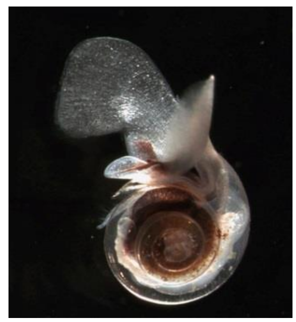
Ocean Acidification
https://www.pmel.noaa.gov/co2/story/What+is+Ocean+Acidification%3F
By Richard A. Feely

What is Ocean Acidification?

A pH unit is a measure of acidity ranging from 0-14. The lower the value, the higher the acidity of the environment. A shift in pH to a lower value reflects an increase in acidity.

The Chemistry

When carbon dioxide (CO_2) is absorbed by seawater, chemical reactions occur that reduce seawater pH, carbonate ion concentration, and saturation states of biologically important calcium carbonate minerals. These chemical reactions are termed "ocean acidification" or "OA" for short. Calcium carbonate minerals are the building blocks for the skeletons and shells of many marine organisms. In areas where most life now congregates in the ocean, the seawater is supersaturated with respect to calcium carbonate minerals. This means there are abundant building blocks for calcifying organisms to build their skeletons and shells. However, continued ocean acidification is causing many parts of the ocean to become undersaturated with these minerals, which is likely to affect the ability of some organisms to produce and maintain their shells.



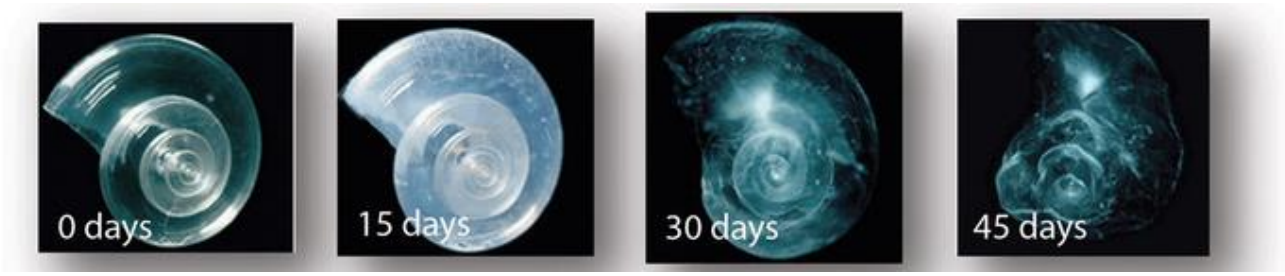
Pteropod Limacina Helicina.

Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units. Since the pH scale, like the Richter scale, is logarithmic, this change represents approximately a 30 percent increase in acidity. Future predictions indicate that the oceans will continue to absorb carbon dioxide, further increasing ocean acidity. Estimates of future carbon dioxide levels, based on business as usual emission scenarios, indicate that by the end of this century the surface waters of the ocean could have acidity levels nearly 150 percent higher, resulting in a pH that the oceans haven't experienced for more than 20 million years.

The Biological Impacts

Ocean acidification is expected to impact ocean species to varying degrees. Photosynthetic algae and seagrasses may benefit from higher CO_2 conditions in the ocean, as they require CO_2 to live just like plants on land. On the other hand, studies have shown that lower environmental calcium carbonate saturation states can have a dramatic effect on some calcifying species, including oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. Today, more than a billion people worldwide rely on food from the ocean as their primary source of protein. Thus, both jobs and food security in the U.S. and around the world depend on the fish and shellfish in our oceans.

