OCEANA Protecting the World's Oceans
www.oceana.org

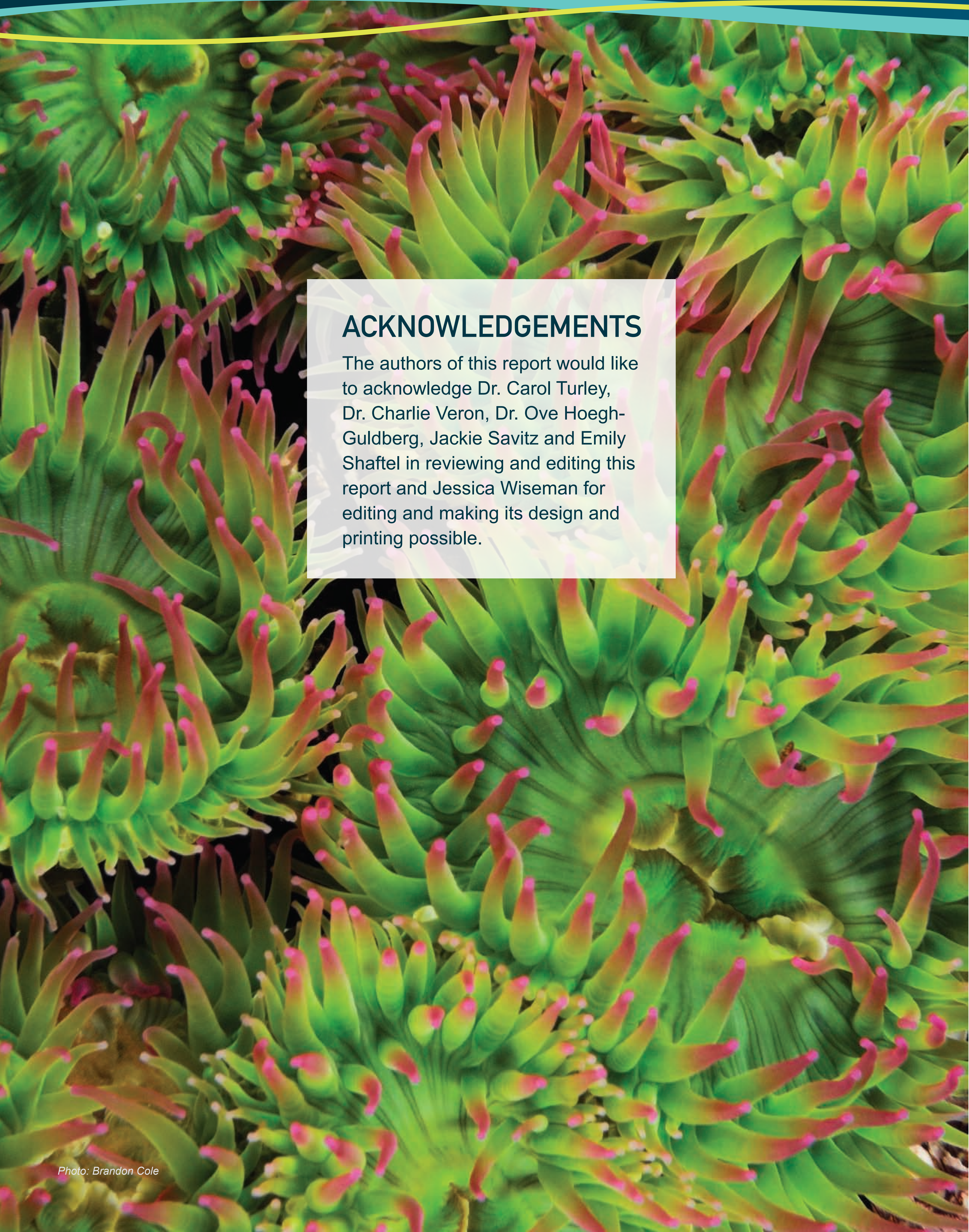
Photo: Brandon Cole

OCEAN ACIDIFICATION

THE UNTOLD STORIES

Ellycia Harrould-Kolieb, Matthew Huelsenbeck and Virginia Selz

November 2010



ACKNOWLEDGEMENTS

The authors of this report would like to acknowledge Dr. Carol Turley, Dr. Charlie Veron, Dr. Ove Hoegh-Guldberg, Jackie Savitz and Emily Shaftel in reviewing and editing this report and Jessica Wiseman for editing and making its design and printing possible.

