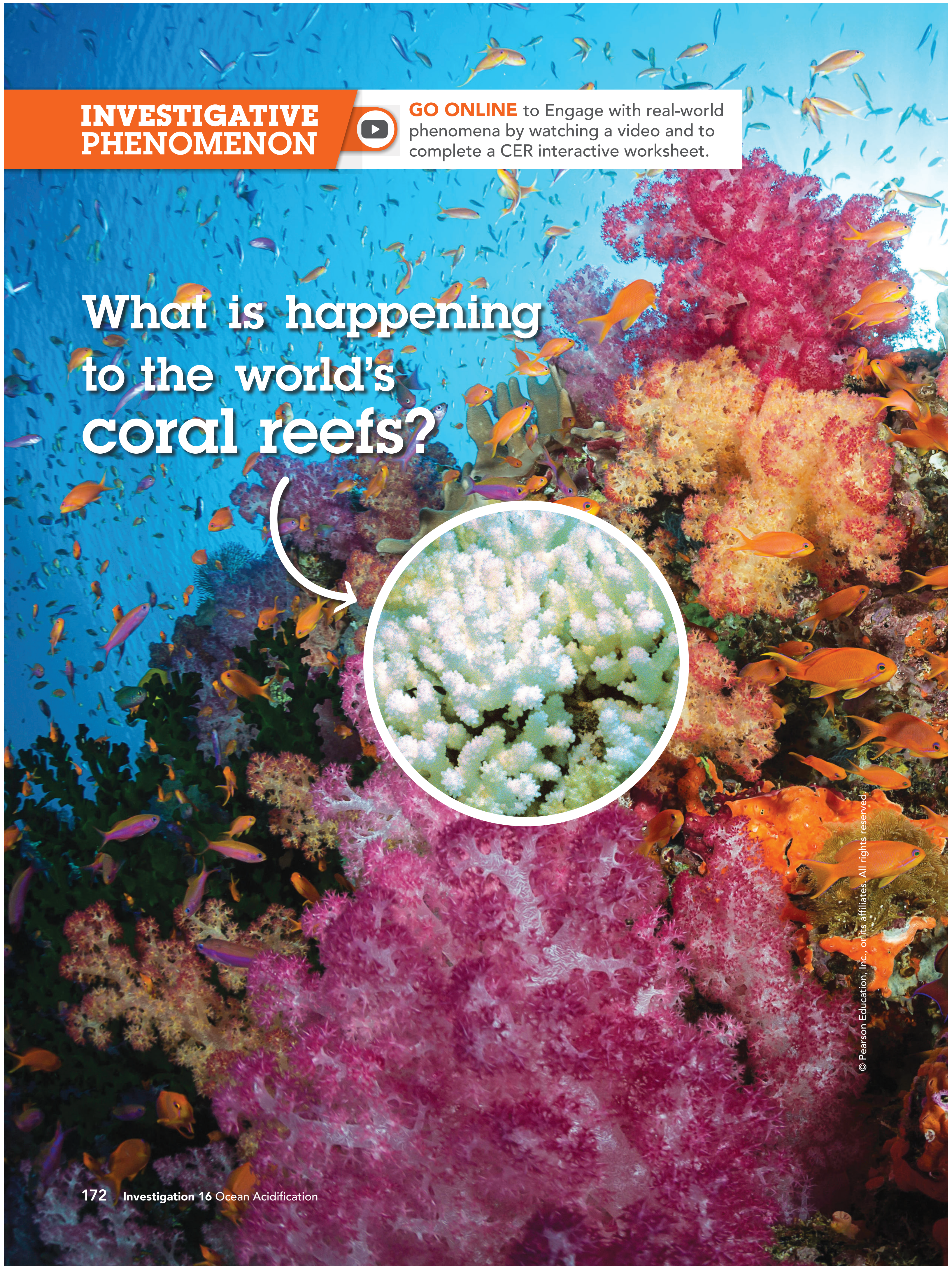

INVESTIGATIVE PHENOMENON

GO ONLINE to Engage with real-world phenomena by watching a video and to complete a CER interactive worksheet.

What is happening to the world's coral reefs?

Ocean Acidification

Once you have viewed the Investigative Phenomenon video and worked on a first draft of a Claim-Evidence-Reasoning exercise to explain "What is happening to the world's coral reefs?" Discuss with a partner the following questions:

1. **CCC Energy and Matter** Coral reefs need three things to thrive: warm water temperatures, good light levels, and the chemical building blocks of a mineral called aragonite that can be extracted from seawater and used to build skeletons. Identify at least three ways that you think rising global temperatures could alter these three parameters.

   Sample answer: Rising global temperatures could increase ocean water above the comfortable threshold for corals. If sea levels rise, the depth of the ocean bottom would increase, so less light could penetrate to reach the corals. Increasing the amount of water in the ocean could change the concentration of calcium and carbonate ions in seawater that corals use to make aragonite.

2. **CCC Cause and Effect** Corals thrive in clear water that sunlight can penetrate. How might algal blooms affect the clarity of water and thus affect the health of coral ecosystems?

   Sample answer: Planktonic algae and other free-floating microorganisms may form large mats that block sunlight or may make the water more opaque so that less sunlight reaches the bottom where corals live. A reduction in sunlight would affect the ability of the algae that live inside corals to produce food for the corals, which in turn affects other organisms that live in a coral reef ecosystem.

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EXPERIENCE 1

Ocean pH Levels

GO ONLINE to Explore and Explain ocean pH and acidification.

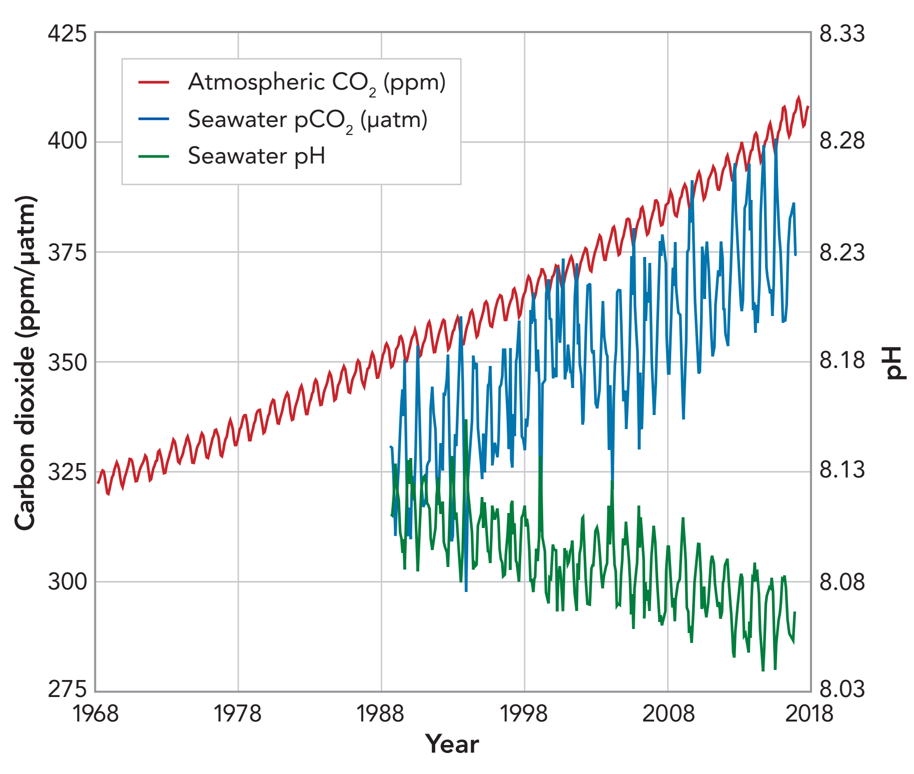
Carbon Dioxide and Ocean pH

The ocean and atmosphere maintain an equilibrium of their concentrations of carbon dioxide. If that equilibrium is disrupted, there will be a net flow of carbon between the two reservoirs until the equilibrium is restored. Atmospheric CO_2 has been increasing due to the human combustion of fossil fuels.

The equilibrium between the atmosphere and ocean has been a helpful counterbalancing feedback that has slowed the rate at which carbon dioxide has increased in the atmosphere. Roughly 30% of the carbon dioxide humans have released has gone into the ocean, lessening the potential greenhouse gas forcings on atmospheric temperature. However, the increased carbon dioxide absorption is dropping ocean pH and making the ocean increasingly acidic.

Correlation between Carbon Dioxide and pH Atmospheric CO_2 levels, ocean CO_2 levels, and ocean acidity (pH) were all measured at stations in Hawaii. As the carbon dioxide concentrations in the atmosphere and ocean increased, ocean pH has gone down.

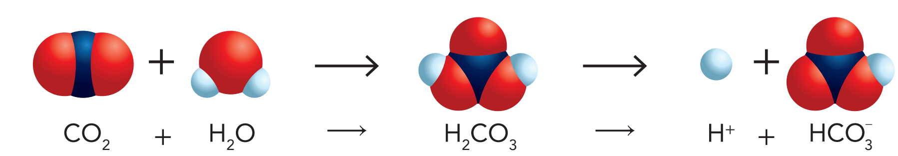
Carbon Dioxide and Acidity in the North Pacific



A series of chemical reactions in seawater results in a greater number of free hydrogen ions, which increases the acidity of the water. First, a carbon dioxide molecule reacts with water to form carbonic acid. Then, the carbonic acid molecule dissociates to form a free H^+ ion and a bicarbonate ion. The bicarbonate ion then dissociate further, releasing another H^+ ion and a carbonate ion.

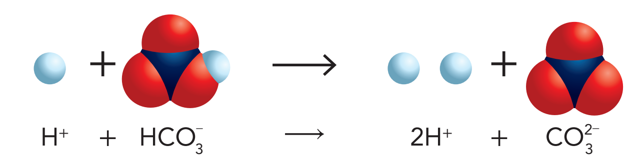
A cause and effect relationship exists between carbon dioxide levels and ocean pH. An increase in dissolved carbon dioxide drives a set of chemical reactions that result in increased ocean acidity.

Acid Forming Reactions in Seawater Adding carbon dioxide to the ocean makes seawater more acidic. One dissolved carbon dioxide molecule may react with water to release two free H^+ ions.

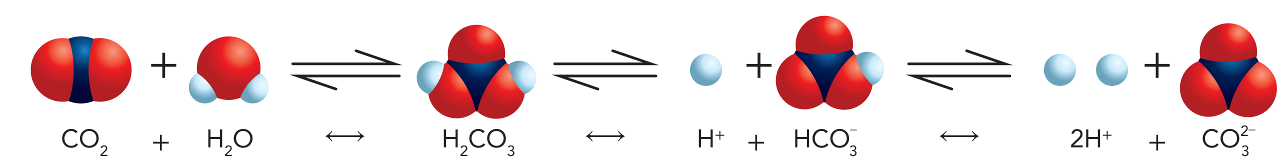


The dissolution of atmospheric carbon dioxide (CO_2) in ocean water forms carbonic acid (H_2CO_3).

Carbonic acid dissociates to form bicarbonate (HCO_3^-) and free hydrogen (H^+) ions, lowering the pH of the solution.



Bicarbonate ions dissociate further to form carbonate ions (CO_3^{2-}) and more free hydrogen ions, further lowering pH.



In a system of dynamic equilibrium, the direction of the chemical reaction can shift depending on the relative concentrations of reactants and products.

The system continually shifts between higher or lower pH depending on the amount of carbon dioxide and carbonate and bicarbonate ions in the seawater.

3 **CCC Stability and Change** Describe what will happen to the flow of these reactions if carbonate ions are continuously removed from the system by marine organisms that use the ions to make calcium carbonate shells.

If carbonate ions are removed from the system, the equilibrium will be altered, and the reaction will shift toward the left, or so that the free hydrogen ions bond with bicarbonate ions to form carbonic acid, which lowers the pH of the water.

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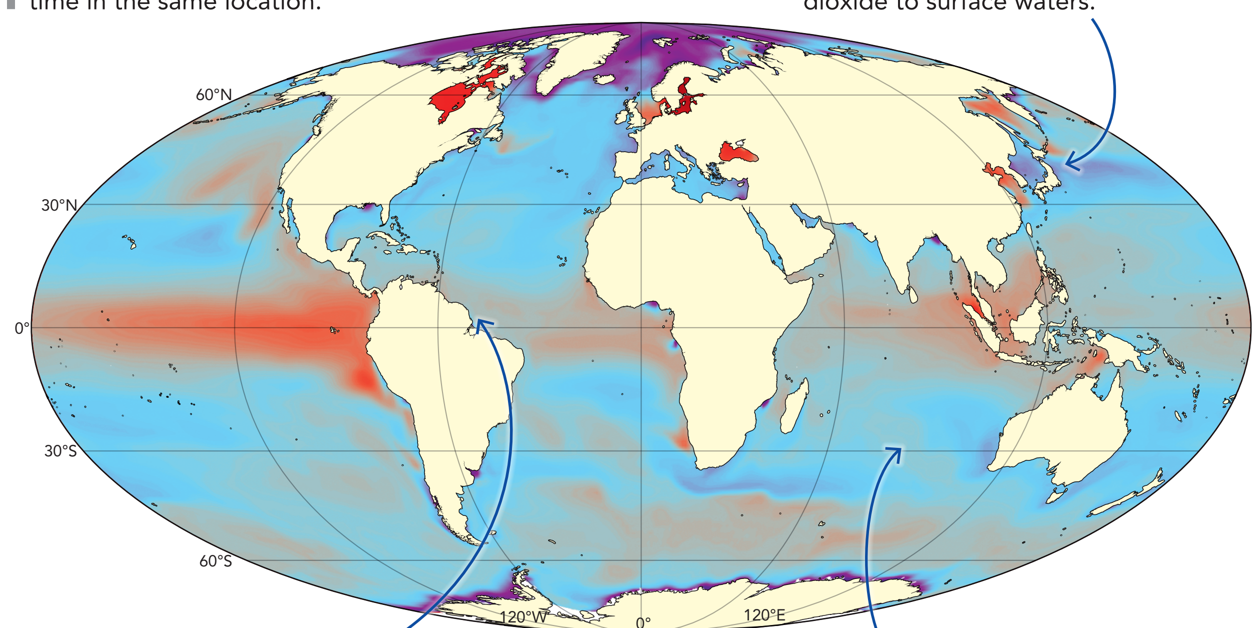
Geographic Ocean pH Variation

Factors Influencing pH Ocean pH varies significantly around the world. Several factors influence horizontal and vertical variance in pH levels. Latitude and ocean currents affect water temperature and salinity. Warmer water and less saline waters have lower pH. The influx of freshwater near coastal areas and upwelling of deep currents make waters more acidic. Runoff of fertilizers from agriculture can lead to algal blooms that increase acidity.

In general, tropical and temperate oceans, where coral reefs grow, have fairly stable pH levels of about 8.05–8.15, though the mid-Pacific varies greatly with El Niño / La Niña oscillations. In polar regions, pH levels rise in the summertime as massive plankton blooms absorb carbon dioxide and fall in the dark winters when the plankton die off. In general, the Indian Ocean is the most acidic ocean basin.

Global pH Variations Ocean pH levels are not constant. pH values vary laterally, vertically, seasonally, and with time in the same location.

Upwelling water from the deep ocean brings dissolved ions and carbon dioxide to surface waters.



Fresh water from rivers and runoff add dissolved ions to the ocean. Fertilizers carried from inland areas cause algal blooms that absorb additional carbon dioxide.

Sea Surface pH, 2010

pH

7.7 7.8 7.9 8.0 8.1 8.2 8.3

Source of data: European Space Agency

Warmer waters and less saline waters have lower pH. Both matter and energy are transported by ocean currents between the equatorial regions and the poles.

Source of data: European Space Agency

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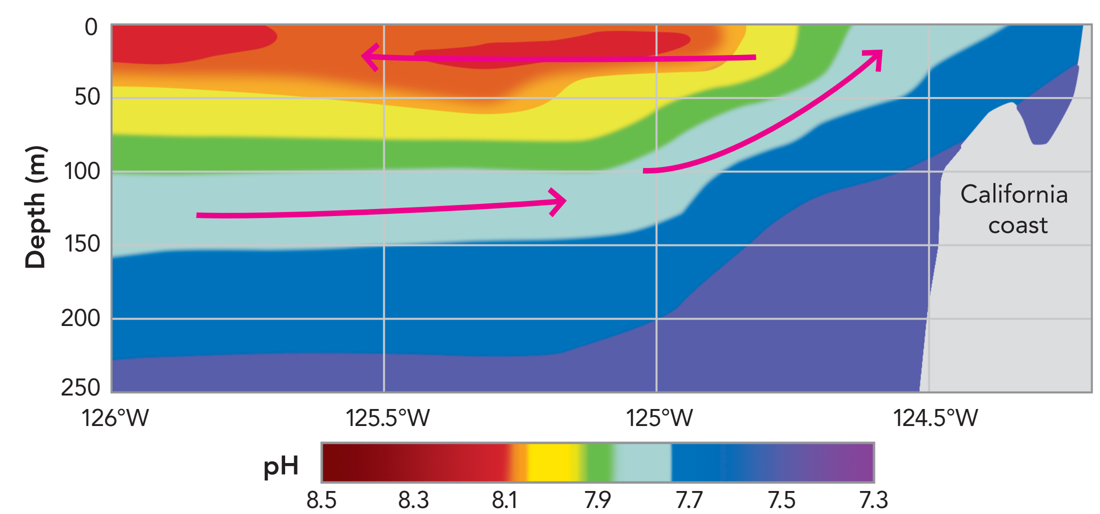
Vertical pH Variations As depth increases, water temperature generally decreases and the amount of dissolved carbon dioxide generally increases. Both of these trends favor the dissolution reactions of carbon dioxide that produce carbonate ions and free H^+ ions. As a result, ocean pH generally decreases with depth.

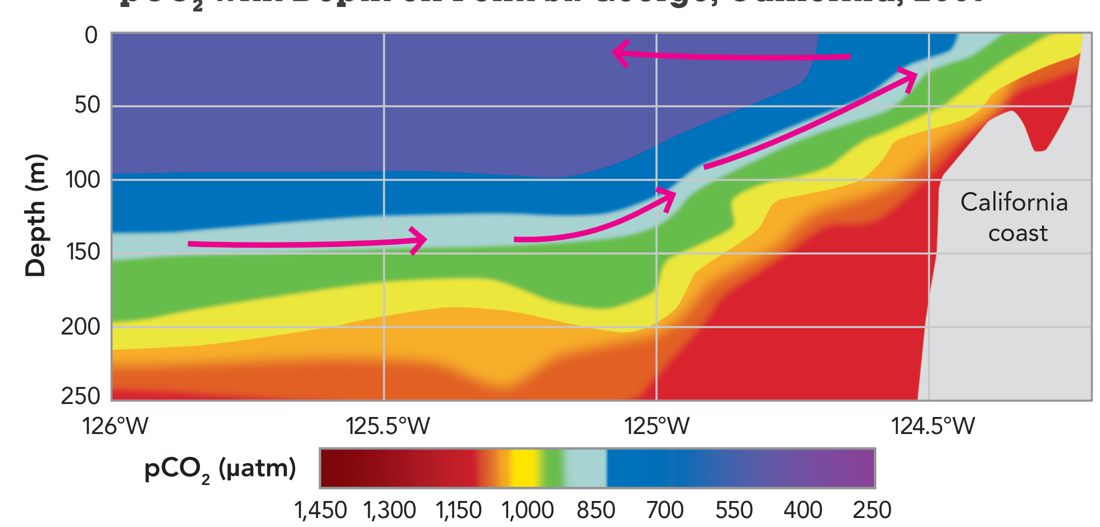
In many coastal regions, surface currents flow parallel to or away from the coastline. Where deep currents encounter seamounts or continental shelves, the acidic deep waters are diverted upward, lowering the pH of surface waters near the coast. While this is a natural process, the significant increase in ocean acidity due to human activities has increased ocean ~~acidity~~ faster than natural processes can buffer the change.