Pteropods
The pteropod, or "sea butterfly", is a tiny sea creature about the size of a small pea. Pteropods are eaten by organisms ranging in size from tiny krill to whales and are a food source for North Pacific juvenile salmon. The photos below show that a pteropod's shell dissolves over 45 days when placed in sea water with pH and carbonate levels projected for the year 2100.



pH

Shellfish
In recent years, there have been near total failures of developing oysters in both aquaculture facilities and natural ecosystems on the West Coast. These larval oyster failures appear to be correlated with naturally occurring upwelling events that bring low pH waters undersaturated in aragonite as well as other water quality changes to nearshore environments. Lower pH values occur naturally on the West Coast during upwelling events, but a recent observations indicate that anthropogenic CO_2 is contributing to seasonal undersaturation. Low pH may be a factor in the current oyster reproductive failure; however, more research is needed to disentangle potential acidification effects from other risk factors, such as episodic freshwater inflow, pathogen increases, or low dissolved oxygen.

Photo: Freshly harvested oysters from Yaquina Bay, Oregon (Credit: NOAA)

It is premature to conclude that acidification is responsible for the recent oyster failures, but acidification is a potential factor in the current crisis to this $100 million a year industry, prompting new collaborations and accelerated research on ocean acidification and potential biological impacts.

Coral
Many marine organisms that produce calcium carbonate shells or skeletons are negatively impacted by increasing CO_2 levels and decreasing pH in seawater. For example, increasing ocean acidification has been shown to significantly reduce the ability of reef-building corals to produce their skeletons. In a recent paper, coral biologists reported that ocean acidification could compromise the successful fertilization, larval settlement, and survivorship of Elkhorn coral, an endangered species. These research results suggest that ocean acidification could severely impact the ability of coral reefs to recover from disturbance. Other research indicates that, by the end of this century, coral reefs may erode faster than they can be rebuilt. This could compromise the long-term viability of these ecosystems and perhaps impact the estimated one million species that depend on coral reef habitat.

Ocean acidification is an emerging global problem. Over the last decade, there has been much focus in the ocean science community on studying the potential impacts of ocean acidification. Since sustained efforts to monitor ocean acidification worldwide are only beginning, it is currently impossible to predict exactly how ocean acidification impacts will cascade throughout the marine food chain and affect the overall structure of marine ecosystems. With the pace of ocean acidification accelerating, scientists, resource managers, and policymakers recognize the urgent need to strengthen the science as a basis for sound decision making and action.

The Socioeconomic Costs of Ocean Acidification
Seawater's lower pH will affect food supplies, pocketbooks, and lifestyles
By Cherie Winner
https://www.whoi.edu/oceanus/feature/the-socioeconomic-costs-of-ocean-acidification