Photo: Brandon Cole

TABLE OF CONTENTS

INTRODUCTION

Our use of fossil fuels, deforestation and land use changes are wreaking havoc on the oceans. Besides causing global climate change, which could cause catastrophic impacts around the world, the release of carbon dioxide from these activities is also leading to ocean acidification. The oceans ultimately absorb most carbon dioxide from the atmosphere, and thus play a critical role in regulating climate. They also help to mitigate human caused climate change. But the unprecedented amount of carbon dioxide being created by human activity has surpassed what the oceans can healthfully absorb, changing ocean chemistry and making them more acidic.[1]

Acidity is measured on a pH scale, where lower pH indicates more acidic water. Ocean pH has dropped by thirty percent globally during the last two hundred years.[2] Even though the drop in pH appears small (from 8.2 to 8.1),[3] the pH scale is logarithmic, meaning that this change is large enough that it may already be beginning to affect some of the oceans most beloved and biologically important residents, including corals.[4]

The changing acidity of the oceans threatens to throw off the delicate chemical balance upon which marine life depends for survival. The scant attention this issue has received has focused primarily on corals, which are threatened with extinction within this century unless we change course. Corals are the framework builders of reefs, by far the most diverse ecosystems of our oceans. However, the effects of acidification are not going to stop with reefs, like dominoes, the impacts are going to be far-reaching throughout the oceans.

The increased acidity in the oceans is expected to lead to a shortage of carbonate, a key building block that some animals (and plants) need to build their shells and skeletons. Besides corals, other animals that use carbonate to build and strengthen their shells (called calcifiers) may also suffer. These animals include shellfish like clams, oysters, crabs, and lobsters.

But the problem is not just about carbonate. Marine life ranging from the smallest plankton to the largest whale may be affected by ocean acidification, with direct and indirect impacts. Direct effects on the physiology of animals and plants may result from a lack of available carbonate needed to build and strengthen shells and skeletons. Within this century, increasing acidity may reduce the ability of certain fish to breathe, and increase the growth rates of some sea stars. In addition, it is likely to inhibit some fish from smelling cues that direct them to suitable habitat or away from predators, and divert energy away from important survival tasks of many species. Indirect effects may occur due to loss of habitat, changes in food availability or the abundance of predator populations. These direct and indirect impacts could all result in animals becoming less fit to survive which could lead to population level consequences and ripple effects throughout marine ecosystems.

pH is important to all living things and changes in internal pH can compromise an animal's health or even kill it. Marine plants and animals must maintain their internal pH relative to that of the surrounding seawater. Some have complex systems that regulate internal pH, preventing it from becoming dangerously acidic or basic. Other species without these systems are more heavily influenced by their surrounding environment and can be quickly threatened by changes in acidity.

Some marine species, such as fish, were once considered immune to the effects of ocean acidification because of their complex buffering capabilities. However, research is showing that even some marine fishes are likely to become overwhelmed by rising ocean acidity. If we allow ocean acidification to continue unabated we risk having the oceans become far less vibrant and dynamic. The future oceans under more acidic conditions will not be like the oceans of today.

It is clear that ocean acidification poses a serious threat to marine life and to the ocean-derived goods and services that we depend on. The only way to prevent these potentially catastrophic changes from taking place, including large losses of coral reefs and the animals that depend on them, is to drastically reduce our carbon dioxide emissions. Our actions over the next few years will determine how acidic the oceans will become. Without any changes the oceans are expected to become more acidic in the coming decades than at any time in at least the last 20 million years.[5] The speed at which we are changing ocean acidity is unprecedented. This is highly concerning because most marine organisms living today have never adjusted to such rapid changes in pH.[6] Luckily, this does not have to be the oceans' fate. We must reduce the risk of catastrophe by quickly and comprehensively reducing our carbon dioxide emissions.