4 **CCC Patterns** Coastal upwelling brings CO_2-rich, low-pH waters toward the surface. Based on the contours for pH and pCO_2, draw on one of the cross-sections what you would expect the pattern of ocean flow would be.

pH with Depth off Point St. George, California, 2007



pCO_2 with Depth off Point St. George, California, 2007



Data from: NOAA

Students should draw arrows that point toward the coastline and curve upward to show upwelling at the coast.

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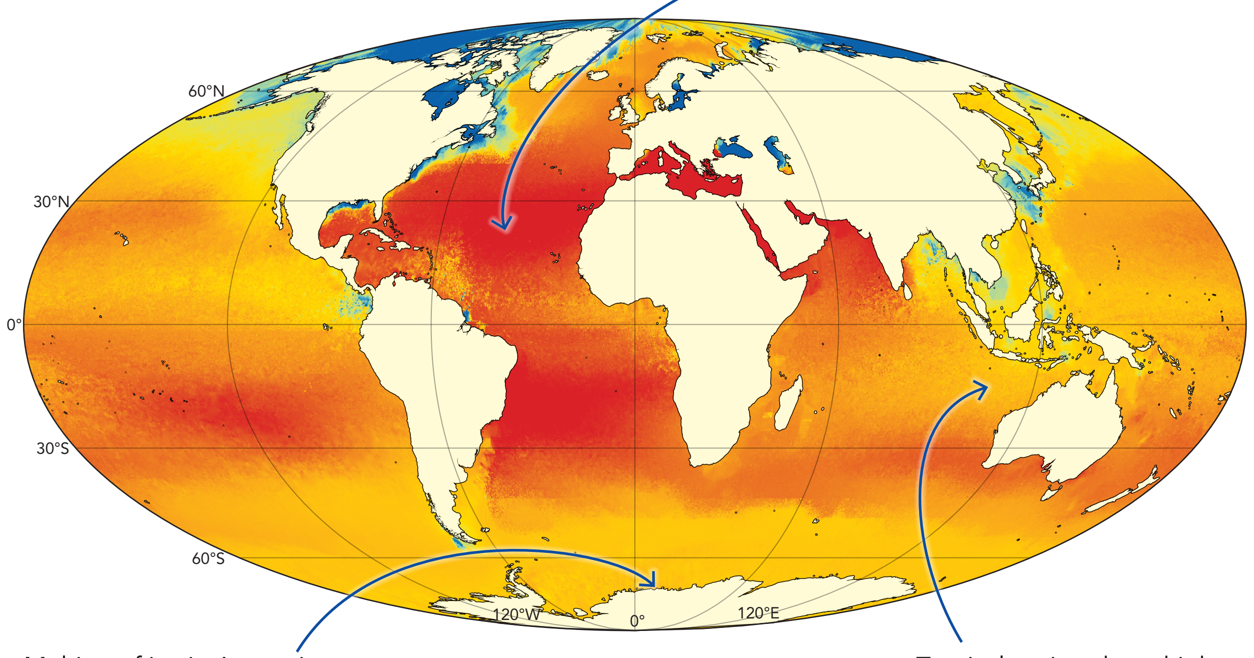
Ocean Salinity

The world's rivers carry salt to the ocean, making seawater saline, or salty. The amount of dissolved salts in water is described as the water's **salinity**. [set salinity bold/highlight] The salt plays critical roles in controlling ocean chemistry and biology. It also controls the pattern of deep ocean currents, because salty water is dense and will sink. In the North Atlantic, water is both cold and salty, making it especially dense. The sinking of this dense water helps to drive the global circulation of deepwater currents.

Ocean Surface Salinity Variations Ocean salinity varies significantly by location. Salinity is affected by air and ocean temperature, evaporation and precipitation rates, and freshwater influx.

The dry latitudes about 30° north and south of the equator have high evaporation rates. ~~Because salts do not evaporate, ocean salinity is high in these regions.~~



Melting of ice in Antarctica and Greenland adds freshwater to the ocean, which lowers salinity.

Sea Surface Salinity, 2005–2017
(practical salinity units, PSU)
31 32 33 34 35 36

Source of data: NOAA

Tropical regions have high evaporation rates, but also high precipitation rates, which adds freshwater to the ocean and lowers salinity.

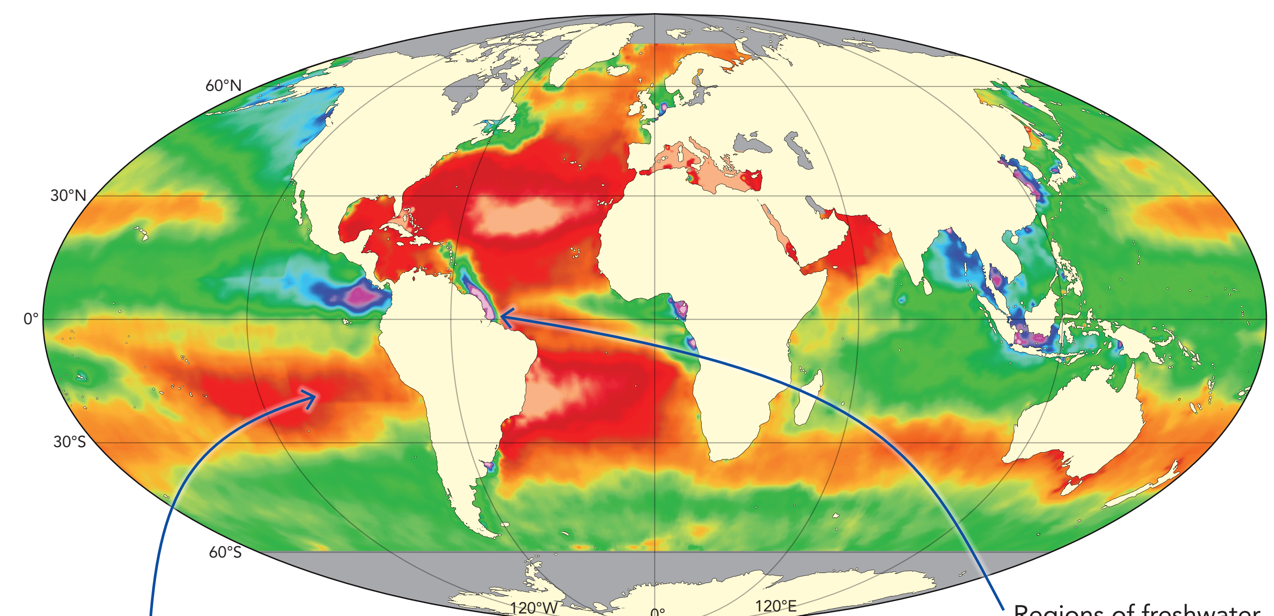
5 **SEP Constructing Explanations and Designing Solutions** Rivers carry about 4 billion tons of salt to the ocean each year, and evaporated water does not contain salt. Construct an explanation for why the mean ocean salinity has stayed roughly constant over Earth's history.

Sample answer: Roughly the same amount of water that is evaporated is replaced by rain and rivers each year. When excess salts accumulate, they precipitate to form deposits on the sea floor.

Ocean Alkalinity

Total alkalinity (TA) is the sum of excess ions in the water that could absorb H^+ ions. Mostly these ions are bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}). Other ions include hydrogen sulfate (HSO_4^-), hydroxide (OH^-), and phosphates (PO_4^{3-}). These ions all accept extra protons, removing them from the seawater. Thus, the alkalinity of the ocean buffers the acidification. The total alkalinity of seawater is not the same thing as the basicity, which is simply a measure of how high the pH is.

Ocean Surface Alkalinity Variations Water with high alkalinity resists acidification by absorbing H^+ ions. The alkalinity itself is not affected by the addition of carbon dioxide.



Alkalinity is higher where evaporation rates are high and where ~~or~~ anaerobic degradation occurs as a result of reducing sulfates or denitrification.

Sea Surface Alkalinity, May 2015
Total alkalinity (umol/kg)
2,100 2,200 2,300 2,400 No data

Source of data: NASA

Regions of freshwater inflow, from heavy rainfall, rivers, or the melting of ice, have lower alkalinity.

6 **SEP Constructing Explanations and Designing Solutions** The map shows two regions in the Atlantic Ocean that have very high alkalinity. Construct an explanation for why these two regions have high alkalinity.

Sample answer: The areas of high alkalinity in the Northern and Southern Atlantic Ocean are at about 30°N and 30°S latitude, where evaporation rates are high and precipitation rates are low.

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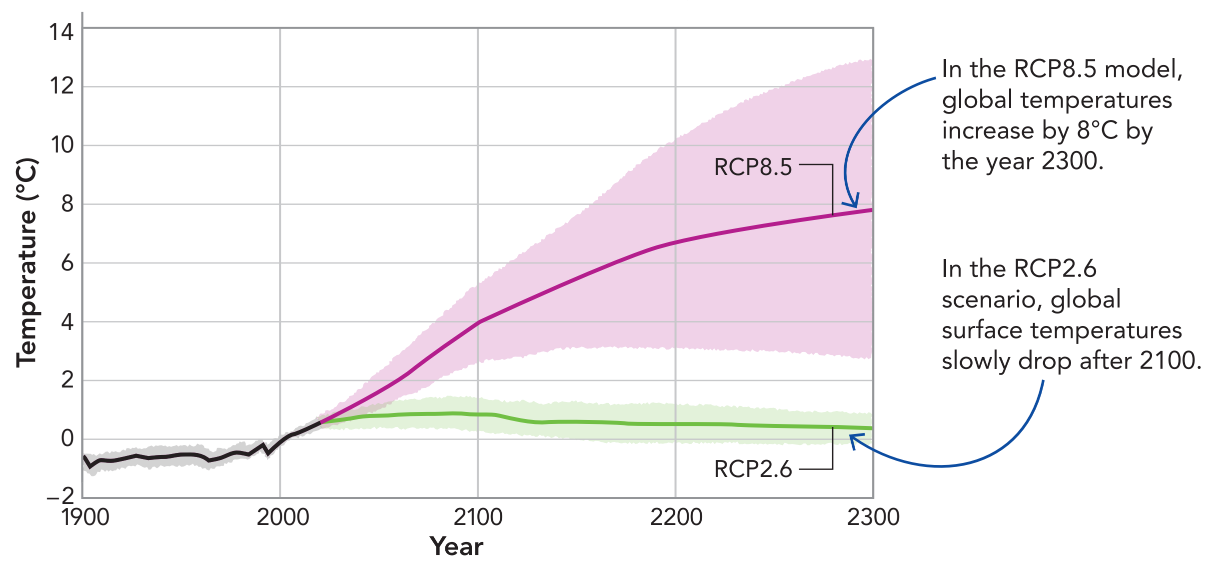
Le Châtelier's Principle and Future Ocean pH

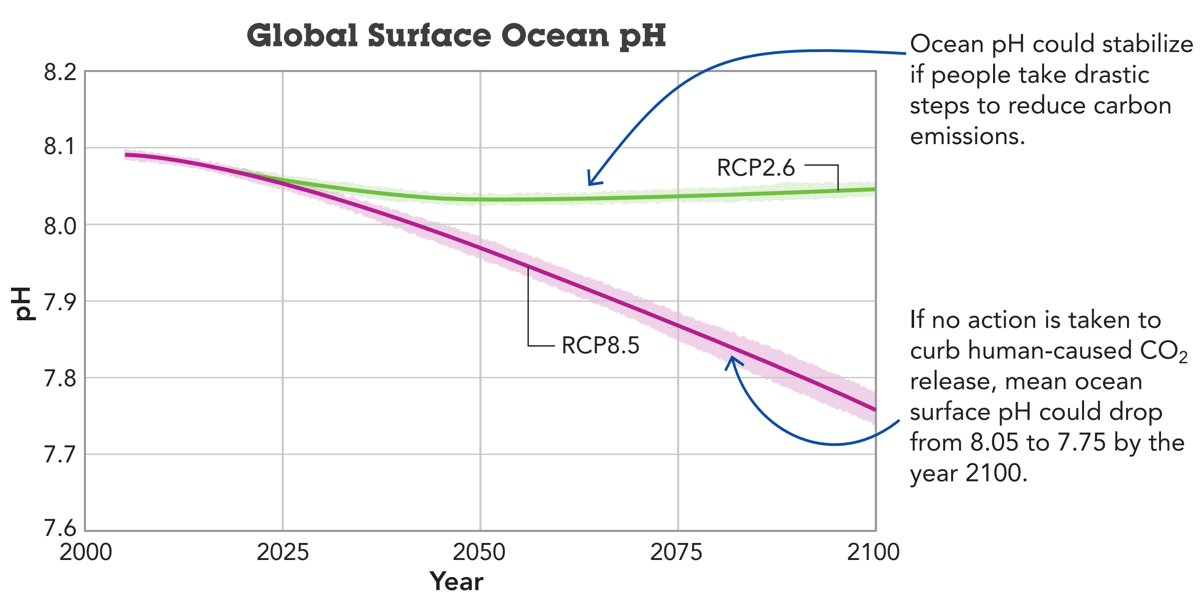
The addition of carbon dioxide to the ocean is disrupting the ocean carbon system, driving the equations for carbon and bicarbonate dissolution toward an increase in carbonate and H^+ ions and increasing acidity. This is a classic example of Le Châtelier's principle: ocean pH had been fairly stable, but human-released CO_2 is now driving that system toward a new equilibrium. Where that equilibrium ends up depends largely on how much CO_2 humans release in the future.

Surface Temperature and pH Projections The International Panel on Climate Change (IPCC) modeled different scenarios of greenhouse gas concentrations called Representative Concentration Pathways (RCPs). In the RCP2.6 model, humans drastically reduce CO_2 emissions in the year 2020. In the RCP8.5 model, humans continue to release CO_2 at high rates.

Global Average Surface Temperature Change (Relative to 1986–2005 mean)



Global Surface Ocean pH



OK to eliminate gray rules at bottom of each graph to avoid overset?

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7 **SEP Stability and Change** Summarize how Le Chatelier's principle can be applied to describe the dynamic equilibrium between carbon dioxide concentrations in the atmosphere, alkalinity, and ocean pH.

Sample answer: Seawater contains a variety of positive and negative ions that are at chemical equilibrium. As the equilibrium state is perturbed, the system adjusts to form a new equilibrium, whether that is by moving toward a more acidic or more basic state. In the ocean system, when alkaline components buffer increasing acidity, the rate at which pH decreases slows.

Revisit

INVESTIGATIVE PHENOMENON

GO ONLINE to Elaborate and Evaluate your knowledge of [TK] by completing the class discussion and data analysis activities.

In the CER worksheet, you drafted a scientific argument to explain what is happening to the world's coral reefs. With a partner, reevaluate the evidence cited in your arguments.

8 **CCC Cause and Effect** Most corals are adapted to survive in tropical, subtropical, and temperate oceans. Based on patterns of alkalinity and salinity in the oceans, why are corals threatened by changes in ocean pH?

Both salinity and alkalinity tend to be high in tropical, subtropical, and temperate regions where corals thrive. These factors correlate to relatively high pH. Thus, corals are adapted to warm waters with higher pH, and lowering pH may affect how the corals build skeletons, reproduce, or get food.

EXPERIENCE 2

Earth's Ocean as a Carbon Sink

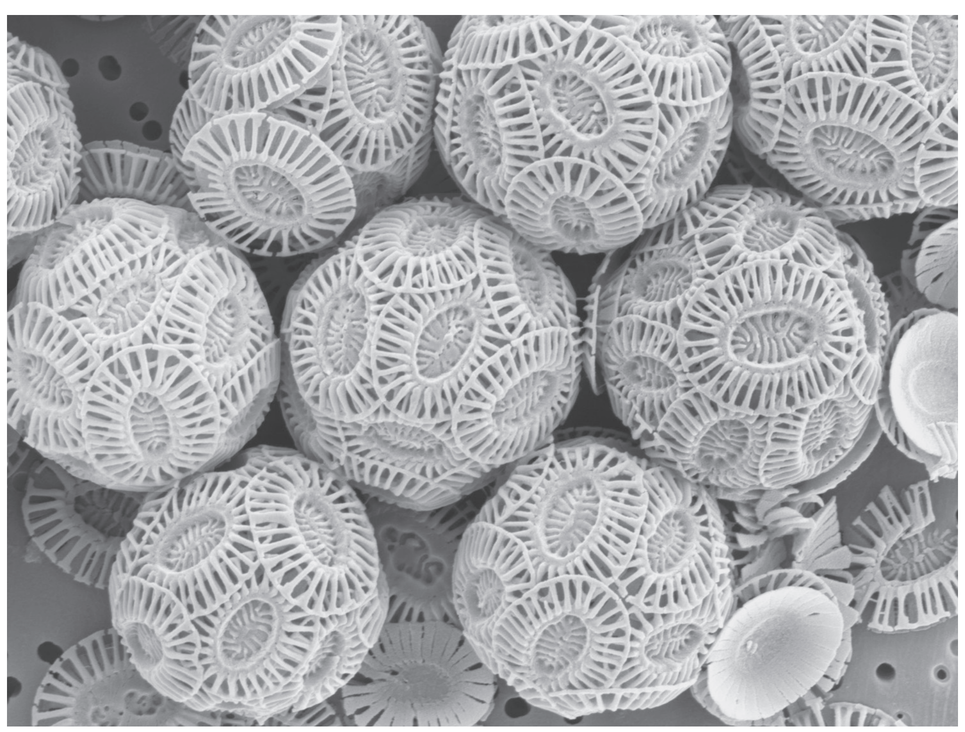
GO ONLINE to Explore and Explain how carbon dioxide is exchanged between the ocean and atmosphere.

Ocean-Atmosphere Carbon Dioxide Exchange

Roughly 80 billion tons (Gton) of carbon is exchanged each year between the atmosphere and the ocean surface layer. The increase in atmospheric carbon from preindustrial levels means that more carbon dioxide is exchanged between the ocean surface and atmosphere each year. However, the cycling of carbon between the ocean and atmosphere is more complicated than a simple gas exchange at the ocean surface.

Marine Organisms Are Carbon Reservoirs Carbon in the ocean cycles through both inorganic and organic pathways. Carbon **reservoirs** are components of the Earth system in which carbon is stored. **Rates** are a measure of how much carbon flows between reservoirs in a given time. Although only about 6 Gton of carbon exists within marine life at any given time, due to the short life-span of plankton, over eight times that amount cycles through the marine biosphere each year.

Ocean Plankton Most of the carbon in ocean organisms is in the form of calcium carbonate ($CaCO_3$) shells of single-celled plankton, such as coccolithophores. About 50 Gton of carbon are consumed each year by marine life to make their shells and skeletons.