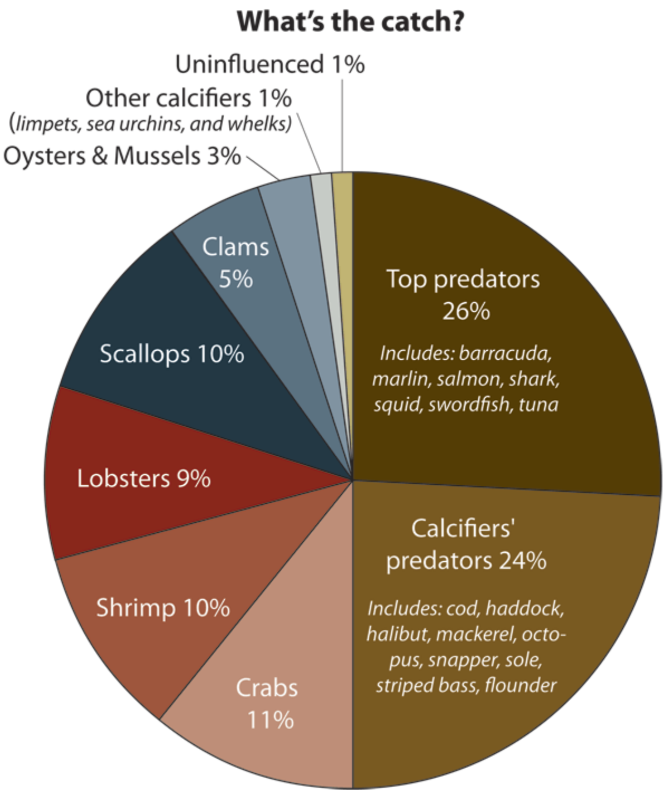
The increasing acidification of the oceans is measured in pH units, but its impacts on people will be measured in dollar signs, says Sarah Cooley. Commercial and recreational fishing, tourism, the protection of shorelines by coral reefs—all could be harmed by ocean acidification that is already well under way. Not to mention the hard-to-quantify-but-significant cultural and lifestyle changes that communities will have to make to adapt to changing marine ecosystems. In other words, ocean acidification is not just a problem for corals and other marine life. It has the potential to change the way humans feed themselves, earn their livings, run their communities, and live their lives.“What goes around comes around,” said Cooley, a postdoctoral researcher at Woods Hole Oceanographic Institution (WHOI). “Ocean acidification is definitely an anthropogenic problem [resulting from human activities] but it will come back and influence human communities.” A marine chemist by training, Cooley sought a way after graduate school to apply her scientific know-how to socioeconomic problems. Working with WHOI marine chemist Scott Doney and Hauke Kite-Powell from the WHOI Marine Policy Center, she is trying to predict what ocean acidification will do to the marine resources that people living in New England, or western Africa, or island nations depend on, and she is looking toward what we can do to prepare for those changes and perhaps mitigate the worst of them. “We’re working on ways to put a dollar value on the potential losses that could occur due to ocean acidification, so we can go to policy-makers and say, ‘It’s going to cost X many dollars in lost jobs and lost fishing revenues, but if we do Y money’s worth of planning now, we’ll be in good shape,' ” she said.

Shell game
Like climate change, ocean acidification is a global problem that results from the enormous increase of carbon dioxide, or CO_2, released into the atmosphere, primarily from burning fossil fuels. Although ocean acidification and global warming stem from the same source, they are different problems, said Cooley; acidification is a matter of simple chemical reactions that have been understood for more than 100 years. Excess CO_2 in the air dissolves in seawater and forms carbonic acid and, through a series of other reactions, reduces the amount of carbonate in seawater.That is bad news for many of the so-called calcifying sea creatures that use carbonate and calcium to build their shells or skeletons. “The waters are becoming less and less welcoming for shelled organisms,” Cooley said. Experiments done at WHOI and elsewhere show that in seawater containing high levels of CO_2,corals have difficulty making new skeleton and may have existing skeleton dissolve away; many calcifying plankton struggle; mollusks such as oysters and scallops find it harder to build and maintain shells; and juvenile mollusks grow more slowly and have more abnormalities and lower survival rates. Among calcifying organisms, only crustaceans such as crabs and lobsters appear to tolerate low carbonate levels; some even make thicker exoskeletons under such conditions. On the whole, though, more acidic seas and lower carbonate levels could spell trouble for hundreds of species, the ecosystems they belong to—and the human communities that depend on them.

'Not just a dollar thing'
In a paper in the December 2009 issue of Oceanography, Cooley and her coauthors described how ocean acidification could endanger some “ecosystem services”—the benefits to human societies provided by healthy ecosystems. Coral reefs, for instance, bring tourism income, protect shorelines from erosion, and provide habitat for fish that may be the main source of protein for local people. Trying to put a dollar value on the benefits provided by coral reefs is difficult, said Cooley. “If my property doesn’t get destroyed by storms because the reef is there, does that save the entire property value? How do I count it over time? Do I amortize it? It’s a squishy thing to value.” Squishy or not, one thing is certain: The figure is very, very high. Cooley found that the worldwide value of shoreline protection by coral reefs has been estimated at $9 billion a year; shoreline protection plus reef-supported fisheries was valued at $30 billion a year. For island nations, the exact figure could be less important than the proportion of the economy that depends on the reefs. In 2006, direct income from coral reef tourism provided 15 percent of the gross domestic product of the Caribbean island of Tobago. Add indirect income—“dinners tourists ate, trinkets they bought, umbrella drinks they bought”—and the total comes to 30 percent of the GDP. “Without that [reef tourism], the economy of Tobago would be one-third smaller,” Cooley said. “And how many people would be out of work?” Healthy reefs and mollusk populations also are a key element in the cultures of many island and maritime societies. “Quality of life is not just a dollar thing,” Cooley said. “Even if we can’t put this into an equation, there’s still an intrinsic value that we need to preserve. “Think about coming to Cape Cod. You go into every gift shop, and there’s the little shell-related doodads. If [in the worst-case scenario] there’s no more scallops because they’ve all been acidified, well then there are no more shell-related doodads, and we will have lost something on the Cape.”