Photo: Brandon Cole

IMPACTS MAY ALREADY BE OCCURRING

Pacific Oyster Farms Fail

Shellfish farmers may already be feeling the devastating impacts of ocean acidification on their livelihood, as they have been experiencing difficulties raising oyster larvae since 2005. This is likely due at least in part to more acidic conditions along the U.S. Pacific Coast.[7] These losses are reportedly having drastic consequences for the 111 million dollar oyster industry of the West Coast.[8]

Other mollusks, including mussels, scallops and clams, also appear to be extremely vulnerable to increasing acidity. These animals all create calcium carbonate shells to protect their soft bodies from predators, disease and harsh ocean conditions. Mollusks create their shells out of a highly soluble form of calcium carbonate. Severe declines in shell growth rate are likely by the end of this century.[9]

Slower shell growth is likely to reduce the ability of mollusks to survive, which would have significant impacts on commercial fisheries. One study suggests that if this slowed growth predicted for 2100 had occurred in 2006, mollusk fisheries would have lost between 75-187 million dollars.[10] This prediction is likely to be an underestimate since it does not take into account other negative impacts of rising acidity, such as reduced reproductive success and larval survival.

Corals Show Decreased Growth

Coral reefs are very important to many coastal communities and national economies, and they too have started to show signs of decline that may be due to ocean acidification. Some of the largest reef-building corals on the Great Barrier Reef are showing more than fourteen percent reductions in skeletal growth since 1990, the largest decrease in growth rate in the last 400 years.[11] Declines in growth rate could result in a mass die-off of tropical coral reefs by the middle to end of this century.[12,13]

Some 500 million people worldwide depend on reefs for coastal protection, food and income.[14] Economists value reefs at between 30 to 172 billion dollars per year.[15] Healthy reefs provide goods and services to society, including fisheries, coastal protection, tourism, education and aesthetic values. In Hawaii alone, coral reefs annually generate some 364 million dollars through tourism.[16] If reefs collapse because of rising acidity, global warming and other threats, coastal communities will bear the brunt of these losses. Serious health consequences could ensue for the estimated 30 million people who rely almost solely on coral reef ecosystems for protein and protection.[17] The potential losses from a decline in coral reefs will be felt from the smallest coastal subsistence communities all the way up through the global economy.

Top Photo: Elizabeth McIntyre
Bottom Photo: David Burdick

Photo: David Burdick

> “This is not something that’s off in the future. This is not something for our children’s children. It’s happening now.”
>
> *– Dr. Christopher Sabine,*
> *NOAA Pacific Marine Environmental Laboratory*

> “It perplexes me that we are still, as a country, and really, globally, denying that there is something going on. I don’t have the background in the natural sciences to tell you it’s one thing or the other. I can just say that over the last 10 years it’s clear to me…something’s changing. There’s no doubt in my mind.”
>
> *– Brian Sheldon, owner of Northern Oyster Co.,*
> *Willapa Bay, Washington*

CORAL REEF HABITAT LOSS

Coral Reefs

Coral reefs are probably home to at least a quarter of the entire biological diversity of the oceans, a seemingly limitless number of species, and serve as some of the most beautiful habitats in the world. Although they cover just over one percent of the world's continental shelves, coral reefs serve as important habitat to as many as one to three million species, including more than twenty-five percent of all marine fish species.[18] These millions of species feed, reproduce, shelter larvae and take refuge from predators in the vast three-dimensional framework offered by coral reefs.[19]

By the middle of this century, if carbon dioxide emissions continue unabated, coral reefs could be eroding through natural processes faster than they can grow their skeletons due to the combined pressures of increasing acidity and global warming.[20] Reefs may become nothing more than eroded rock platforms, greatly changed from the structures that so many species rely upon for habitat.[21] Corals face severe declines and even extinction,[22] which will in turn threaten the survival of reef dependent species.[23,24]

> **"These organisms [corals] are central to the formation and function of ecosystems and food webs, and precipitous changes in the biodiversity and productivity of the world's oceans may be imminent."**
>
> *– Dr. Glenn De'ath and colleagues, Australian Institute of Marine Science in Townsville*

Photo: Brandon Cole

Fish

As many as four thousand species of fish depend on coral reefs for habitat.[25] Some of these fish, such as butterfly fish, feed exclusively on the coral itself. Other species of fish also depend on coral reefs as sources of food, shelter and nurseries. Loss of coral reef-dependent fish can be expected as reef habitats become less available.[26]

Extensive die-offs of coral due to bleaching events can serve as an example of how interrelated coral reef fish are with their coral habitats. After one event in Papua New Guinea, 75 percent of the coral reef fish species declined in abundance and several species even went extinct.[27] Unfortunately, these examples give us a clue about what we might expect in the future as reefs begin to disappear due to rising ocean acidity.