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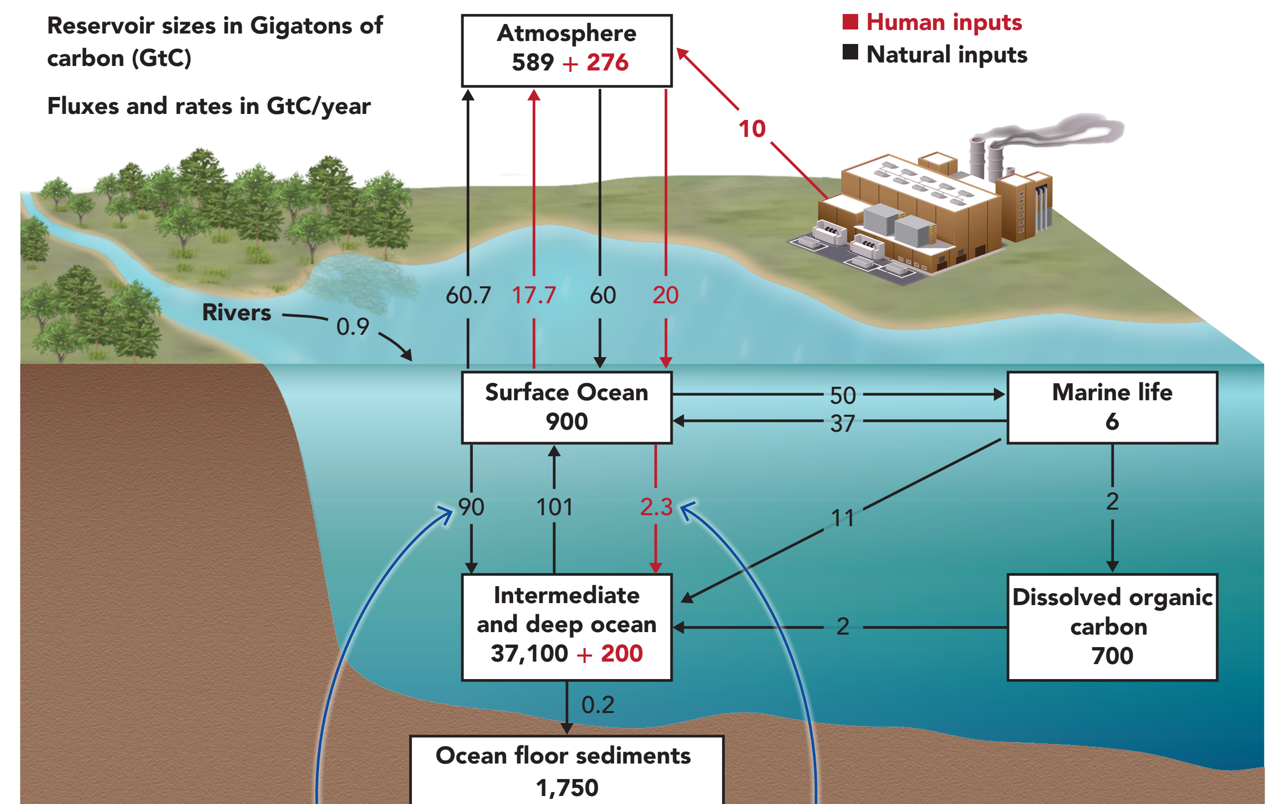
Ocean–Atmosphere Carbon Reservoirs and Rates Black numbers show pre-industrial values, some of which are roughly unchanged. Red numbers show the changes to the system due to human atmospheric carbon dioxide releases.



Carbon flows between reservoirs at different rates. Carbon from the surface ocean enters the deep ocean at a natural rate of 90 GtC/year.

Human activity has increased the amount of carbon in the surface ocean, which increased the rate of flux into the intermediate and deep ocean by 2.3 GtC/year.

Deep Ocean Carbon Cycling Carbon doesn't stay in the surface ocean layer for long. About one tenth of it sinks down into the intermediate and deeper ocean, where it remains for hundreds or thousands of years. Thus, the deep ocean holds most of the ocean's carbon. Because of the carbon exchange between the ocean and atmosphere, the human contributions to atmospheric carbon are changing the dynamics of the ocean carbon cycle. An additional 2.3 Gt of carbon are added to the deeper ocean each year, making the deep ocean ~~more~~ acidic.

9 **SEP Analyze Data** Most carbon sediment accumulation on the seafloor is in the form of calcium carbonate. These sediments largely become the sedimentary rock limestone. Using the rate of carbon accumulation on the seafloor and the atomic mass of calcium carbonate (~~about 100~~ g/mol), compute the mass of new limestone that is generated each year (in tons).

~~Sample answer: The diagram indicates that 0.2 Gton of carbon settles to the ocean floor as sediment each year. About 3 billion tons of calcium carbonate sediments form in the oceans each year.~~

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Temperature, Pressure, and the Carbonate Compensation Depth

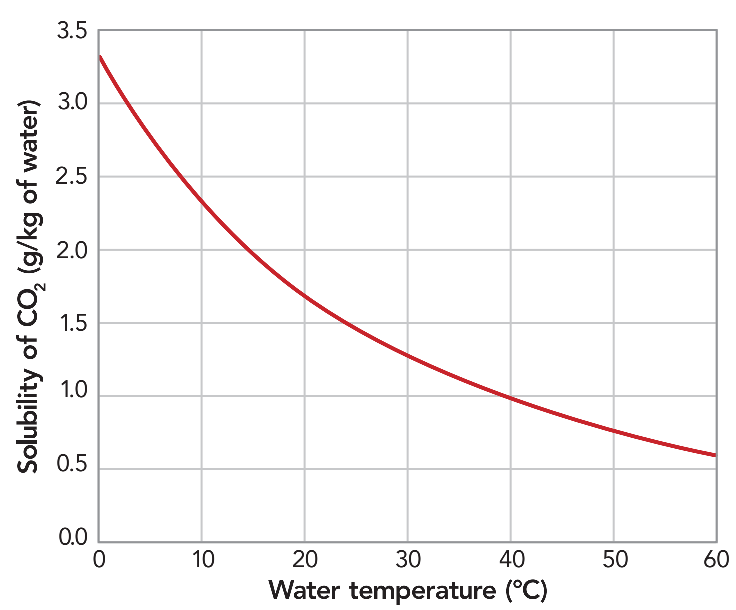
The rate of a chemical reaction and its equilibrium point vary as a function of temperature, pressure, and the concentrations of reactants and products. These dependencies affect how ocean CO_2 levels respond to changing global atmospheric conditions. Increasing atmospheric CO_2 concentrations are driving carbon into the ocean, but they also create feedbacks that affect what becomes of that carbon.

Warmer atmospheric temperatures have led to warmer oceans. Near the ocean surface, this process can drive some dissolved carbon dioxide gas out of the ocean and into the atmosphere. However, deeper in the ocean this process drives the chemical dissolution reaction of CO_2 toward an increase in carbonate ions and H^+ ions, lowering the pH and making the ocean more acidic.

Temperature and CO_2 Solubility The solubility of carbon dioxide in water decreases with increasing temperature. An increase in ocean temperature decreases the amount of CO_2 gas that can stay dissolved within the seawater.

Cold water holds carbonation better than warm water does.

Solubility of CO_2 at Different Temperatures



That's why fizzy carbonated water goes flat as it warms.

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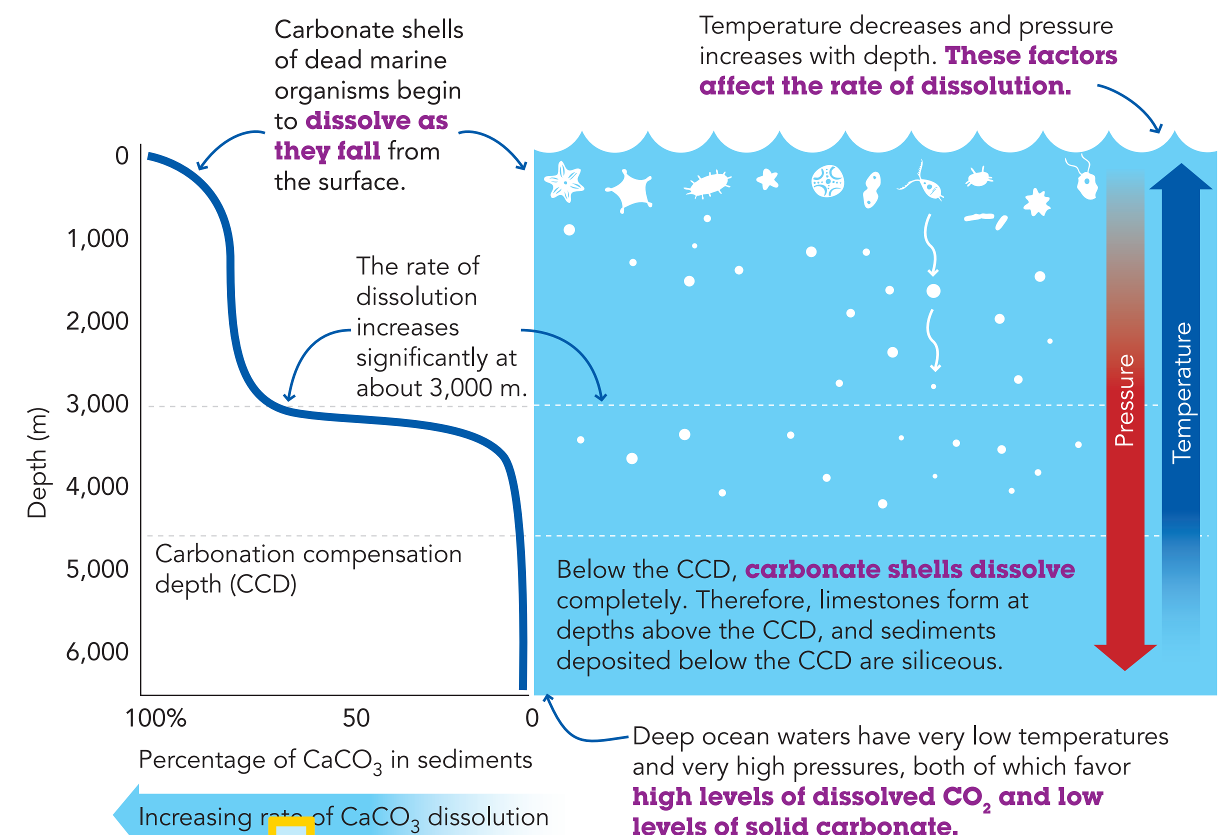
The solubility of CO_2 in water is also affected by pressure: higher pressures—~~generally~~ found at deeper depths—allow more carbon dioxide to be dissolved within the water. In the ocean, calcium carbonate ($CaCO_3$) becomes increasingly unstable with increasing pressure. Below a certain depth, called the **carbonate compensation depth** or CCD, the $CaCO_3$ shells of organisms dissolve into Ca^{2+} and bicarbonate ions.

Carbonate Compensation Depth

How does **$CaCO_3$ solubility** change with **depth**?

Dissolved vs Deposited Calcareous Sediments The relative amount of calcium carbonate that is stored in sediments or dissolved in seawater varies with depth.



10 **CCC Stability and Change** The solubility of carbon dioxide within liquid magma also increases with pressure. Explain how this could contribute to the explosive nature of some volcanic eruptions.

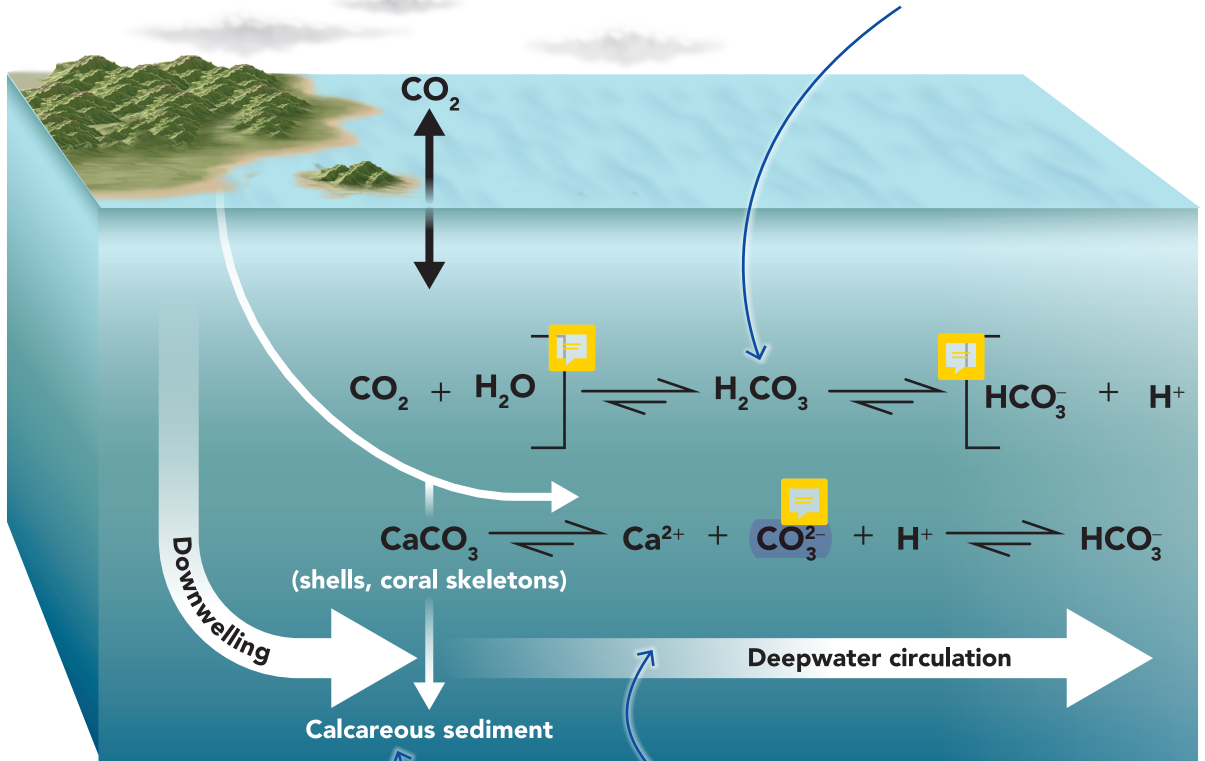
Below Earth's surface, pressure on magma and the gases it contains is high. As magma rises toward Earth's surface, pressure decreases, gas solubility decreases, and gas bubbles form and expand, sometimes explosively.

Biogenic Carbon

The inorganic and organic chemical reactions involving ocean carbon provide a complex set of cycles. Though they are closely linked, these cycles are often separated out into two parts: a largely inorganic solubility carbon pump and an organic biological carbon pump. The solubility pump takes dissolved carbon and brings it into the deep, vast reservoir of dissolved carbon. The biologic pump takes that dissolved carbon and builds organic material from it when currents return it toward the surface.

Solubility Carbon Pump Inorganic chemical reactions begin with the influx of carbon into the ocean in the form of atmospheric CO_2 and the dissolved Ca^{+} and CO_3^{2-} ions of weathered continental rock.

Carbon dioxide and water combine to form carbonic acid, which dissociates into bicarbonate and hydrogen ions.



Calcium carbonate crystals and shells eventually fall to the ocean floor, forming calcareous sediment.

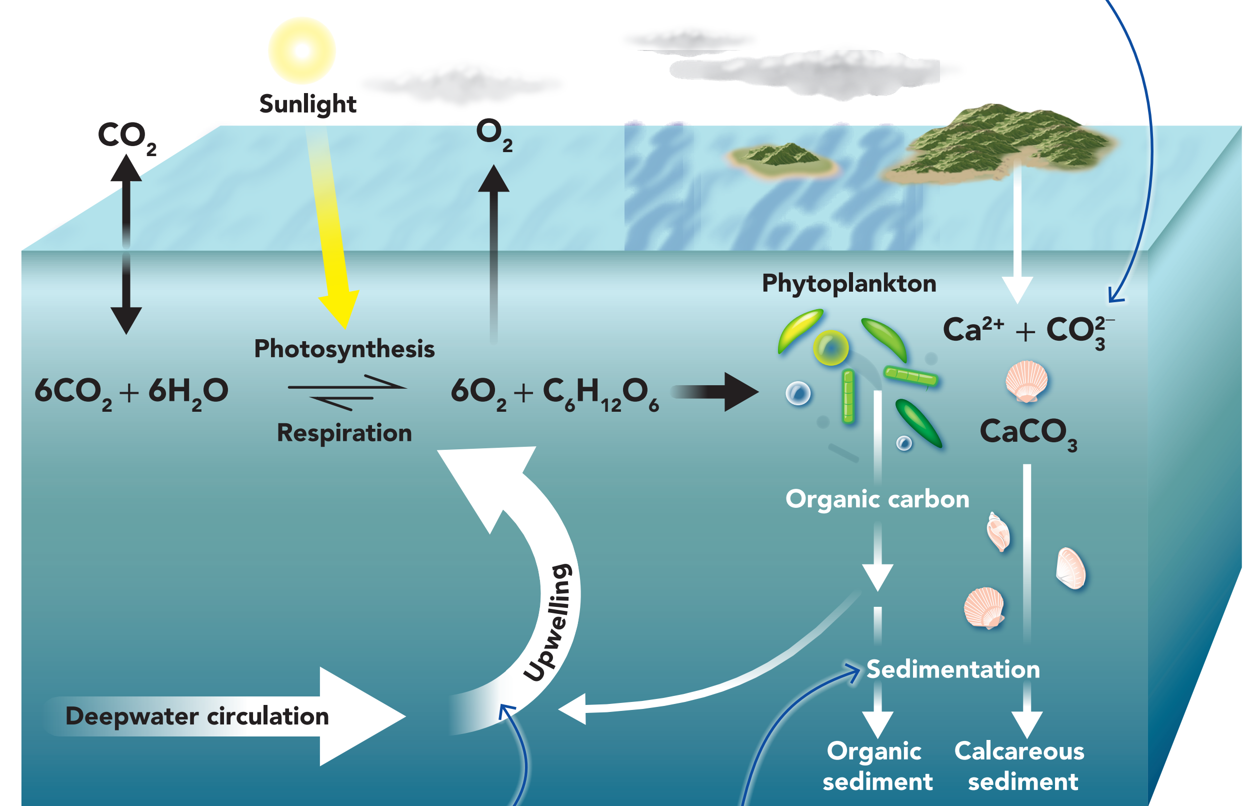
Cold, carbon-rich surface water sinks deep into the ocean. Currents carry it thousands of miles before it resurfaces through upwelling. This can take hundreds of years.

Ocean Currents The solubility and biologic carbon pumps are closely connected with the deep ocean currents that move water around Earth's ocean basins. As currents drop below the carbonate compensation depth (CCD), carbonate particles dissolve into bicarbonate ions. These ions are able to form solid carbonate again once the water rises back above the CCD in areas of upwelling.

Carbon in the Marine Biosphere The base trophic level of the marine biosphere is single-celled phytoplankton, which consume CO_2 and water to make organic molecules such as glucose. Phytoplankton use the energy from sunlight, so they live in the shallow ocean. All life forms require carbon, but some phytoplankton such as coccolithophores also use carbon to build calcium carbonate shells. The phytoplankton are eaten by zooplankton which also usually have carbonate shells or skeletons. The plankton are eaten by successively larger organisms, and the carbon moves up the food chain.

Biologic Carbon Pump Organic chemical reactions use CO_2 from the atmosphere and dissolved carbon from weathered land rocks. They also draw heavily upon the upwelling of deep ocean currents, which carry dissolved carbon back toward the surface.