People, protein, and pressures

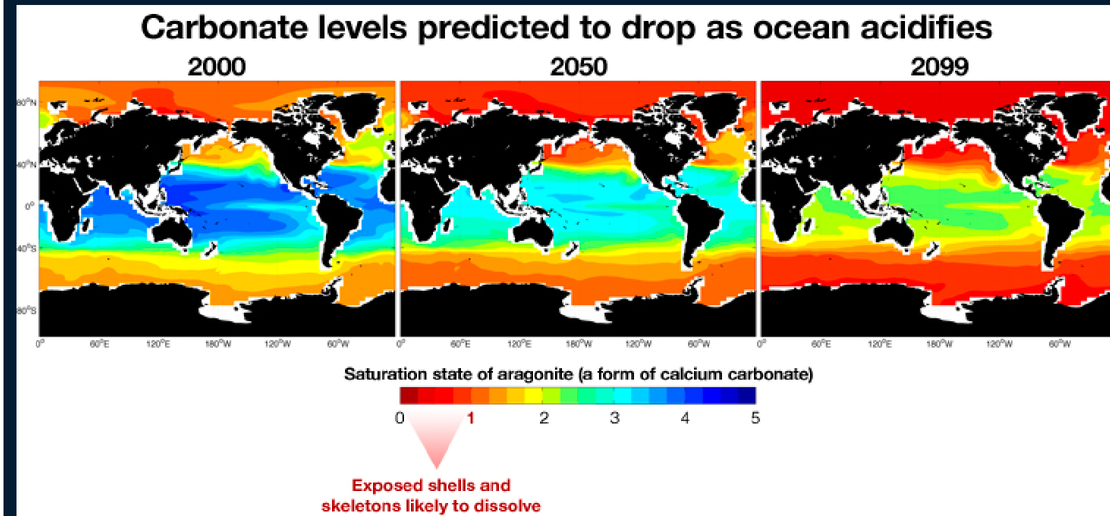
Cooley found that ocean acidification's likely impacts on the seafood industry are easier to predict. According to the Food and Agriculture Organization of the United Nations, the first-sale value of ocean fisheries worldwide was more than $91 billion; aquaculture of marine organisms generated another $79 billion. Although the oceans are global, ocean acidification isn't uniform, and its effects are not the same everywhere and on every species. Fisheries that depend heavily on mollusks, such as those in New England, would likely be hit harder. Fisheries in Hawaii and Alaska should be less vulnerable, because mollusks make up a tiny fraction of the catch there. Then again, Cooley said, the finfish catch may also decline, because many of the fish we like to eat, such as haddock, halibut, herring, flounder, and cod, depend heavily on mollusks for their own nourishment. Even top predators, the animals that eat the haddock, herring, and cod, could be affected. Swordfish, tuna, shark, and salmon are on that list.



