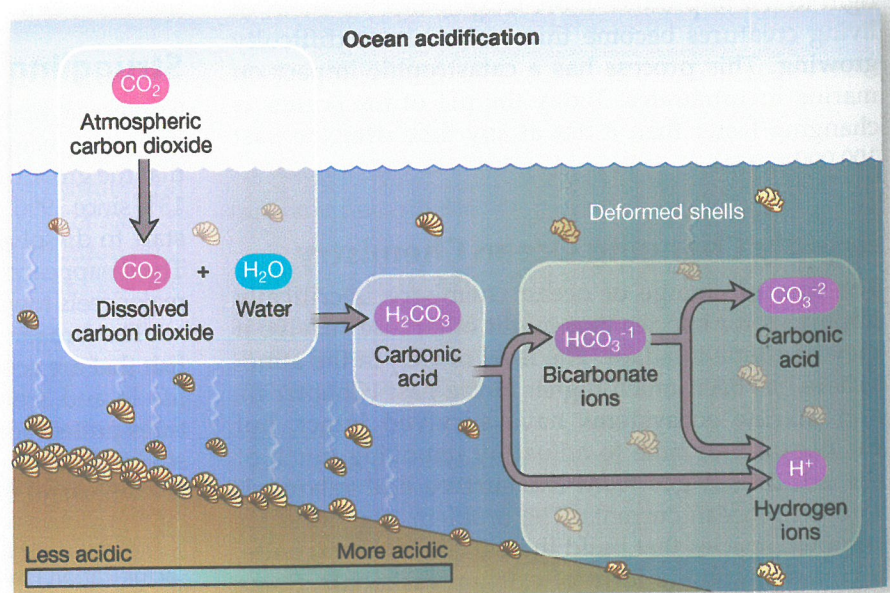


▲ **Figure 7.27:** The possible impact of ocean acidification on some marine ecosystems. These corals have died and have been replaced by algae and sea grasses that thrive under these new conditions.

The Social and Human Impacts of Ocean Acidification

Ocean acidification is not just a problem for marine life but also an economic problem. In Queensland, Australia, home of the Great Barrier Reef, fishing is a \$360 million-per-year business that employs more than 2,000 people. The area also attracts 1.6 million tourists, who bring important additional income to the economy. Local indigenous communities are also affected by ocean acidification, as more than 70 aboriginal and Torres Strait Islander clans depend on a healthy reef for their livelihood. In the United States, coastal fisheries bring in over \$30 billion a year, and many of the most important species depend on a healthy reef system as part of their life cycle. A global decline in the number

► **Figure 7.28:** Ocean acidification is a complex chemical process that threatens a broad range of invertebrate species, including coral reefs. As the oceans become more acidic the number of shelled animals living in the sediment decreases. In deep water, even the shells of plankton that fall from the surface dissolve before they reach the ocean floor.



of healthy reef systems could cost more than 70,000 jobs in fishing, processing, and transport. However, the greatest impact would be in the developing world, where many communities are totally dependent on reef fisheries and tourism. More than 655 million people, 10% of the world population, live within 100 kilometers (62 miles) of a reef, and many of these people live in developing nations where reefs are already stressed by overfishing and water pollution.

CHECKPOINT 7.27 ► Discuss why reefs are so economically important.

Waiting for Political Action

The prospect of acidification has generated worldwide concern. In the **Monaco Declaration** in 2009, more than 155 scientists from 26 countries called on policymakers to stabilize CO_2 emissions "at a safe level to avoid not only dangerous climate change, but also dangerous ocean acidification." The declaration, supported by Prince Albert II of Monaco, built on findings from an earlier international summit.

The sea will eventually recover from this increase in acidity as the excess carbon is slowly absorbed into the vast reservoir of the deep oceans, but it can take hundreds of years for the surface waters to mix with deeper waters. By the time that happens, it may be too late to avoid widespread extinction in the shallow oceans. Some estimates put the likely extinction rate as high as 32%.

Case Study 5: The Roof of the World

The Himalayas form an active and growing mountain belt that separates the Indian subcontinent from the Tibetan Plateau (**Figure 7.29**). Tall, glaciated peaks