Marine organisms use Ca^{2+} and CO_3^{2-} ions to build their shells. The shells eventually fall toward the ocean floor.



Decomposition of dead organisms and dissolution of shells contribute ions and nutrients that are brought to the surface by upwelling and are used by organisms at the surface.

Most of the carbonate sediment from dead organisms becomes part of the dissolved carbon within the deepwater circulation. Above the CCD, these shells for calcareous sediments.

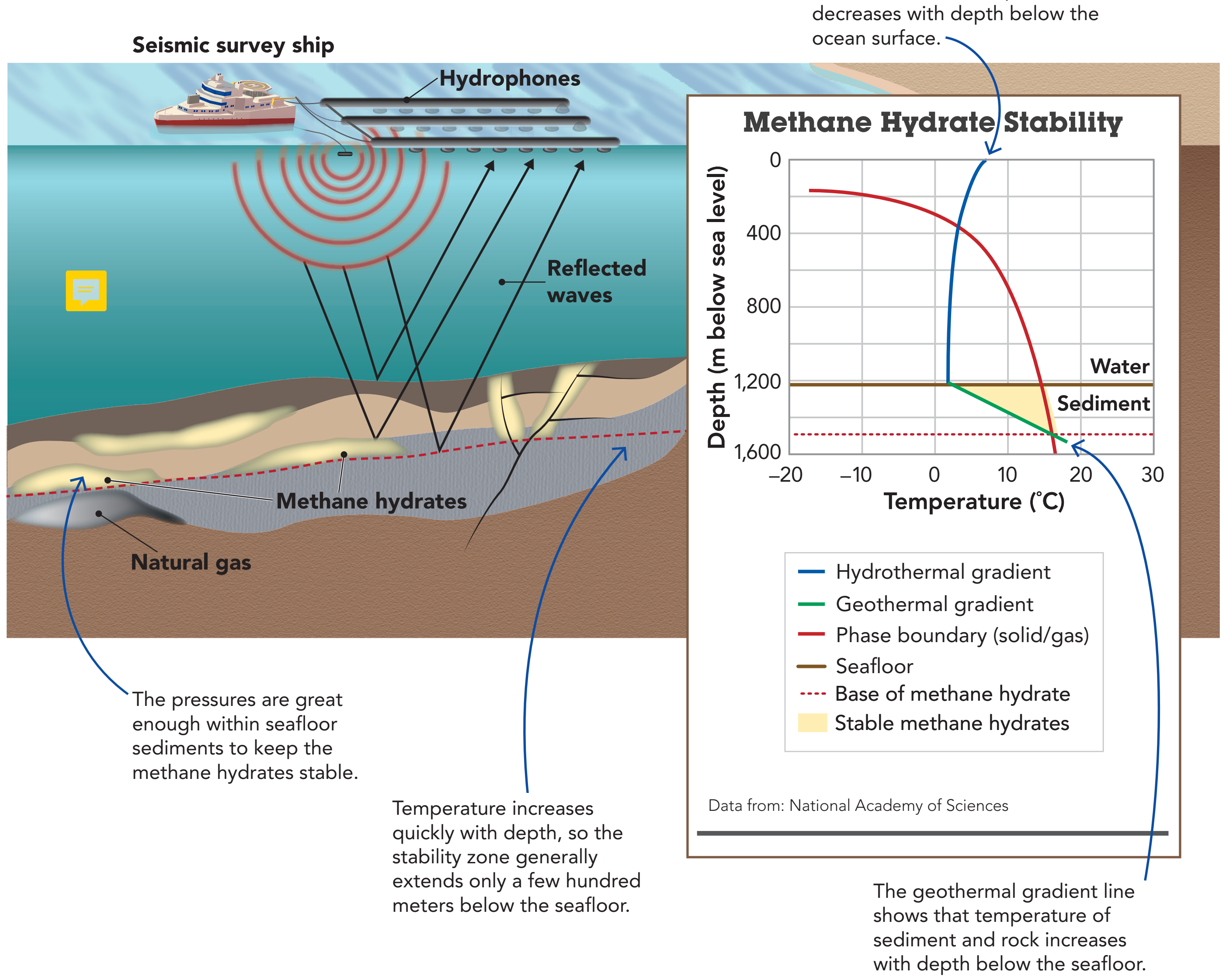
11 **SEP Developing and Using Models** What will happen to the annual rates of limestone precipitation in the ocean if the ocean water were to become much warmer and more acidic. (Hint: first describe what will happen to the CCD.)

Sample answer: The CCD will get shallower as the ocean warms, carbon dioxide solubility decreases, and pH drops. As a result, the annual rates of limestone precipitation would decrease.

Methane Hydrates

Methane Gas Deposits Methane gas is formed by bacteria in seafloor sediments. When the methane rises through the seafloor sediments, it reacts with water in the sediments to form ice if the conditions are correct. The frozen combinations of methane and water are called **methane hydrates.** These methane ices are stable at temperatures warmer than water ice is usually stable. They are abundant on land within the frozen permafrost of the Arctic tundra and are extremely abundant in shallow marine offshore sediments. Seismic imaging has identified the occurrence of layers of methane hydrates within the top kilometer of ocean sediments all around the globe, and the total global amount of methane within them may be as great as 8 trillion tons.

Methane Hydrate Stability The stability of methane hydrates varies as a function of depth (pressure) and temperature. The frozen hydrates are stable at higher pressures and lower temperatures.



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Feedbacks with Global Warming Climate change will impact the stability zone of offshore methane gas hydrates. Rising sea levels and higher pressure favor methane stability. However, warming ocean temperatures are beginning to raise the lower boundary of the frozen methane hydrate, releasing methane gas into the ocean and atmosphere.

Because methane is a greenhouse gas, a positive feedback loop exists between global warming and the release of methane gas from hydrates.

12 **CCC Stability and Change** Would you expect the thickness of the methane hydrate stability zone to be thicker or thinner for deeper ocean locations compared to shallow ocean locations? Explain.

Sample answer: I would expect the methane hydrate stability zone to be thicker in deeper ocean locations because the water pressure is higher and the water temperature is lower.

Revisit

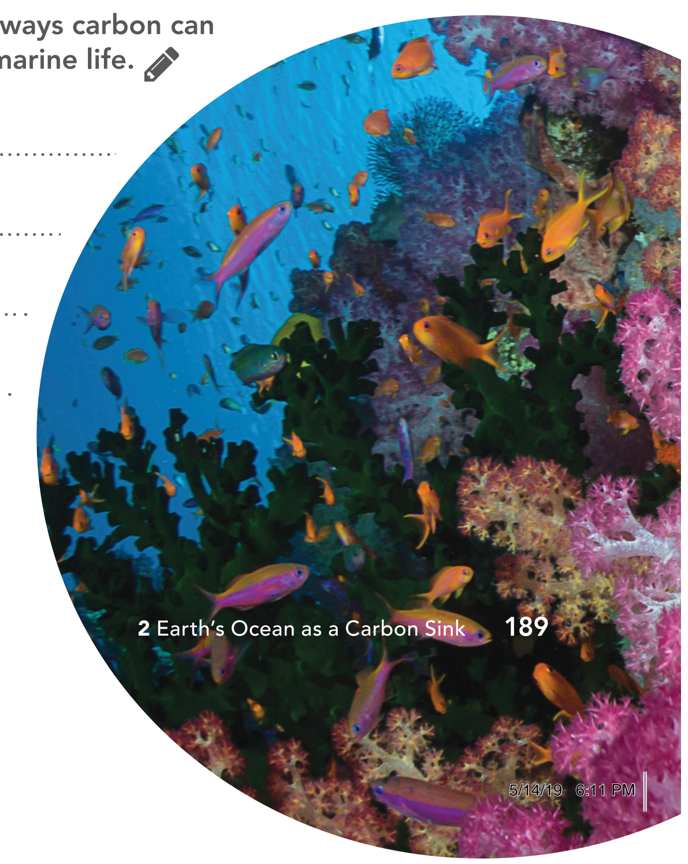
INVESTIGATIVE PHENOMENON

GO ONLINE to Elaborate and Evaluate your knowledge of the exchange of carbon between the ocean and atmosphere by completing the class discussion and data analysis activities.

In the CER worksheet, you drafted a scientific argument to explain what is happening to the world's coral reefs. With a partner, reevaluate the evidence cited in your arguments.

13 **CCC Identify Patterns** Explain two different pathways carbon can take to enter the ocean to become available for marine life.

Carbon enters the ocean as dissolved ions in runoff, as dissolved carbon dioxide from the atmosphere, and from the decomposing bodies of marine organisms.



EXPERIENCE 3

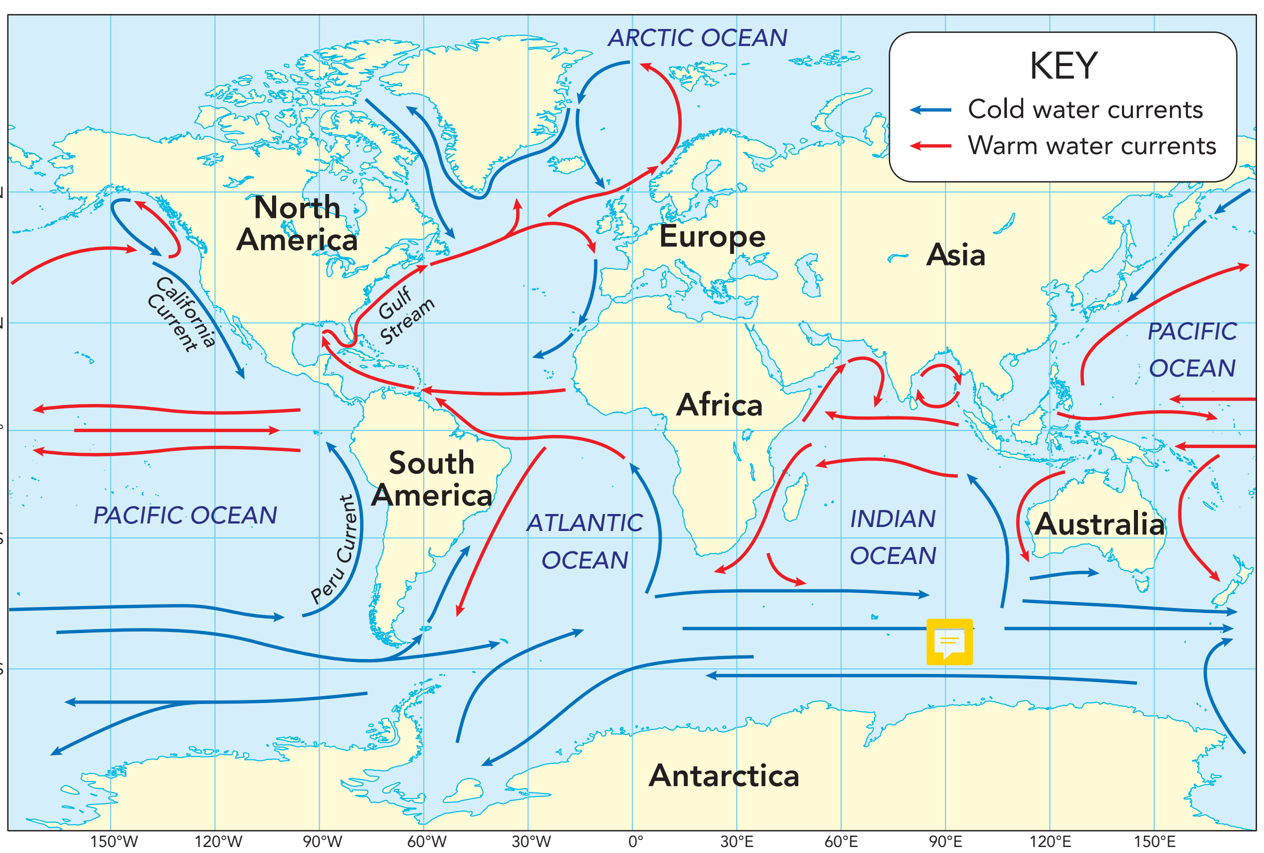
The Ocean and Climate Change

GO ONLINE to Explore and Explain how the ocean influences Earth's climate.

Ocean Surface Currents

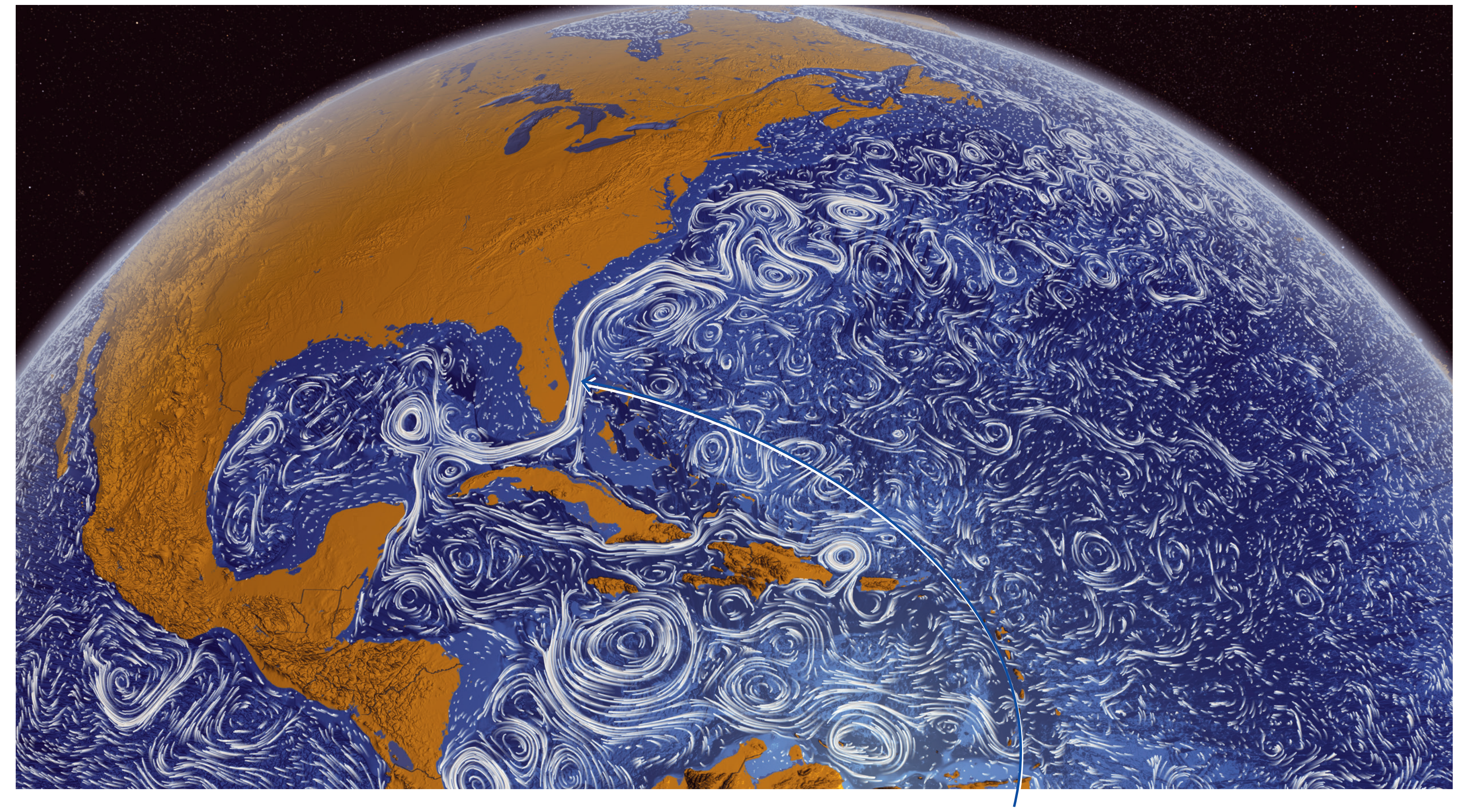
Ocean water plays a central role in determining regional climate patterns. The reason for this starts with the high specific heat of water, which allows ocean water to store vast amounts of heat. This energy can be transferred to the atmosphere along the surface of the ocean. Ocean **surface currents** are areas of ocean water that flow steadily in a particular direction close to the ocean's surface. As these currents move water from one part of the globe to another, they also redistribute heat, affecting regional atmospheric patterns.

Large-scale Surface Ocean Currents This map shows a simplified representation of the main surface ocean currents. The currents are mostly separated among the Pacific, Atlantic, and Indian Ocean Basins, and connected only around Antarctica (and by a few narrow straits).



Currents within ocean basins largely take the form of rotating spirals called gyres. Gyres spin clockwise in the Northern Hemisphere and counter-clockwise in the Southern Hemisphere.

Gyres often bring warm water toward the poles along the west sides of the ocean basins and return cold water back toward the equator along the east sides of the basins.



Small-scale Surface Ocean Currents A graphic representation of the actual pattern of surface ocean currents in the mid-Atlantic ~~between June 2005 and December 2007.~~ Note how currents take the form of many small gyres, within the overall pattern of the large North Atlantic gyre.

The strong narrow current coming out of the Gulf of Mexico and snaking up the eastern U.S. coast is the Gulf Stream.

Surface ocean current patterns are determined by a combination of continental outlines, deep ocean currents, and surface winds. Because winds are always shifting in direction and strength, the exact patterns of surface currents are variable over periods of days, months, years, decades, centuries, and even longer. Surface currents may look very different during ocean storms than during periods of calm winds.

Surface currents can also change over Ice Age cycles. Currently, the Atlantic and Pacific Ocean basins are connected across the Arctic Sea through the Bering Strait (next to Alaska), and the Indian and Pacific Ocean basins are connected through Indonesia. However, during the last Ice Age, when sea levels were ~125 m lower, these shallow straits were all above sea level and the ocean basins were even more cut off from each other.

14 **CCC Energy and Matter** The coast of central New Jersey and northern California both share the same latitude, about 40° north. However, if you went swimming in the summer you would likely find the water in New Jersey comfortably warm but the water in northern California uncomfortably cold. Use the ocean surface currents map to explain why this would be so.

The Gulf Stream brings warm water from the equatorial region up along the coast of New Jersey. The California Current brings cold polar water down along the coast of northern California.

Having trouble with callout arrow legibility. Suggestins?