Sea Turtles

Sea turtles are some of the most endangered marine animals and are often found resting and feeding within coral reefs. They like to feed on reef species such as sponges, mollusks, algae and soft corals.[28] Declines in coral reefs could impact turtle feeding behaviors and could cause them to turn to less nutritious food sources or even go hungry.

The ability for a turtle to dig a nest and successfully incubate eggs has also been connected to healthy coral reefs, as these activities are in part connected to the type and amount of sand on nesting beaches.[29] Beach sand near coral reefs is most often made up of the skeletal remains of plants and animals that live on the reef, including parts of the reefs themselves. As ocean acidification worsens the abundance of reef species will likely diminish, which could result in changes to the type and amount of sand reaching nearby beaches. Changes in the make up of the sands on nesting beaches could negatively impact sea turtles' ability to successfully produce new hatchlings and could reduce the population size of these already endangered species.[30]

FOOD WEB DISRUPTION

Pteropods

Pteropods, abundant, tiny swimming sea snails are sometimes referred to as the “potato chips of the sea” because of their importance as a food source for so many species. They can reach densities of thousands of individuals per cubic meter,[31] and are particularly important in the polar and sub-polar food webs and serve as an important part of the diets of zooplankton,[32] salmon,[33] herring,[34] birds[35] and baleen whales.[36] Pteropods build calcium carbonate shells, a process that is particularly vulnerable to increasing ocean acidity. As early as the year 2050, pteropods may be unable to form these shells, threatening their ability to survive.[37] If they cannot adapt to living in more acidic waters, their populations will plummet,[38] which could result in ripple effects throughout the food webs that depend on them.

Salmon

The high-latitude seas are home to some of the most lucrative fisheries on the planet, fisheries that are heavily dependent upon pteropods and other marine calcifiers for food. Some areas of the Arctic Ocean are already experiencing corrosive conditions that within the decade could be more common throughout the high-latitude waters of both the North and South. By the end of this century surface waters of the Arctic and Southern Oceans and parts of the Northern Pacific will be corrosive to marine calcifiers,[39] with obvious cascading effects for the fisheries that rely on them.

North Pacific salmon depend heavily upon pteropods for food. In fact, pteropods can make up 45 percent of the diet of juvenile pink salmon.[40] The North Pacific salmon fisheries provided three billion dollars worth of personal income to fishermen and others in 2007, and supported 35 thousand jobs in just the harvesting and processing of the fish.[41] Other commercially important fish species that eat pteropods include mackerel, herring and cod—all of which could risk collapse if pteropod populations decline.[42,43]

Background Photos: Brandon Cole
Inset Photo: NOAA

> "Ocean acidification really scares me, because the effects could hit us in our lifetime and the potential disruption to the marine food chain would be catastrophic."
>
> *– Dr. Bob Rheault, president of the East Coast Shellfish Growers Association*

Killer Whales

One of the most devastating impacts of rising ocean acidity could be the collapse of food webs. Declines in the smallest of species, like pteropods and other plankton, could reverberate throughout the oceans, ultimately impacting the largest marine species. The Chukchi and Northern Bering Seas are some of the richest fishing grounds in the oceans and are home to predators as varied as gray whales, seals, sea ducks and walruses that all depend on marine calcifiers for food.[44] By the end of this century parts of these seas will be inhospitable to many shell-making organisms,[45] which could result in food web collapse.

For example, resident killer whales in the North Pacific prefer to eat salmon, in fact 96% of some killer whales diet is made up of salmon.[46] When the base of the food web disappears, the effects can travel all the way to the top. If predators are unable to supplement their diets with other food sources, food webs may even collapse entirely. Top predators like the emblematic killer whale could suffer, which in turn could have further implications. This iconic species and important tourist attraction could be threatened by cascading impacts from the loss of pteropods.