In 2007, first-sale revenues from U.S. commercial fisheries totaled about $4 billion. Four groups of animals contributed almost equally to that total. Two groups are calcifiers, which means they make shells, spines, or exoskeletons out of calcium carbonate: crustaceans (lobsters, crabs, shrimp) and mollusks (clams, oysters, mussels, scallops, and other non-crustacean calcifiers). The other two groups are animals that prey on calcifiers (such as flounder and octopus) and top predators that eat the calcifiers' predators (such as salmon and tuna). Of these groups, the mollusks appear most vulnerable to direct effects of ocean acidification. But a decline in those species could cause problems for predators above them on the food chain.

Cooley said ocean acidification might be especially harmful to island nations and parts of the developing world where seafood is a major source of protein. Established models show that carbonate will become increasingly scarce in the oceans over the next 90 years, squeezing most calcifying organisms into a shrinking zone of tropical waters where carbonate levels will be highest (though still much lower than today's levels). Working with estimates of human population growth and food needs, Cooley determined that tropical regions will come under simultaneous stresses from ocean acidification and increasing demand for dietary protein. These stresses occur in combination with other environmental pressures, such as temperature rise, watershed changes, and pollution. "We're layering pressure upon pressure, and as a result, in 20 years or 30 years—within our kids' lifetime—things are not going to be the same anymore," said Cooley. In particular, "more people may be going hungry."

Images: The Socioeconomic Costs of Ocean Acidification



Model-calculated aragonite saturation states throughout the surface ocean in 2000, 2050, and 2099. Aragonite is a form of calcium carbonate often used by calcifying organisms to create shells and skeletons. Saturation state measures the amount of calcium and carbonate, the mineral building blocks of aragonite, present in the water. In areas where the aragonite saturation state is below 1 (shades of red), most exposed aragonite structures will dissolve. However, the growth of calcifying organisms may decrease with declining saturation state, even if it remains above 1. This model predicts that as ocean acidification continues over the next 90 years, surface aragonite saturation states will drop throughout the global oceans. By 2099, only tropical and subtropical waters may have saturation levels high enough to support the growth of calcifying organisms such as some mollusks, crustaceans, and corals.
Surface values were calculated with the Community Climate System Model 3.1 of the National Center for Atmospheric Research.
(Richard A. Feely, Scott C. Doney, and Sarah R. Cooley, 2009, *Oceanography* 22:36-47)

Coping with the changes

Ocean acidification won't lead to empty oceans, Cooley said. Some animals will tolerate higher acidity; some may even thrive on it. But there will probably be fewer species overall, and the mix of species in a given locale will almost certainly change. Already, along the coast of Washington state, upwelling currents have brought more acidic water from offshore into near-shore areas and are suspected to have contributed to a drop in shellfish hatchery yields. At the same time, in a nearby coastal area, a pH decrease of about half a pH unit was associated with a shift from a thriving community dominated by mussels and calcifying algae to one dominated by seagrasses, non-calcifying algae, and invertebrate species that don't make shells—and that humans don't like to eat. Similar changes have been observed elsewhere. "The world is probably going to march on without these species, but it might be darn uncomfortable" for us, forcing our economic and cultural systems to change, she said. "The [natural] communities are going to be very, very different. And different might be OK—maybe. There still is an ecosystem to be had. But a lot of the things that we really enjoy, that our communities depend on, are not going to be there. We may be able to find other awesome things about the new communities, but chances are, the options will be limited."

The only long-term remedy for ocean acidification is to reduce the amount of CO_2 we discharge into the atmosphere. That will involve the same sorts of actions touted to combat climate change: conserve energy, use renewable energy sources, and so forth. But, Cooley said, even if we were to end CO_2 emissions tomorrow, there is so much already in the atmosphere that the oceans would continue to acidify for centuries to come. In other words, we have no choice but to deal with ocean acidification. "We need to make adaptations first, as we look toward [longer-term] solutions," Cooley said. One example, she said, is establishing and maintaining marine protected areas that provide refuges for species that might be under a number of stresses. Another is to shift from single-species to ecosystem fisheries management strategies—for example, to focus less exclusively on managing one species, such as cod, and instead consider the many factors, such as weather, human-caused pressures, and interactions with other organisms that affect the ecosystem where the cod live. Aquaculture operations, which could become a major source of protein for human communities, could begin cultivating species that are fairly resistant to ocean acidification; or they could join forces to adjust the pH of ocean water brought into their facilities. "I think it's feasible if several aquaculturists were to get together now and think, 'OK, in the next 10 years we want to do a larger facility that treats incoming water before we rear the young. That's going to be a better use of our resources than competing individually and some of us going out of business,' " Cooley said.