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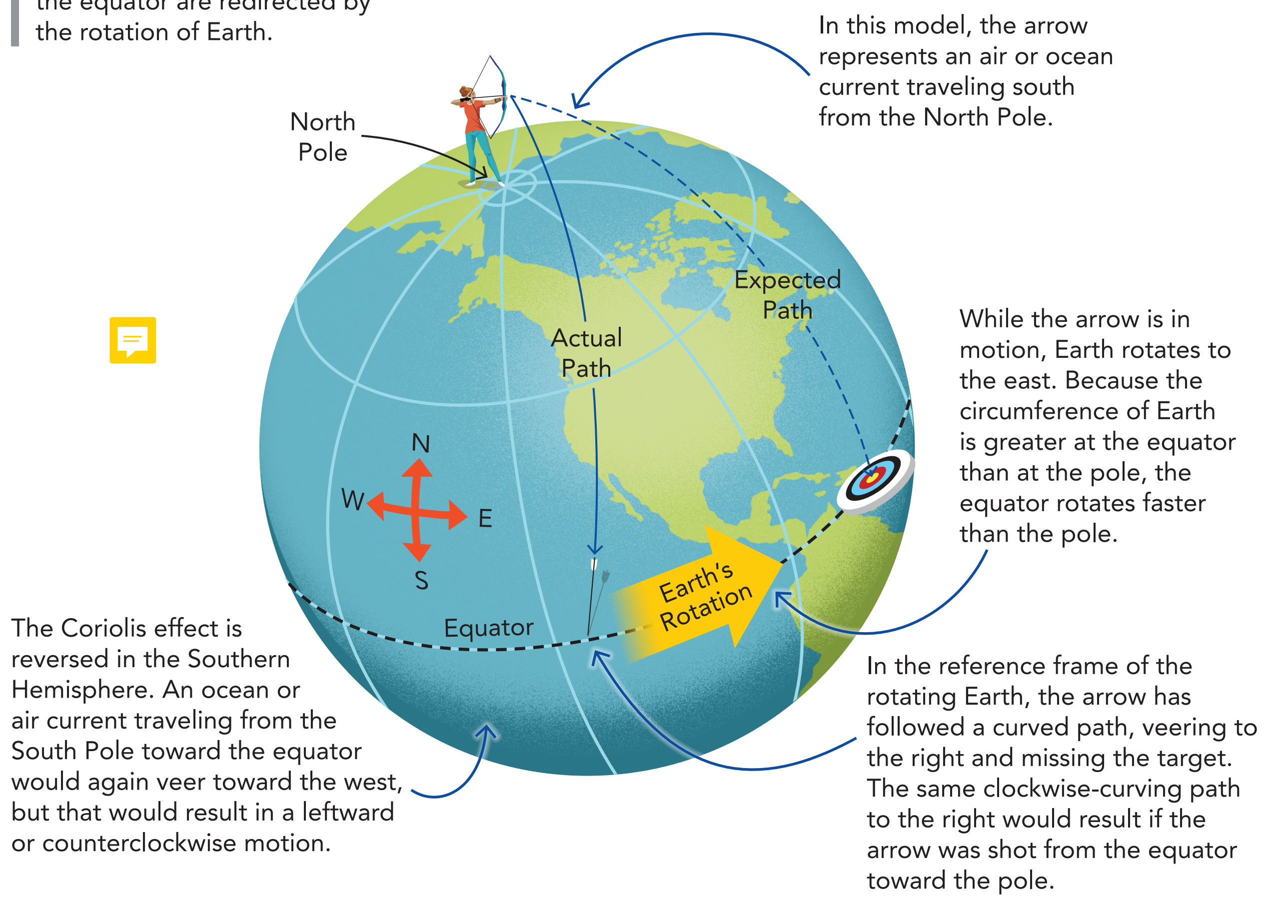
Coriolis Effect

The patterns of clockwise rotation in ocean current gyres in the Northern Hemisphere and counter-clockwise rotation in gyres in the Southern Hemisphere are a result of the Coriolis effect. The **Coriolis effect** describes the curved path that an object takes when it moves in a straight line across a rotating object perpendicular to the axis of rotation.

On Earth, the Coriolis effect causes ocean water, atmospheric air, and even liquid iron in the outer core to move in curved paths as it travels north or south. Because ocean water is trapped within ocean basins, the result is a connecting set of rotating gyres.

Coriolis Model Currents traveling toward or away from the equator are redirected by the rotation of Earth.



(15) **SEP** ~~**Developing and Using Models** Review the ocean surface currents map. Then use the model of a ball thrown west to east to explain the path of ocean currents along the equator.~~

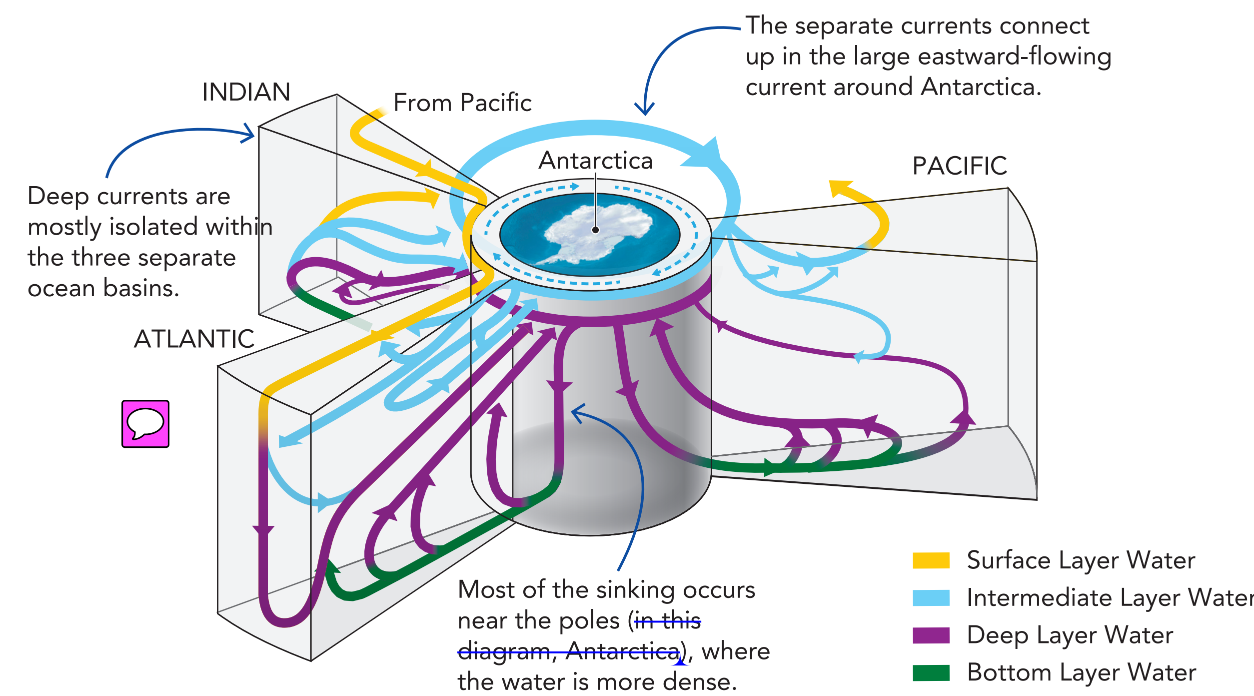
~~Currents moving along the equator are not redirected left or right. They move in a straight line because the Coriolis effect only affects objects traveling from the poles to the equator, or vice versa (perpendicular to the axis of rotation).~~

Deep Ocean Currents

Connected to surface ocean currents from below is a complex network of deep ocean currents. **Deep ocean currents** are ~~masses of ocean water below the ocean surface that flow steadily in a particular direction.~~ Unlike surface currents, deep currents are driven by differences in density.

The density of water depends on its temperature and salinity. An increase in temperature means a decrease in density, so warmer water resists sinking. An increase in salinity, on the other hand, means an increase in density, so salty water sinks more easily. In general, colder and denser water near the poles sinks while warmer water near the equator rises. Water moves slowly through the system, taking centuries or even millennia before returning to the surface.

Sinking Polar Water This simplified diagram of deep ocean currents shows some of the horizontal and vertical patterns.



Source of data: Woods Hole Oceanographic Institution

(16) **CCC Stability and Change** The rate of ice melting in Greenland, located in the northern Atlantic Ocean, is accelerating as global temperatures rise. Predict how this melting could alter the pattern of deep ocean circulation within the Atlantic Ocean basin. (Hint: Ice is fresh water.)

Melting freshwater ice would decrease the density of ocean water in the north Atlantic, ~~potentially interfering with patterns of sinking.~~

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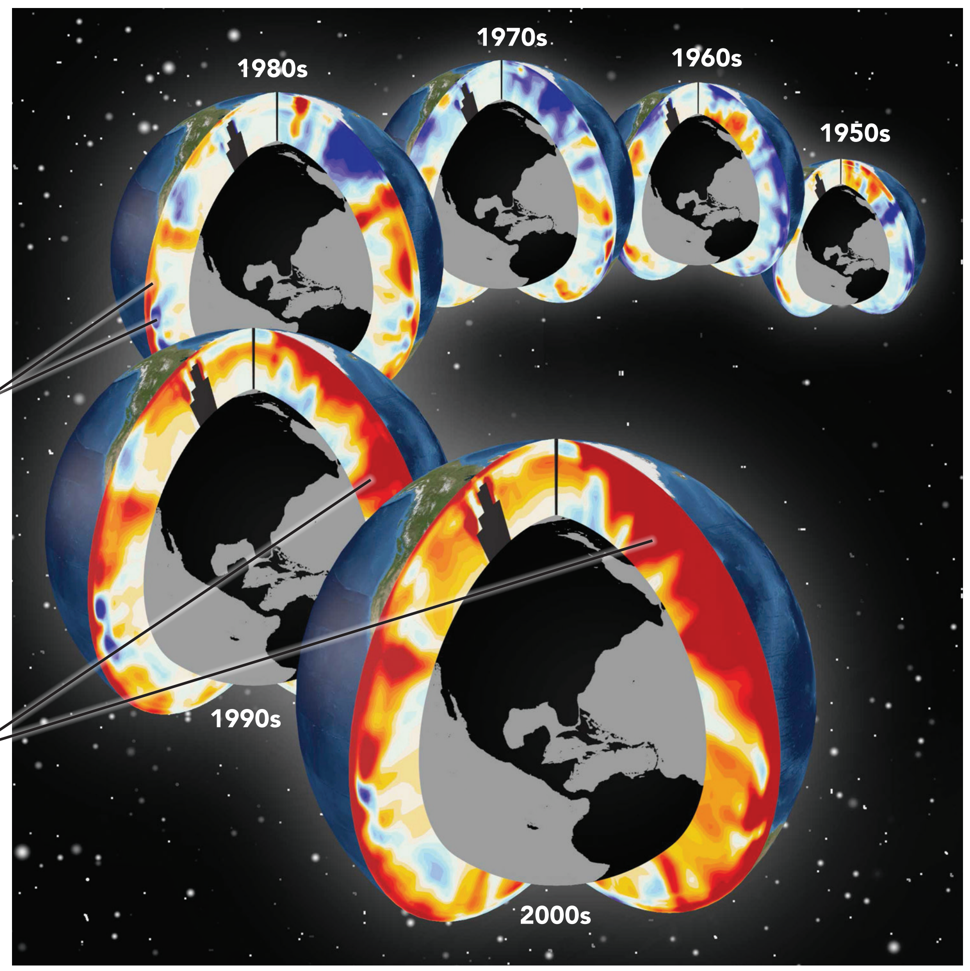
Ocean Heat Reservoirs

As surface waters are warmed by the atmosphere, deep ocean currents carry the heat below the surface. In this way, the ocean is like a giant battery, storing massive amounts of heat energy, and ocean currents are like electric currents, carrying energy around the globe to power atmospheric systems.

By storing heat from the atmosphere, the ocean acts as a buffer for global warming and delays climate change. Current warming is ~~also~~ reduced by the upwelling of colder water that sank into the deep ocean during the Little Ice Age, from 1250–1850 CE. ~~Eventually, today's warmer deep waters will rise to the surface again, raising atmospheric temperatures.~~

Warming Ocean The "shells" on these globes represent cross-sections of the Pacific (left) and Atlantic (right) oceans indicating temperature changes at different depths for a succession of decades.



Blue represents cooler temperatures, while red represents warmer temperatures.

Over the past several decades, the surface ocean has warmed and heat has moved deeper into the ocean.

(17) **CCC Patterns** Is the overall temperature of the ocean increasing or decreasing? Has the rate at which ocean temperature is changing increased, decreased, or stayed the same? Explain your answer.

Overall, ocean temperature is increasing. The rate at which the temperature is rising is accelerating (increasing) each decade, as indicated by the rapid change from mostly blue to mostly red colors in the models.

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SAMPLE PROBLEM

Calculate the Heat Carried by the Gulf Stream

The Gulf Stream flows at a rate of 100,000,000 m^3/s. Calculate how much power (in terawatts, TW, trillion Watts, or 10^{12} J/s) the Gulf Stream carries.

Analyze List the knowns and unknowns.

Knowns	Unknowns
flow rate = 100,000,000 m^3/s	Power in TW of the Gulf Stream
$\Delta T = +10°C$	
Specific heat of seawater = 4,000 J/m^3-°C	

Calculate Solve for the unknowns.

Write the equation for the power in the current.

Power of current flow
= flow rate × temperature difference
× specific heat of seawater

Substitute the knowns into the equation and solve.

Power of current flow
$= 100{,}000{,}000\ \cancel{m^3/s} \times 10\cancel{°C} \times 4{,}000\ J/\cancel{m^3\text{-}°C}$
= 4 trillion J/s
= 4 TW

Evaluate Does the result make sense?

A huge volume of warm water flows through the Gulf Stream, so it makes sense that it would transport significant amount of thermal energy.

Michael, all sample problems are followed by a question where students practice what was explained in the sample problem. So, we've added this question.

(18) **CCC Scale, Proportion, and Quantity** The Kuroshio Current is a warm water current that flows northward along the coast of Japan. It flows at a rate of 40,000,000 m^3/s, and its temperature difference is the same as the Gulf Stream's. Calculate the power, in TW, of the Kuroshio Current.

Power of current flow = flow rate × temperature difference × specific heat of seawater

Power of current flow
= 40,000,000 m^3 /s × 10°C × 4,000 J/m^3-°C
= 1,600,000,000,000 J/s, or 1.6 trillion J/s
= 1.6 TW

GO ONLINE for more practice problems.

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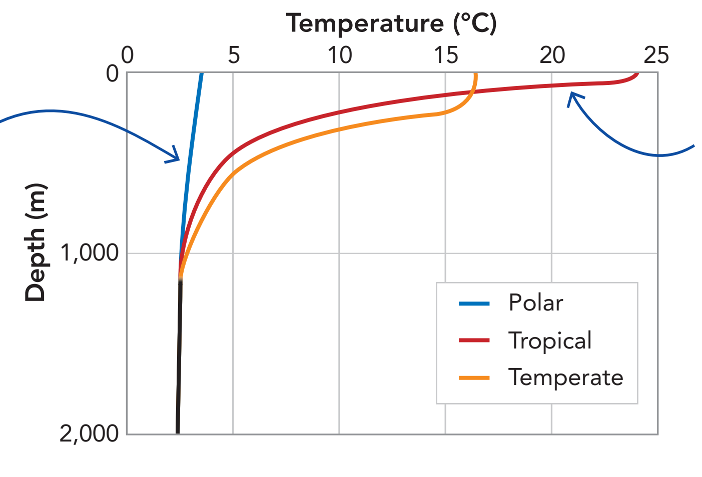
Ocean Thermoclines

The ocean is divided into horizontal temperature layers, with a warm layer near the surface, and a cold layer below. The **thermocline** marks the transition zone between the upper and lower layers. It is ~~thicker~~ in tropical regions and almost non-existent in polar regions.

In many parts of the ocean, the ~~thermocline~~ is home to large populations of photosynthetic phytoplankton who require the sunlight found there. These organisms also rely on the upwelling of ocean currents to bring a steady supply of nutrients up to the surface. However, if the thermocline gets too ~~warm, it~~ becomes very buoyant, suppressing ocean convection and upwelling. Plankton then ~~suffer~~ because they don't get the nutrients they need.

Thermocline Variation This graph shows sample thermoclines for polar, temperate, and tropical regions.

Ocean Thermoclines by Latitude



In **cold polar regions**, the surface water temperature is not that different from deeper water, so **ocean convection can easily occur** and huge phytoplankton blooms occur in the sunny summer.

In **warm tropical regions**, there is no shortage of sunlight, but the surface layer is so **thick and warm that it often prevents upwelling**. As a result, the tropics generally have the lowest phytoplankton activity, and therefore minimal marine life.

19 **SEP Construct Explanations** As global atmospheric temperatures continue to rise, scientists are concerned that populations of marine animals that rely on phytoplankton for food might decrease. Construct an explanation for this idea based on what you know about upwelling and the thermocline.

Rising atmospheric temperatures will ~~raise ocean surface temperatures above the thermocline, suppressing~~ upwelling and depriving phytoplankton of vital nutrients.

Populations of phytoplankton and other organisms will decline.

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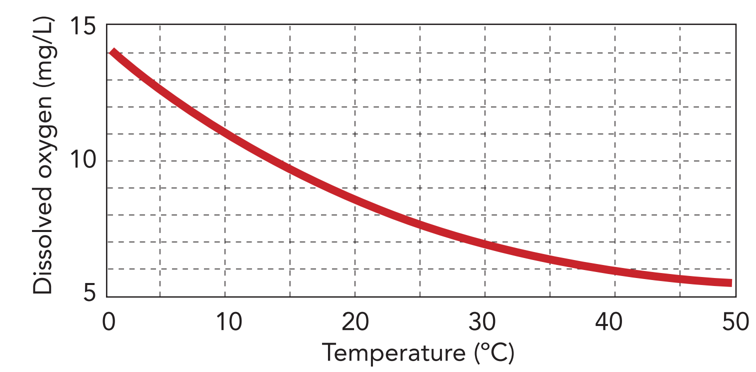
Ocean Deoxygenation

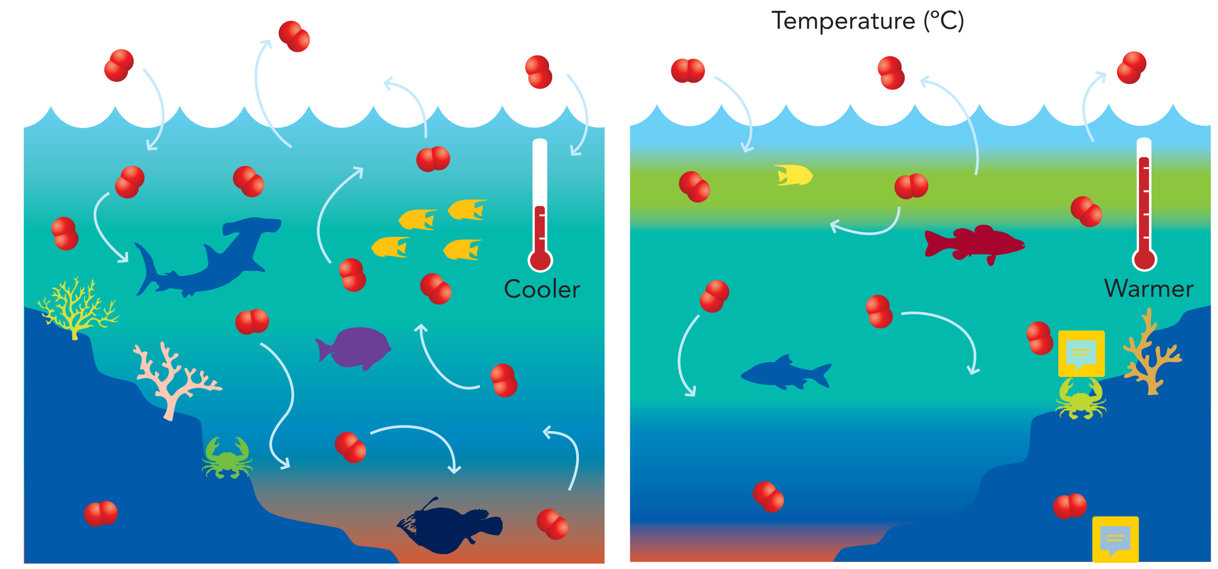
Another problem associated with global warming is ocean deoxygenation. **Ocean deoxygenation** is the expansion of low-oxygen zones in the ocean as a consequence of rising temperatures. Ocean water loses oxygen when it gets warmer for two main reasons—decreased O_2 solubility and the decline of oxygen-producing phytoplankton populations.

Deoxygenation and Hypoxia

How do **rising ocean temperatures** affect **oxygen dissolution**?

Solubility and Temperature Solubility of oxygen decreases as water temperature increases. Therefore, warming oceans hold less dissolved oxygen gas.





In a **cool ocean,** natural layers or masses of oxygenated water easily mix. **Mixing transfers oxygen** throughout the water column all the way to the ocean floor.

As ocean **water warms,** it holds **less dissolved oxygen** gas, and **layers don't mix** as well. This results in hypoxic, or low-oxygen, layers where organisms struggle to survive.

20 **SEP Using Mathematics and Computational Thinking** Suppose that a beaker of water is 15°C and you raise the temperature by 5°C. Calculate the percentage decrease in the amount of dissolved O_2 gas.

The amount of dissolved oxygen at 20°C is ~~1 mg/L less than it is at 15°C; 9.3 mg/L ÷ 10.3 mg/L = about 9% decrease in dissolved oxygen.~~

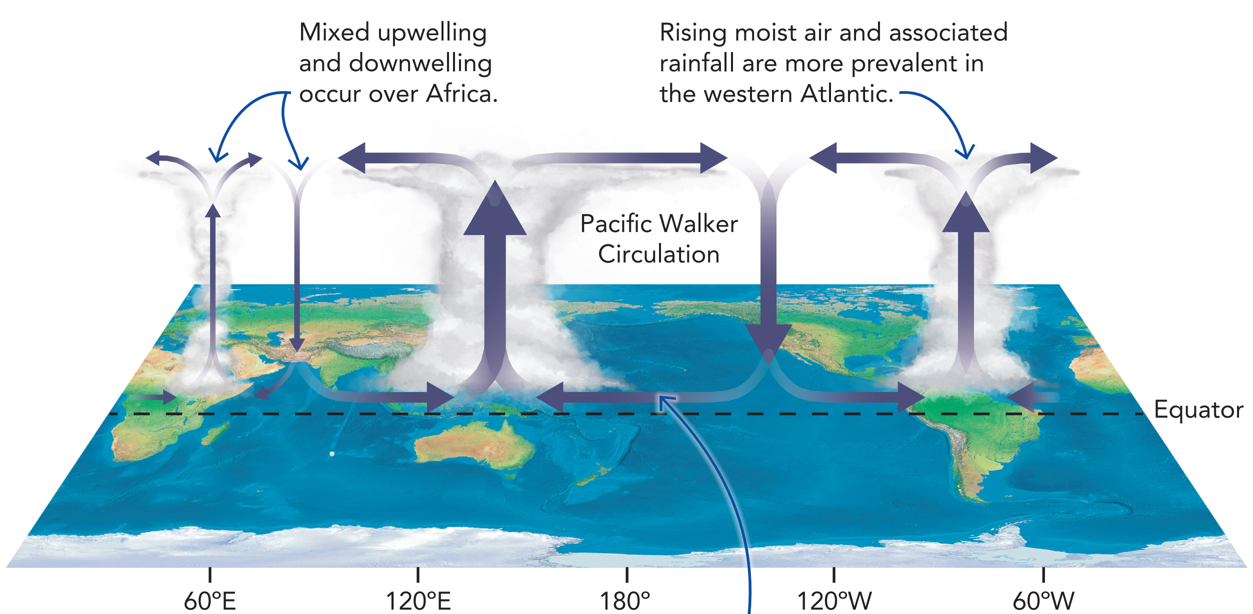
El Niño-Southern Oscillation

As we have seen, ocean currents have a significant effect on regional climates as they redistribute heat around the globe. ~~But ocean circulation patterns are also affected by cyclical changes.~~

The cycling of matter and energy between Earth's ocean and atmosphere creates changes in climate patterns around the globe.

Perhaps the most significant cyclical ocean circulation pattern in terms of energy redistribution is what is known as ENSO. The **El Niño-Southern Oscillation (ENSO)** is a cyclical circulation pattern in the tropical Pacific that results in periodic variation between below-normal and above-normal sea surface temperatures and dry and wet conditions. The ENSO pattern cycles through three phases: Neutral, El Niño, and La Niña. Neutral indicates that conditions are near their long-term average.

"Neutral" ENSO Walker Circulation ENSO cycles are driven by a pattern of atmospheric flow called the Walker Circulation, with warm moist air rising in the western Pacific (bringing rain) and cold dry air falling in the eastern Pacific. Because the atmospheric systems are all coupled, this Neutral ENSO pattern influences atmospheric flow patterns in the Atlantic and Indian Oceans.



Data from NOAA

During the Neutral phase of ENSO, ~~a westward ocean current along the Pacific Ocean equator brings~~ warm water to the Asian coast.

Michael, please check if my edit is correct.

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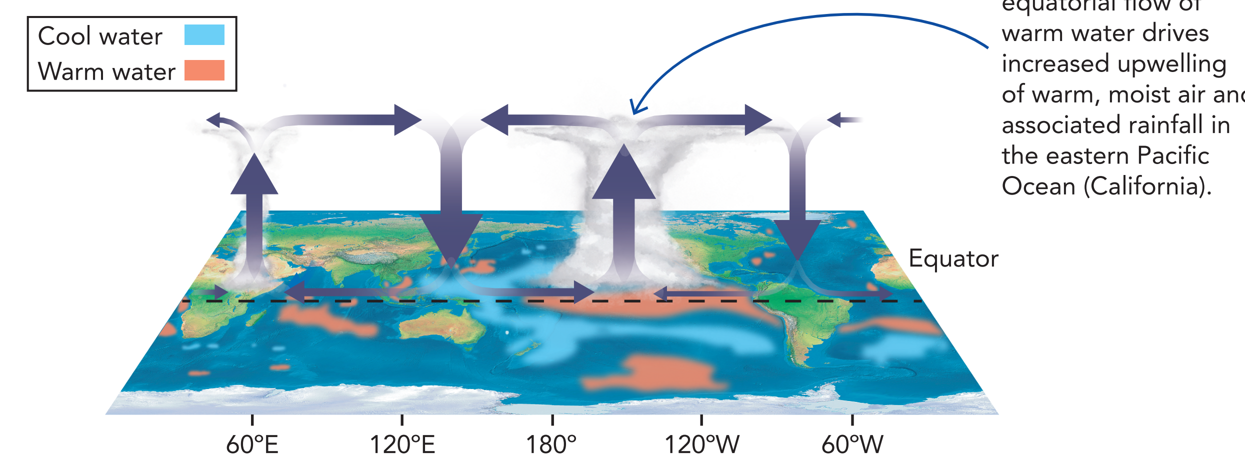
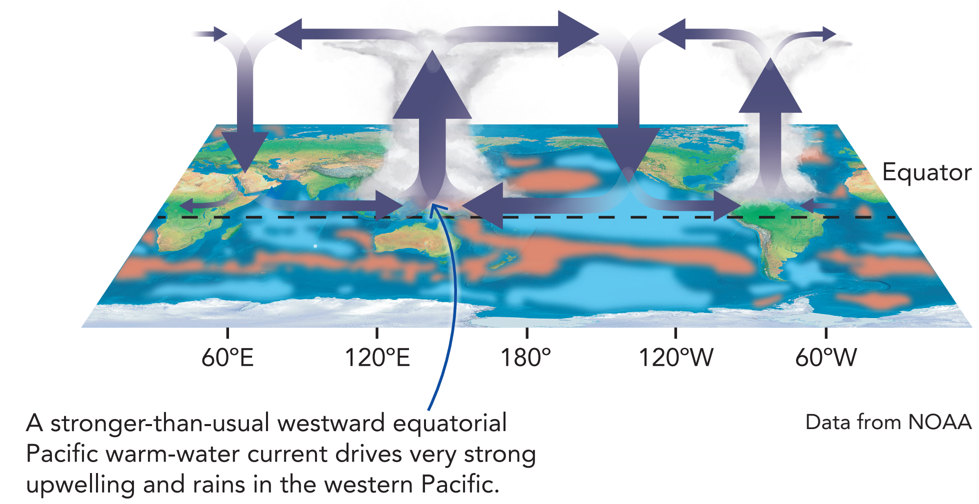
El Niño is the warm phase of ENSO, as average ocean surface temperatures rise. La Niña is the cool phase, as surface temperatures fall. These two phases shift back and forth irregularly every 2–7 years, trigging predictable disruptions of temperature, air currents, and rainfall that lead to droughts in some places and floods in others. Typically, El Niño occurs more often than La Niña.

El Niño Walker Circulation During ~~an~~ El Niño, there is an increase in rainfall over California and equatorial Africa, but a decrease in rainfall in the Atlantic and western Pacific.



La Niña Walker Circulation La Niña triggers more intense tornadoes in the central U.S. and more hurricanes in the Caribbean and central Atlantic Ocean. It also brings heavy monsoon rains to India, but decreased rainfall over central Africa.



Data from NOAA

21 **CCC Patterns** During a La Niña event, rainfall and hurricanes/cyclones generally increase along the east coasts of both North America and Asia, but they all generally decrease during an El Niño event. Use the diagrams on this page to explain why.

During La Niña, warm moist air is rising above these regions, where it cools and produces precipitation. During El Niño, cooler dry air sinks over these regions, so rainfall is less.

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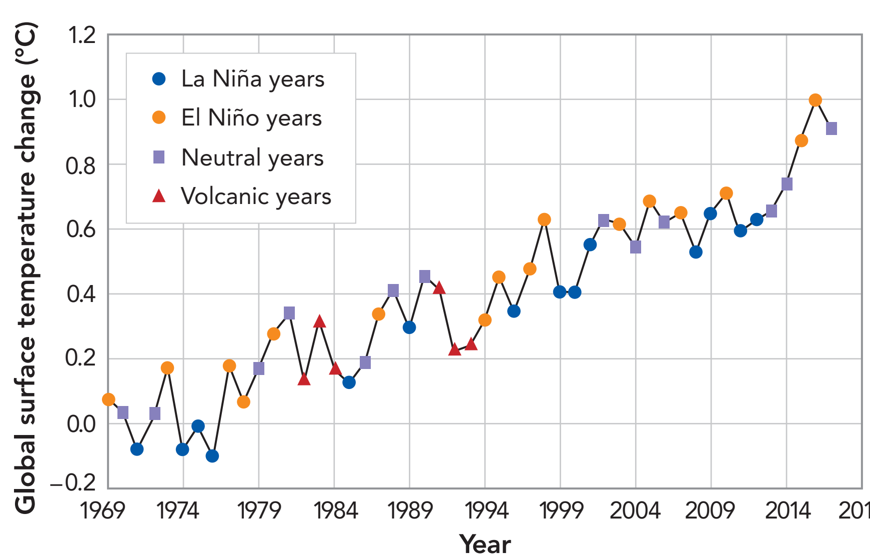
ENSO Variability and Upwelling

ENSO cycle patterns directly impact global temperatures. During ~~an~~ El Niño, Pacific Ocean surface temperatures are warmer than usual and the heat borrowed out of the Pacific Ocean generally causes global temperatures to rise. During ~~a~~ La Niña, heat goes back into the Pacific Ocean and global temperatures usually fall. These cycles of heating and cooling impact human societies, sometimes in surprising ways.

Flu Epidemics In 1917–1918, the Spanish Flu pandemic killed almost 100 million people worldwide. This pandemic, along with the next three big flu epidemics (1957, 1968, 2009), were each preceded the year before by ~~a~~ La Niña. One hypothesis proposes that the La Niña ocean circulation patterns caused changes in atmospheric circulation patterns, which caused changes in bird migration patterns. Because the birds flew places they didn't normally go, large segments of the human population were exposed to new strains of avian flu viruses, which caused the human flu epidemics.

ENSO Variability and Global Temperature Change Global mean temperatures vary annually. The average temperature for El Niño years (yellow line) is warmer than for La Niña years (blue line). The purple line shows the temperature trend for neutral years.

Global Surface Temperature Anomalies



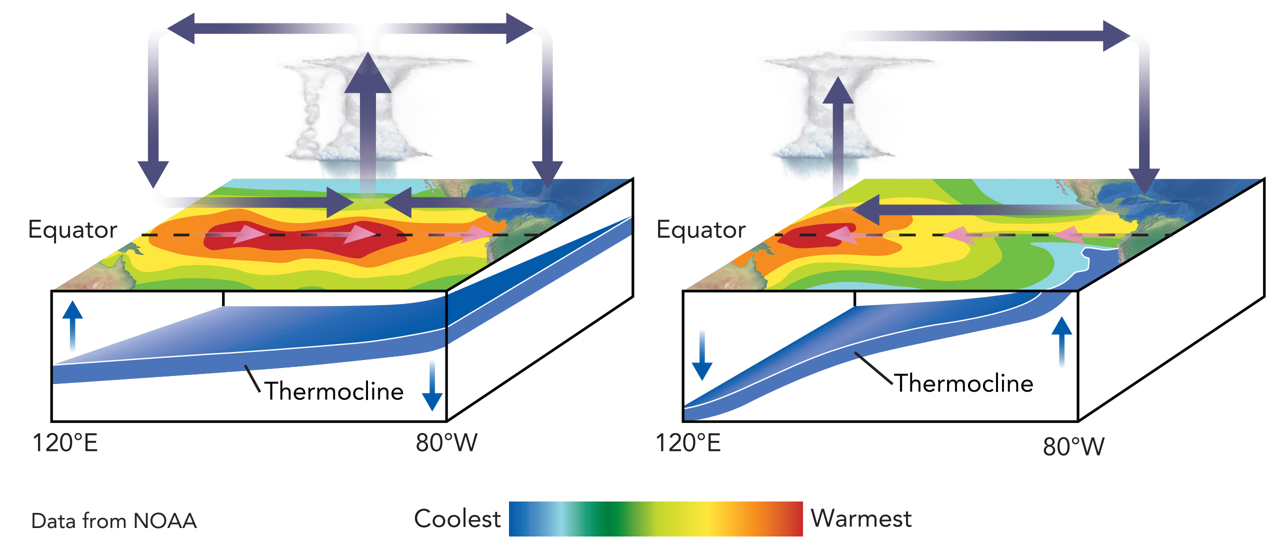
Data from skepticalscience

(22) SEP ~~Analyzing and Interpreting~~ Data ~~Look at the data for volcanic years in the graph. How can you explain the data?~~

Two data points indicate higher than normal temperatures for volcanic years, but most indicate lower than average temperatures. Volcanic ash can block sunlight, reducing the amount of energy that reaches Earth and reducing temperatures.

El Niño and the Thermocline During an El Niño phase, the eastward Pacific current of warm water pushes down the thermocline along the South American coast, limiting upwelling and causing a decrease in marine life there.

La Niña and the Thermocline During a La Niña phase, the westward Pacific current causes the thermocline to lift up along the South American coast, bringing nutrient rich waters that feed booming plankton and fish populations.



Data from NOAA

Economic Effects The ENSO cycle also affects fishing industries. In neutral years, a westward equatorial Pacific current causes upwelling along the coast of South America. This brings nutrients to shallow waters, which supports plankton growth and therefore larger fish and the South American fishing industry.

In addition, a coastal current that travels north along the South American coast veers westward due to the Coriolis effect. This pulls water away from the coast, bringing up more nutrients. This effect is amplified by the stronger currents during a La Niña event, which is usually very good for the fishing industry.

During an El Niño period, warm waters flow east across the Pacific equator and then down the South American coast. The Coriolis effect causes these currents to bend left into the coast and sink, suppressing the upwelling of nutrients. The plankton die and the fishing industry collapses.

(23) **SEP Analyzing and Interpreting Data** Global temperatures actually decreased slightly in the years 2017 and 2018. Some suggest that this means global warming has stopped. Construct another more plausible explanation for the data.

These years coincided with a La Niña period, which usually produce lower than average global temperatures.

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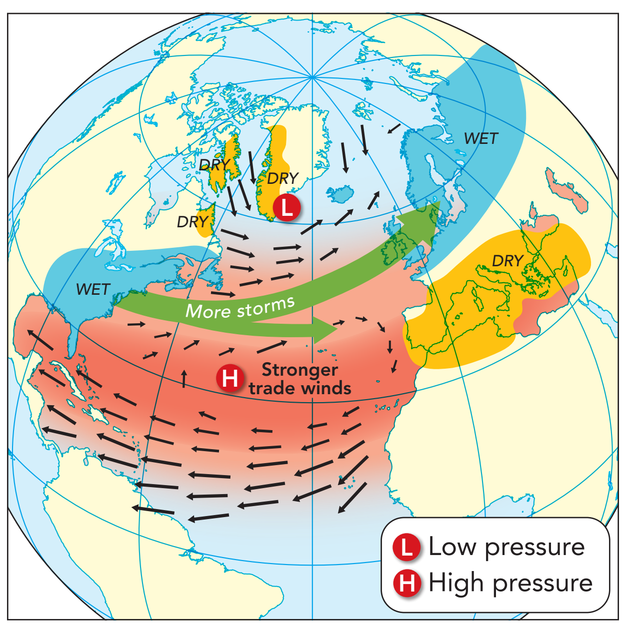
Other Modes of Ocean Variability

The ENSO cycle of El Niño/La Niña is not the only pattern of oscillating ocean and atmosphere currents. There are many others. For example, the Indian Ocean Dipole (IOD) is an irregular cycle of changing sea-surface temperatures between the east and west sides of the Indian Ocean, with corresponding changes in rainfall. The Antarctic Oscillation (AAO) is a fluctuation in the shape of the ring of winds and waters that circle around Antarctica, changing the locations of heavy winds and storms.

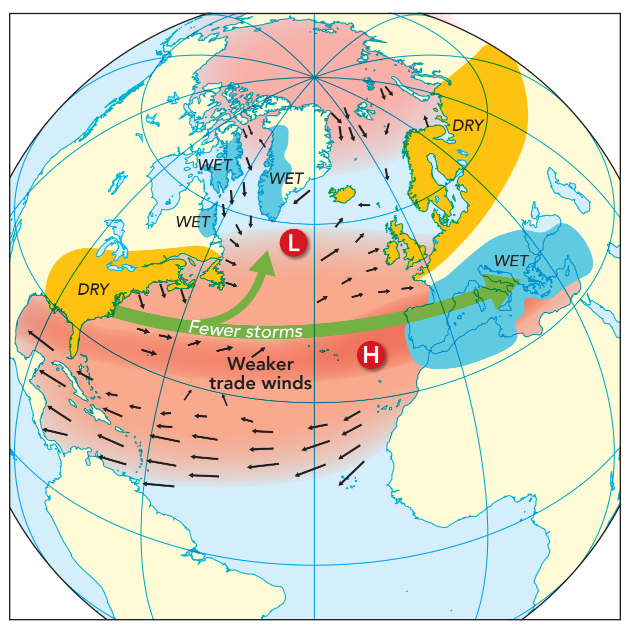
North Atlantic Oscillation (NAO) A significant oscillation in the North Atlantic is the NAO, which is primarily an atmospheric oscillation, closely connected with Arctic air patterns. The NAO oscillates between two modes, referred to as the Positive and Negative modes. These modes involve a shifting in the strengths of various high and low pressure zones, and determine which parts of Europe and eastern North America receive warm or cold (and wet or dry) air masses.