Global problem, regional answers

And when people are put out of work by ocean acidification and other pressures on ocean ecosystems, said Cooley, “we need to have community measures in place to retrain them and help them move into [jobs] that are equally valuable for themselves and the community." If a person who has lost his maritime job "is flipping burgers or greeting people at a big-box store, is he going to be a happy guy? No, because he went into fishing as a career because he loved the water and he loved doing that. And some kind of dramatic shift from what his traditional role has been may not be all that satisfying to him.” Any proposed strategies will have to be regional, because impacts from ocean acidification are regional, said Cooley. Policy-makers and communities in each locale will have to ask, “How are we going to manage our fisheries in the face of this additional pressure? There’s definitely no one-size-fits-all answer, unfortunately.” Cooley said she’s glad communities and policy-makers are starting to think about ocean acidification. “Our ultimate goal is to talk to people about ocean acidification and how it might affect their endeavors,” she said. “One of the best currencies to do that, no pun intended, is economics. Because people always want to know when their interests are at stake.”

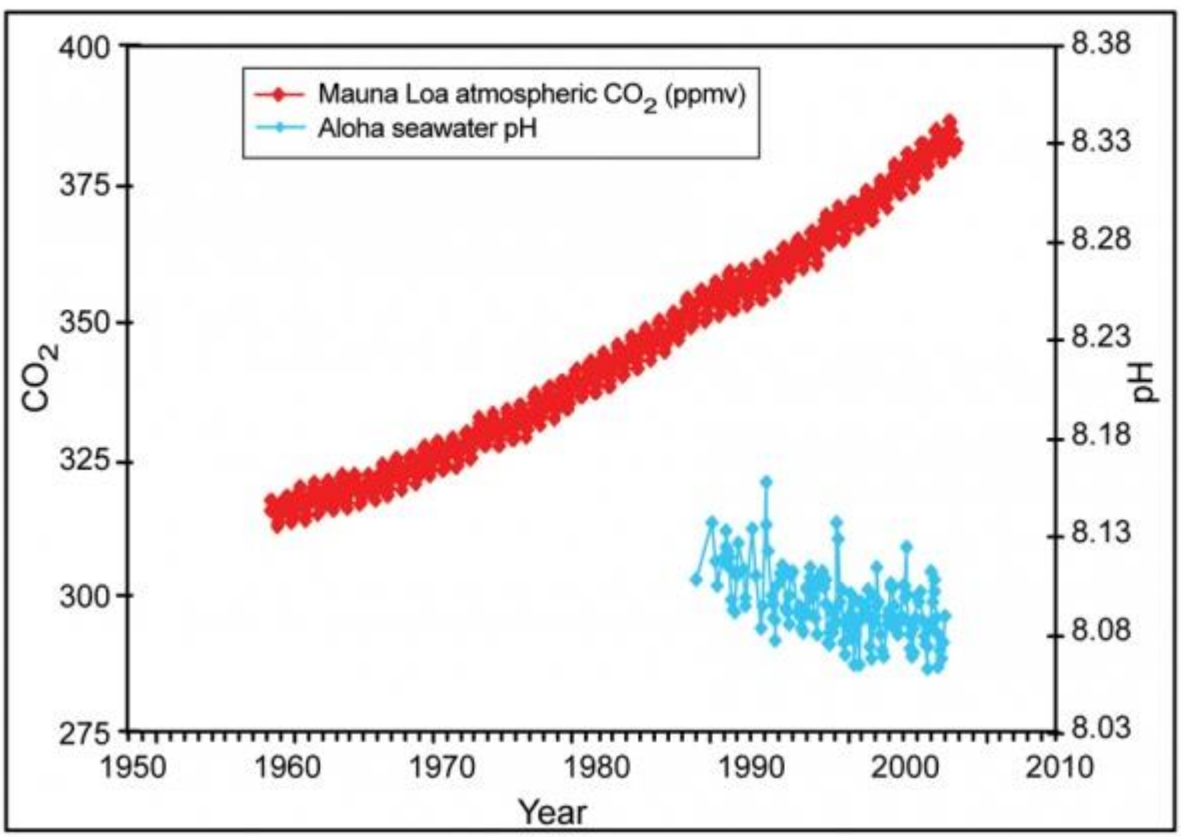
Ocean Acidification Data

Oceans absorb atmospheric carbon dioxide. The table below depicts changes to ocean chemistry and pH estimated using scientific models calculated from surface ocean measurement data.

	Preindustrial (1750)	Today (2013)	Projected (2100)
Atmospheric concentration of CO_2	280 ppm	380 ppm	560 ppm
Carbonic acid, H_2CO_3 (mol/kg)	9	13	19
Bicarbonate ion, HCO^{3-} (mol/kg)	1,768	1,867	1,976
Carbonate ion, CO_3^{2-} (mol/kg)	225	185	141
Average pH of surface oceans	8.18	8.07	7.92
Calcite saturation	5.3	4.4	3.3
Aragonite saturation	3.4	2.8	2.1

Ocean Acidification in the North Pacific

Time series of atmospheric CO_2 at Mauna Loa (ppmv) and surface ocean pH at Station ALOHA in the subtropical North Pacific Ocean. Note the overall decrease in surface water pH caused by dissolution of atmospheric CO_2 into the surface ocean.
Credit: R.A. Feely, NOAA/Pacific Marine Environmental Laboratory.