Atlantic Multi-decadal Oscillation (AMO) Another oscillation in the Atlantic Ocean is the AMO. The AMO involves 20-40-year oscillations of long-term sea-surface temperatures in the North Atlantic Ocean. These variations affect air temperatures and rainfall patterns over much of the Northern Hemisphere to the extent that there is a significant correlation between the AMO and mean global temperatures over the past century.

North Atlantic Oscillation: Positive Mode The polar jet stream follows a relatively straight course from North America to Europe. Eastern North America gets warm air, northern Europe gets wet and warm air, and southern Europe gets cool and dry air.

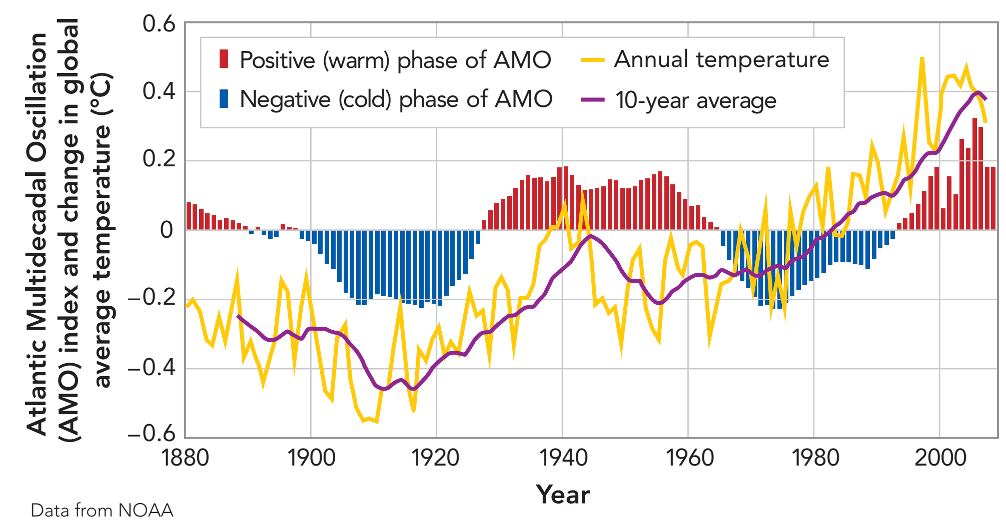


North Atlantic Oscillation: Negative Mode The polar jet stream meanders up over Greenland. Eastern North America is cold and snowy, northern Europe is cold and dry, and southern Europe is warm and wet.



24 **CCC Energy and Matter** The histogram below shows the positive and negative phases of the AMO index. The green and red lines show annual variations in the global mean temperature and its 10-year moving average. The correlation between the AMO index and mean global temperature is strong, but not perfect. Draw a box around the parts of the two curves where their trends do not correlate.

Global Average Temperature and the AMO



The curves do not correlate during the following intervals: 1942–1948, 1953–1959, 1960–1969, and 1981–1987.

Revisit

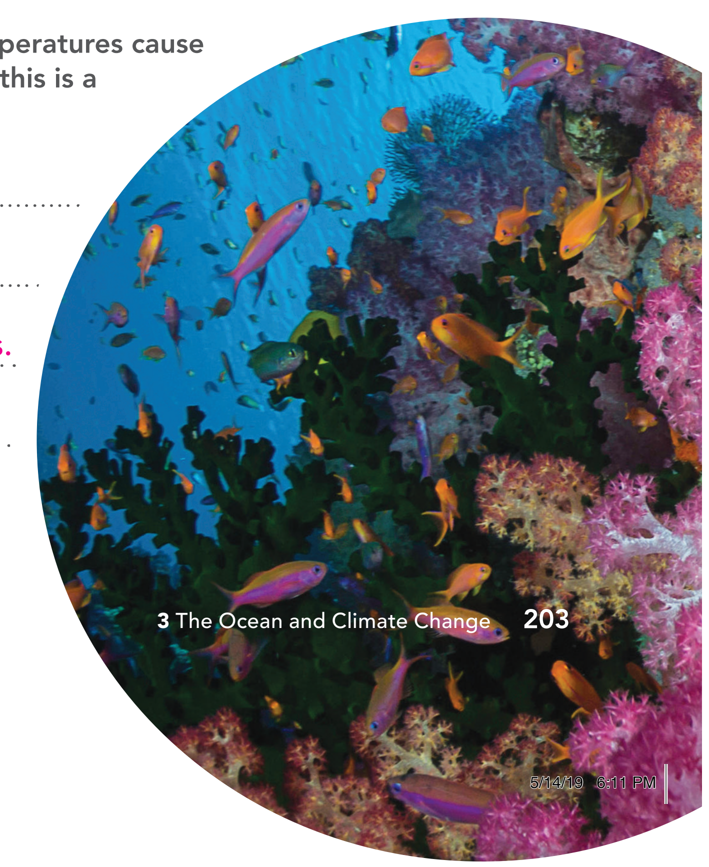
INVESTIGATIVE PHENOMENON

GO ONLINE to Elaborate and Evaluate your knowledge of the ocean's influence on Earth's climate by completing the class discussion and data analysis activities.

In the CER worksheet, you drafted a scientific argument to explain what is happening to the world's coral reefs. With a partner, reevaluate the evidence cited in your arguments.

25 **SEP Engage in Argument** Increasing ocean temperatures cause a decrease in ocean oxygen levels. Explain why this is a problem for coral reefs.

Like other animals, coral polyps depend on oxygen to live. If oxygen levels dip too low, they will suffocate like other marine animals.



EXPERIENCE 4

Consequences of Ocean Acidification

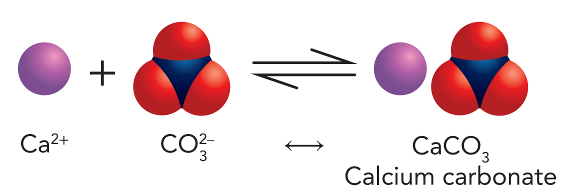
GO ONLINE to Explore and Explain the effects of ocean acidification.

Calcification

Many marine organisms use carbon from dissolved carbon dioxide to build their shells out of calcium carbonate, $CaCO_3$, in a process called **calcification.** Calcification is a form of biomineralization. The calcium enters the ocean as dissolved ions from the weathering of rocks at or below Earth's surface.

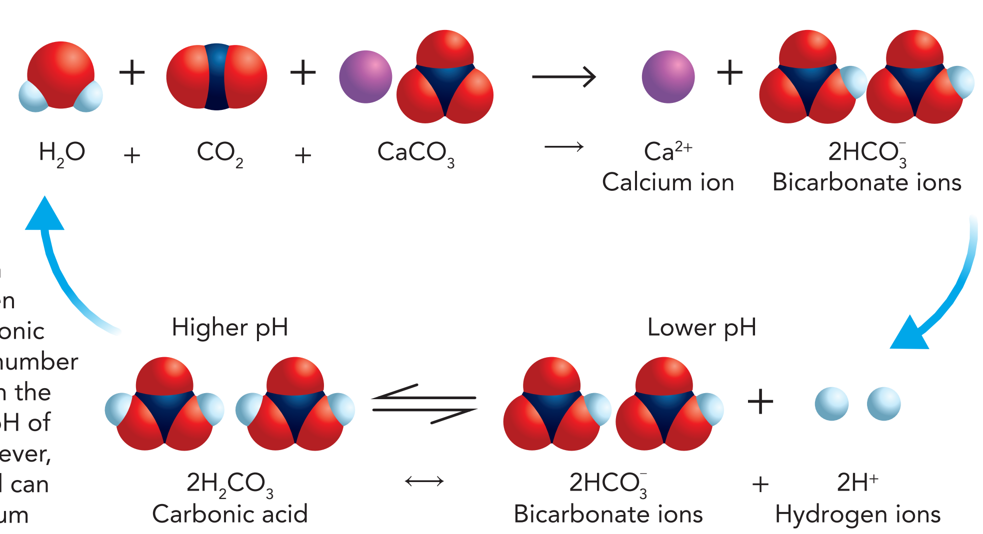
Calcium carbonate has two main crystal forms, or polymorphs, used for making shells and skeletons: calcite and aragonite. These crystals have the same chemical composition, but the calcium, carbon, and oxygen atoms are arranged in different structures. Some organisms prefer one form over the other and some organisms use both forms to make their shells harder.

Calcification in Acidic Seawater Marine organisms use calcium ions (Ca^{2+}) and carbonate ions (CO_3^{2-}) in seawater to build their shells of calcite or aragonite.

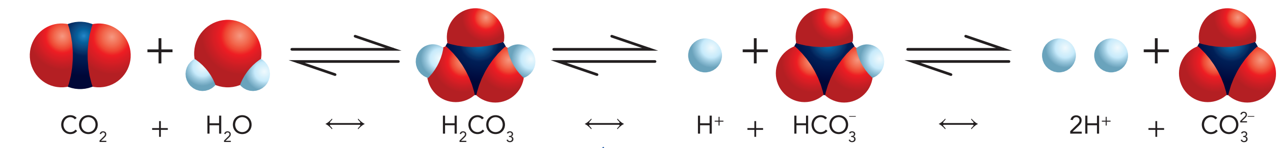


Calcium carbonate reacts with carbonic acid to form calcium ions and bicarbonate ions.

Excess bicarbonate can react with free hydrogen ions to form more carbonic acid. This reduces the number of free hydrogen ions in the system and raises the pH of the entire system. However, increased carbonic acid can break down more calcium carbonate shells.



Buffering the Solution Changing the relative concentrations of reactants and products can shift the pH in either direction. This buffers the solution and slows the rate at which the ocean water's acidity changes.



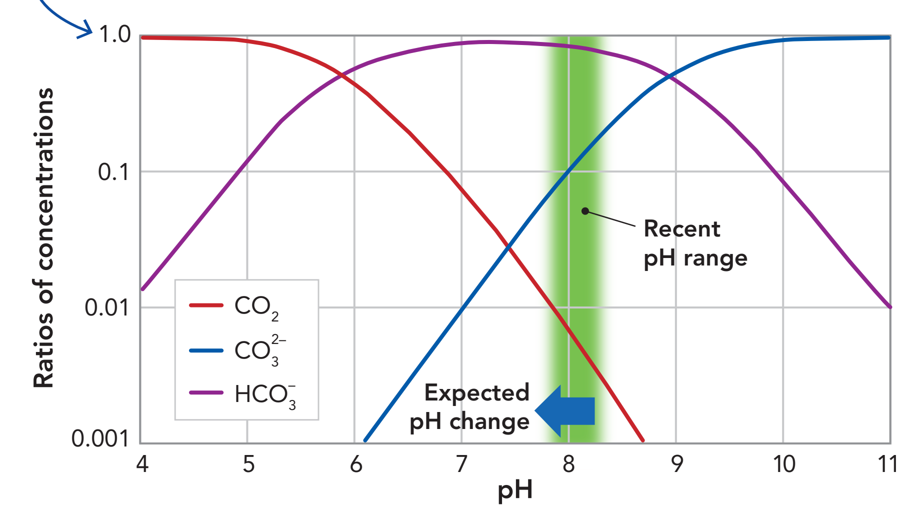
When excess bicarbonate ions react with free hydrogen ions in seawater, more carbonic acid forms, pushing the equation to the left and resisting a drop in pH of the solution.

However, this decreases the amount of carbonate ions available for organisms to use to build shells.

Dynamic Equilibrium As the ocean becomes more acidic, the relative concentrations of carbonate ions, bicarbonate ions, and carbon dioxide shift to reach a new equilibrium. As pH drops, carbonate concentrations decrease and bicarbonate and carbon dioxide concentrations increase.

The vertical axis is a logarithmic plot of the reactant concentrations.

Change in Carbonate System of Seawater from Ocean Acidification



The horizontal pH scale is a logarithmic plot of H^+ ion concentrations.

26 **SEP Analyzing and Interpreting Data** Use the vertical logarithmic scale to explain why carbonate ions are mostly converting to bicarbonate ions and not to CO_2 molecules as pH levels fall from the mean ocean surface value of ~8.1.

~~anno: TK~~

Marine Shell Dissolution

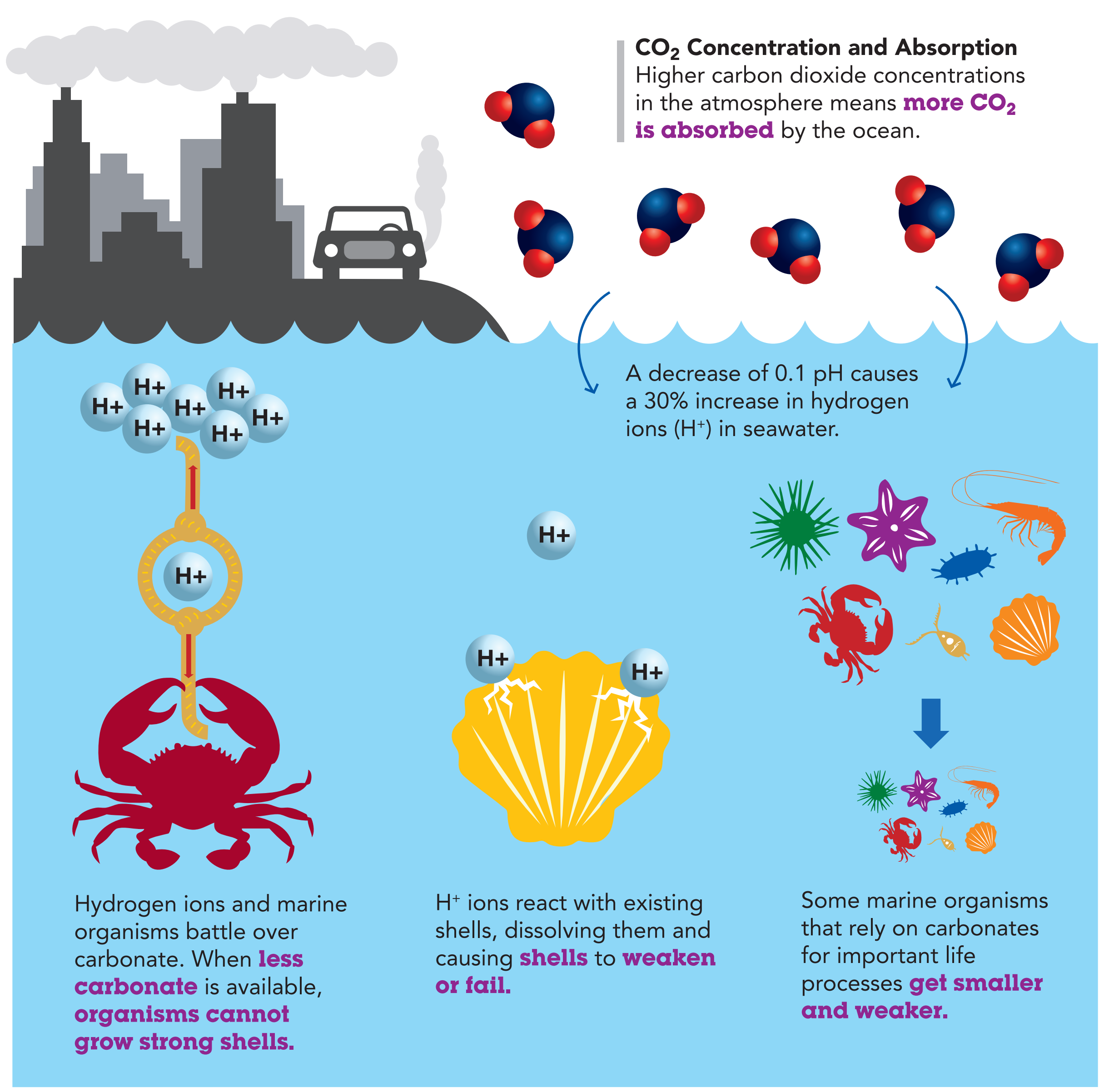
stacking to be done by comp

Adding free H^+ ions to the water drives the chemical reactions away from carbonate stability. As the amount of CO_2 in the ocean increases, the amount of CO_3^{2-} decreases, and carbonate ions convert into bicarbonate ions (HCO_3^-), ~~increasing~~ the energy required by organisms to build shells. These changes lower calcification rates and increase dissolution rates.

Changes to carbon dioxide levels and ocean pH disrupt the chemical equilibrium that many ocean organisms depend on to make their shells.

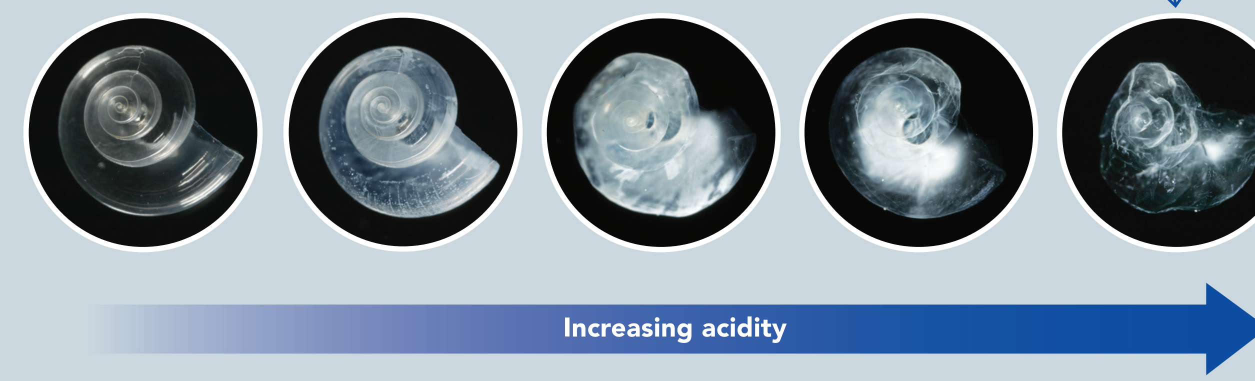
Dissolution of Calcium Carbonate Shells

How are **pH** and **CO_2 concentration** related to **carbonate dissolution?**



Calcium Carbonate Dissolution in Acid
Increased ocean acidity increases the dissolution rate of calcium carbonate shells once they are built.

Shells become weaker over time and may fail completely. As shells weaken or fail, populations of carbonate-shelled organisms will likely decline over time.



Calcite and Aragonite Organisms that use aragonite to build their shells are more at risk than organisms that use only calcite. Aragonite is a harder mineral than calcite, so it adds extra protection from predators, but it is only weakly stable at Earth's surface and is 1.5 times as soluble in seawater than calcite.

Arctic Food Webs Cold, arctic waters absorb atmospheric CO_2 faster than other regions and act as carbon sinks. The Arctic food web is very dependent upon shelled molluscs that have aragonite shells. Damage to the base of the Arctic food web would cause damages all the way up the chain, including fish, seals, and whales.

Larval Stages Ocean acidification is particularly damaging to marine organisms that have a larval stage, such as plankton, bivalves, and sea urchins. The larvae of marine organisms ~~grown~~ in high-CO_2 waters tend to be stunted and deformed, making them less able to feed and function properly.

27 **CCC Stability and Change** Suppose there are two closely related species of clam. One makes its shell out of aragonite, the other out of calcite. As the ocean becomes more acidic, predict what will happen to the relative populations of the two species, and what will happen to the population of a predator species that feeds on the aragonite-shelled clams.

Sample answer: Because aragonite is more soluble in seawater than calcite is, the aragonite-shelled clams will likely struggle to build and maintain their shells. As a result, their population will likely decline relative to the population of the calcite-shelled clams. The population of predators that rely on the aragonite-shelled clams will likely also decline unless they adapt their hunting and feeding habits.