https://www.globalchange.gov/browse/multimedia/ocean-acidification-north-pacific



Document-Based Questions:
Read through the articles and information provided and answer the following questions on a separate piece of paper.

(1) The primary source of carbon dioxide in the atmosphere is burning of _____________ _____________.
Preindustrial carbon dioxide was measured about ______ ppm, current levels are about ______ ppm, and projected levels (for 2100) are estimated to be about ______ ppm.

(2) Increasing levels of carbon dioxide in the atmosphere have caused _____________ (increased or decreased?) levels of dissolved carbon dioxide in the ocean along which has resulted in _____________ (increased or decreased?) pH. This has caused a(n)_____________ (increase or decrease?) in the saturation state of carbonate minerals including _____________ and _____________.

(3) By how many pH units has the ocean pH changed by since the beginning of the industrial revolution?
By what percent has acidity changed?
By what percent is acidity projected to change (by the end of the century)?

(4) Give two examples of marine organisms that benefit from increased carbon dioxide levels. Explain.

(5) Calcifying organisms or “calcifers” depend on calcium carbonate minerals to build their _____________ or _____________.
Give three examples of calcifying organisms.
What types of calcifying organisms are better able to tolerate low carbonate levels?

(6) What happens to the shells of pteropods over time when exposed to sea water with pH and carbonate at projected levels for 2100? Give three examples of organisms that rely on pteropods as a food source.

(7) Even though top predators (like sharks or tuna) and finfish (like halibut and cod) are not directly affected by the saturation levels of carbonate, how are they being impacted?
By the end of the century, what locations are predicted to be the only places that will have sufficient saturation levels to support calcifying organisms?

(8) Give three ways that coral reefs are beneficial.
By the end of this century, what problem could coral reefs face?
What does this imply for their future?

(9) Name the two main industries impacted by ocean acidification.
Describe how each could be affected.

(10) What is one suggestion to fight ocean acidification?