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Disruption of Marine Ecosystems

Increased CO_2 concentrations and ocean acidification are impacting marine organisms and communities in many different ways. Some organisms, such as the jumbo squid, are suffering from reduced metabolism rates. Others, such as the longfin squid, are taking longer to grow and are more frequently small and misshapen. Some species, such as blue mussels, are showing a reduced immune system. Others are showing a decrease in their ability to smell or hear predators.

Some organisms are actually doing better and are thriving in higher-CO_2, lower-pH waters. One study of an ecosystem found that predators such as crabs and lobsters were become bigger and stronger, while their prey, such as clams and oysters, were doing worse, disrupting the predator-prey dynamics. In many environments, disruptions and damages to the ecosystem are ~~being damaged by~~ increased temperature, higher acidity, and deoxygenation. These combined effects are much greater than the effects from just one factor.

Jumbo Squid Studies have shown that increased ocean carbon dioxide levels can damage the metabolic rates of marine organisms such as the Humboldt, or jumbo, squid.

Red Tides Blooms of toxic cyanobacteria and algae, commonly called red tides, occur more frequently in warmer and more acidic oceans. When the algae and cyanobacteria die and decay, oxygen is stripped from the water and large "dead zones" form in the ocean. In these hypoxic zones, oxygen levels are so low that fish, turtles, marine mammals, and seabirds cannot survive. Algal blooms often occur near the mouths of large rivers, which carry phosphates and other chemicals from fertilizers that run off of farm lands into rivers.

Toxic Red Tides Warm water and higher carbon dioxide levels favor photosynthesis, which leads to blooms of toxic cyanobacteria and algae, such as this bloom off the coast of South Africa.

Plastics Another ecological hazard comes from human use and disposal of plastics. Plastic floats and degrades slowly, and often accumulates within broad ocean gyres, which may hold 100 million tons of plastic. One such gyre had more than 6 times as much plastic in the water as plankton. One of the largest sources of plastics in the ocean is synthetic fabrics, which release huge numbers of microfibers with each washing. These microfibers pass through filtration plants and into the ocean.

28 **SEP Constructing Explanations and Designing Solutions** Propose two different ways that the number of damaging toxic ocean red tides could be reduced.

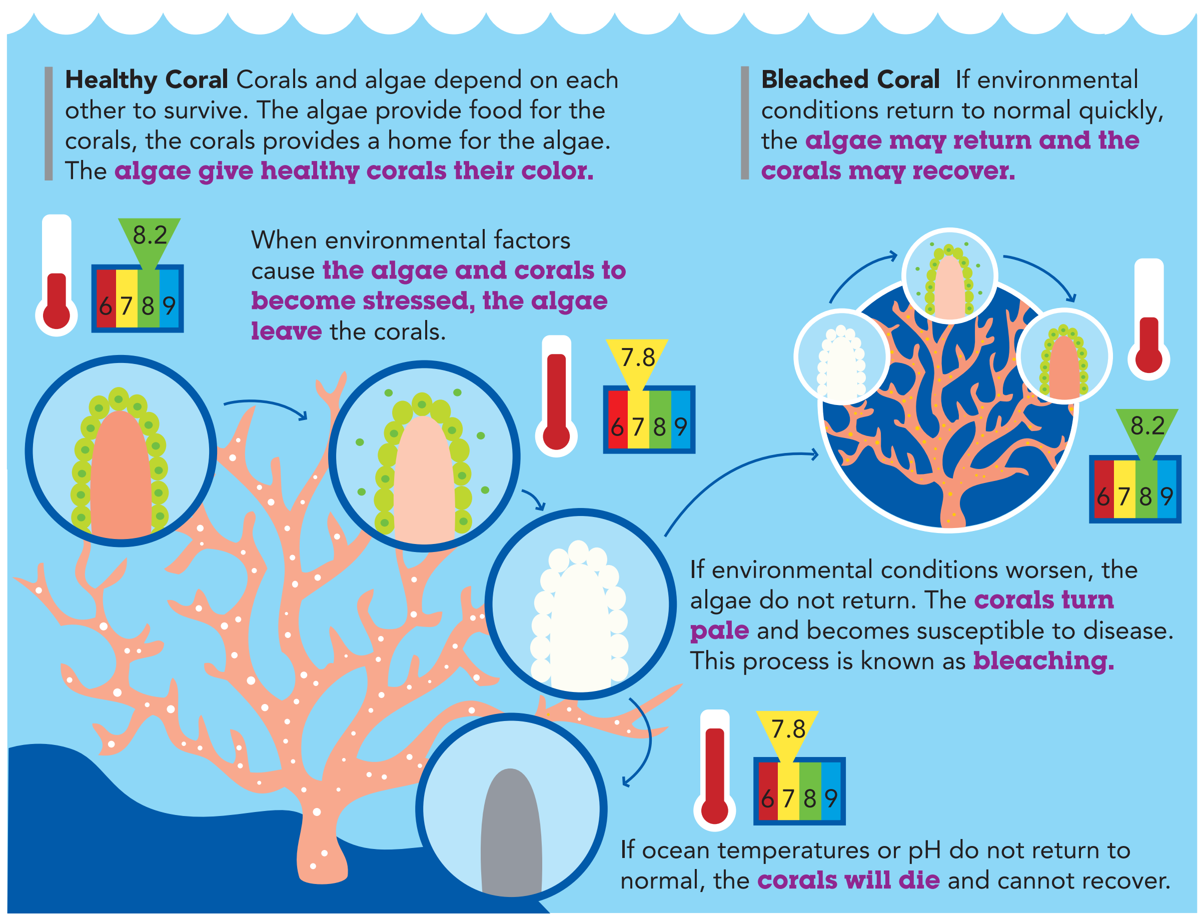
Sample answer: Reduce the amount of fertilizers used on crops or lawns, or change the methods of application to result in less runoff. Reduce the rate at which ocean temperatures and acidity are increasing by reducing fossil fuel consumption.

Coral Bleaching

Corals are tiny marine ~~organisms~~ that enjoy a symbiotic relationship with photosynthetic algae that live in their tissues and supply them with a source of food. If the corals become stressed, the algae will leave, causing the corals to turn white, a phenomenon known as **coral bleaching.** There are many different causes of coral bleaching, including ocean acidification and water pollution. But the greatest cause is warming ocean temperatures.

Corals Response to Ocean Changes

How do **temperature** and **pH** affect corals?



(29) **CCC Stability and Change** Coral reefs play an important role in many marine ecosystems. Describe what you think would happen to coral reef ecosystems if the corals died.

~~Sample answer:~~ If the corals died, the coral reefs would start to break down, depriving other marine animals of shelter and feeding and mating grounds. ~~These animal~~ populations would also suffer as a result.

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SAMPLE PROBLEM

Calculate Rates of Coral Bleaching Events

Between 2014 and 2017, an ocean heat wave caused 75% of the world's coral reefs to demonstrate bleaching-level heat stress. About 30% of the corals died. Before the 1980s, mass-bleaching events were occurring approximately once every 30 years. As of 2017, these events were happening every 6 years. How much more frequently are these events occurring now than in the 1980s?

Analyze The knowns and unknowns.

Knowns	Unknowns
frequency before 1980s = 1/30 years	change in frequency (Δ_{freq})
frequency in 2017 = 1/6 years	

Michael, the Sample Problem on the change in the CCD was not working well. However, if you prefer we revert back to that then we can. I think it may work better though if we integrate it into the basal text instead of as a Sample Problem.

Calculate Solve for the unknown.

Write the equation for calculating change in rate.	change in frequency = new rate ÷ old rate
Solve the fractions for common denominators	1/6 = 5/30
Substitute the knowns into the equation and solve.	change in frequency = 5 ÷ 1 = 5

Evaluate Does the result make sense?

Mass-bleaching events are happening five times more frequently than before the 1980s. This makes sense because global ocean temperatures have increased significantly since the 1980s.

(32) **SEP Use Mathematics** Scientists project that the frequency of mass-bleaching events will continue to accelerate at a rate of 4% per year. Using the current frequency as the rate for 2020, how much more frequently will mass-bleaching events occur in 2050?

~~Sample answer:~~ new rate = 4% × 30 years = 120%, 1/6 × 120% = 0.2, or 1/5 or once every 5 years; change in frequency = new rate ÷ old rate; change in frequency = 1/5 ÷1/6, or 6/30 ÷ 5/30; Δ_{freq} = 5/6 = 1.2 times more frequently]

GO ONLINE for more practice problems.

stacked fractions to be done by comp

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Calcite and Aragonite Stability Depths

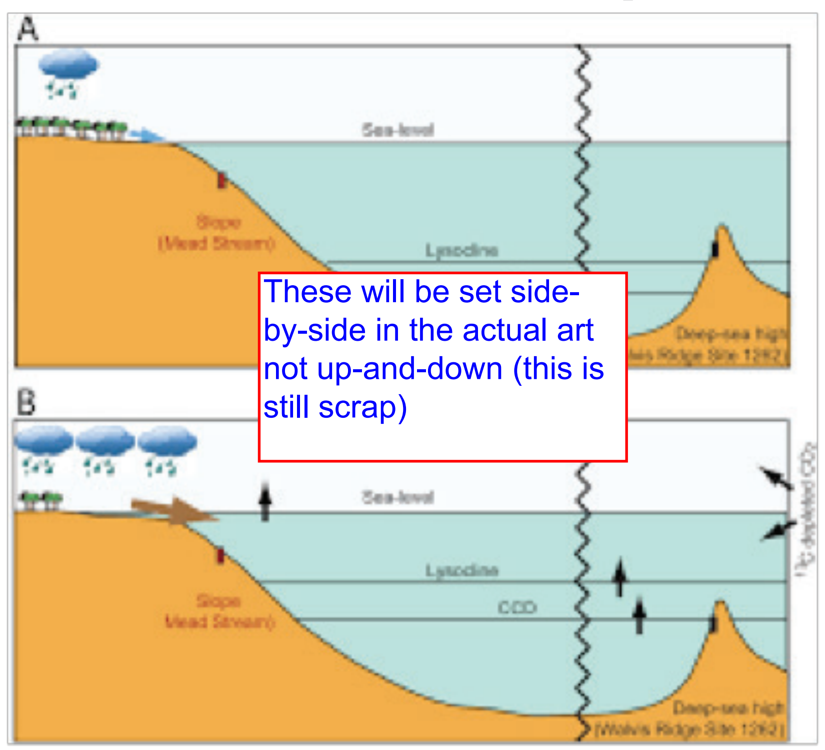
Recall that the Carbonate Compensation Depth (CCD) is the depth below which $CaCO_3$ is not stable and will dissolve according to the equation:

$$CaCO_3 + CO_2 + H_2O \Longleftrightarrow Ca^{2+} + 2\,HCO_3^-$$

However, this reaction is different for the two different forms of $CaCO_3$—calcite and aragonite. Because aragonite is more soluble than calcite, its compensation depth (also called the saturation depth) is shallower. Solubility also depends on ocean temperature and CO_2 concentrations, so the CCDs for calcite and aragonite vary according to geographic location.

Concentrations of CO_2 are often highest in regions of ocean upwelling, causing shallower CCDs in the northern and eastern Pacific Ocean. Concentrations of CO_2 tend to be lower in sinking waters, such as those in the northern Atlantic Ocean. Calcite stability depths are generally similar to those in the map for aragonite but are deeper everywhere because of the higher stability of calcite.

30 **SEP Develop Models** New caption to come based on new art New caption to come based on new arte map, stion to come based on new art New caption to come based on new arte ma.



These will be set side-by-side in the actual art not up-and-down (this is still scrap)

Original plan for the activity has been scrapped due to permission issues. New spec circulating with Pearson as of 5/10. Activity for it TK.

anno TK

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39p wide x 23p deep

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Paleocene-Eocene Thermal Maximum

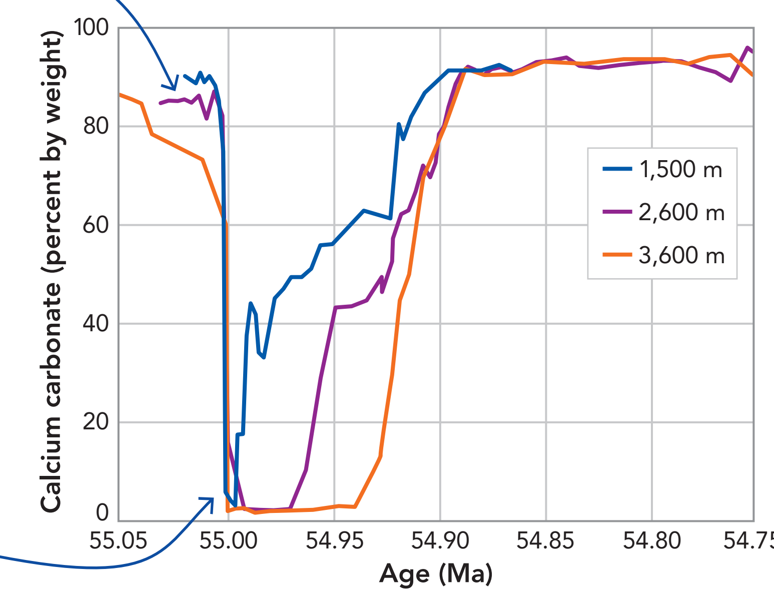
The fossil record tells us that 55 million years ago, during a time called the Paleocene-Eocene Thermal Maximum (PETM), there was a huge and sudden release of atmospheric carbon, and global temperatures rose 5–8°C. In the ocean, there was a massive die-off of some organisms, but an upsurge in others. Fossils show that it took almost 100,000 years for ocean conditions to stabilize. This event gives us some idea of what might occur in the ocean if atmospheric carbon and temperatures continue to rise.

PETM Carbonate Compensation Depths About 55 million years ago, the ocean quickly became very warm and CO_2-rich. The carbonate compensation depth became so shallow that no $CaCO_3$ fossils are found from this time.

These three curves show the weight percentage of $CaCO_3$ in seafloor sediments as a function of time in three different locations at three different depths.

All three curves go to zero at 55 million years ago, but recover at different rates over the next 100,000 years.

Calcium Carbonate Content of Ocean Sediments Across the PETM



Based on report from Science Magazine, 10 June 2005, Vol 308.

31 **SEP Developing and Using Models** How does the fossil record serve as a model to help us understand what impact we are having on the planet today?

By examining the fossil record, we can find patterns that show what impact different variables, such as temperature and amount of carbon in ocean and atmosphere, have had on other variables, such as living things, during the course of Earth's long history.

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Revisit

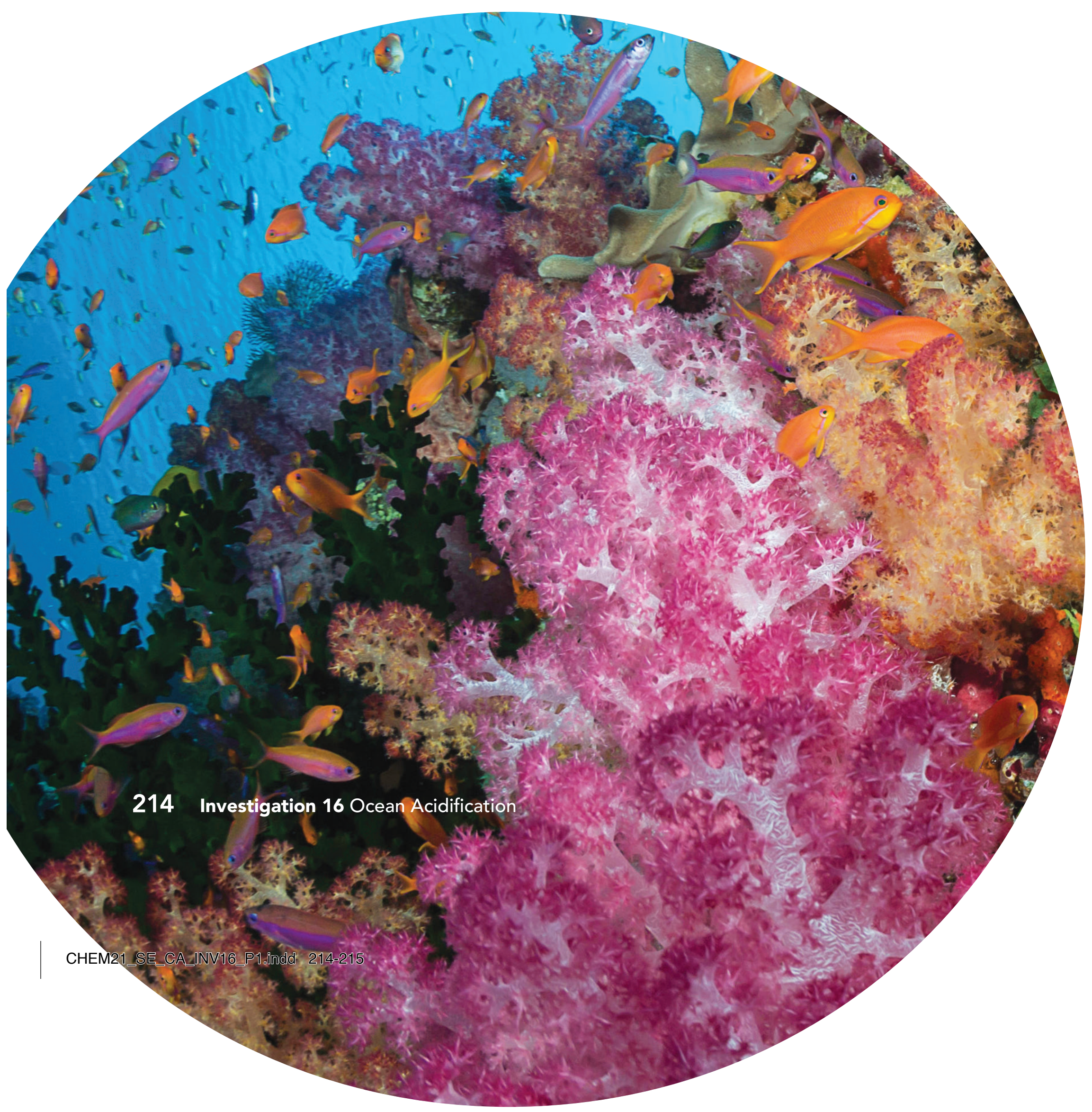
INVESTIGATIVE PHENOMENON

GO ONLINE to Elaborate and Evaluate your knowledge of the effects of ocean acidification by completing the class discussion and data analysis activities.

In the CER worksheet, you drafted a scientific argument to explain what is happening to the world's coral reefs. With a partner, reevaluate the evidence cited in your arguments.

33 **SEP Construct Explanations** Corals are made of calcium carbonate, $CaCO_3$. Carbon dioxide is required to make these coral skeletons. Explain why having too much CO_2 makes it harder for these shells to form.

When too much carbon dioxide enters ocean water, the chemical reactions shift to favor the addition of free H^+ ions to the water. This lowers the pH and causes carbonate ions convert into bicarbonate ions. Less carbonate is available for organisms to use to build shells and the energy required by organisms to build shells increases. Lowered calcification rates and raised calcium carbonate dissolution rates make it harder for corals to form and maintain their skeletons.



GO ONLINE to Evaluate what you learned about TKTKTK.

TK TK

Revisit

ANCHORING PHENOMENON

35 To come

GO ONLINE to come

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