ACIDIFICATION MAY AFFECT SHELLFISH

Sea Urchins

Sea urchins are found in various environments, from coral reefs to rocky coasts, and are crucial grazers in any environment. Sea urchins on a reef help to protect the reef by eating some of the algae that might otherwise encroach on corals and displace them from the reef.[47] Sea urchins are also the target of a lucrative fishery that brought in nearly six million dollars in revenue for the state of Maine in 2009.[48]

Sea urchins reproduce by releasing eggs and sperm directly into the surrounding seawater. Under acidified conditions the sperm of some sea urchins swim more slowly,[49] which reduces their chances of finding and fertilizing an egg, forming an embryo and developing into sea urchin larvae.[50,51] Even under normal conditions, only a small percentage of sperm are able to locate and fertilize the eggs. The majority of sea urchin embryos and larvae are eaten by fish and only a few survivors mature into adults. To make up for this low success rate, sea urchins normally release millions of eggs and sperm into the surrounding water. However, the more acidic conditions predicted for the end of this century could reduce the number of sperm certain species release,[52] thereby further decreasing the size of the next generation of sea urchins.

Sea urchins are in the category referred to as calcifiers since they create their skeletons, called tests, out of calcium carbonate. Like many other calcifiers, such as corals,[53] pteropods,[54] and oysters,[55] sea urchins are likely to find it more difficult to build their calcium carbonate skeletons in an acidified ocean. Young sea urchins have been observed to grow slower and have thinner, smaller, misshapen protective shells when raised in acidified conditions, like those expected to exist by the year 2100.[56] Slower growth rates and deformed shells may leave urchins more vulnerable to predators and decrease their ability to survive.[57]

Photo: Brandon Cole

Lobsters

Lobsters are long-lived and are found through all the oceans of the world. Under more acidic conditions, their larvae had lighter, less dense shells, which could make them more susceptible to predation and less able to survive.[58] Declines in lobster populations may also result from losses in food sources, such as sea urchins, which are also vulnerable to increased acidity.

Lobsters and other crustaceans such as crabs periodically molt throughout their lives and grow new shells out of calcium carbonate and chitin. They use the calcium carbonate to harden their shells in a very different process than the one used by other marine calcifiers.[59] This process of calcification is very important as hard exoskeletons protect lobsters, crabs and other crustaceans from predators and disease.[60] The creation of a new shell requires a lot of energy—energy that is also needed for other functions like growing, breathing and reproducing. Increasing ocean acidity may drive some lobsters to create larger shells. The exact reason for this is unknown; however, it is likely to have negative consequences as it will almost certainly result in energy being diverted away from other activities that are vital to survival.[61]

Decreased survival of lobsters and crabs due to increased predation and abnormal shell growth could have serious implications for the economies of many local communities. In 2008, the U.S. lobster fisheries alone brought in an estimated 300 million dollars.[62] Crabs also provide an important part of the fishery for many coastal states, including Maryland, where half of the total fisheries catch is often made up of blue crabs.[63]

Photo: Brandon Cole

Brittle Stars

Brittle stars play a crucial role in their environment as burrowers and as a food source for larger predators, like flatfish.[64] Burrowing stirs up sediment and allows oxygen to mix with it, which is very important to many bottom dwelling species.[65] Brittle stars, like sea stars, have a calcium carbonate skeleton made up of many small plates held together by skin and tissue. As their name implies, brittle stars are quite fragile, but this trait is usually to their advantage. The spindly arms of a brittle star break off when the animal senses danger and, under normal conditions, can quickly regenerate.[66] However, this process is likely to be disrupted in the future as the oceans become more acidic.

Studies have shown that brittle stars can still regenerate their arms under acidic conditions but do so with less muscle mass than usual. It appears the brittle stars are sacrificing building muscle in order to create the calcium carbonate parts of their arms.[67] The brittle stars not only created insufficient amounts of muscle for their new arms to function correctly, they also devoured muscle from their already existing arms to provide energy for the now much harder process of building calcium carbonate. Muscle is essential for movement, finding food, and burrowing in sediment, which are all tasks vital to survival. Weakened arms could decrease the ability of brittle stars to survive in a more acidic ocean.[68]

Increased acidity is also likely to threaten brittle star larvae. By the middle of this century it is likely that they will have difficulty developing and many, if not all, are expected to die after exposure to acidified conditions.[69] Thus, brittle stars appear to be very vulnerable to increasing ocean acidity both as adults and larvae, which could result in severe population declines in the future.

Photo: Brandon Cole

Sea Stars

Sea stars help to maintain diversity on a reef by acting as important predators, keeping the populations of other species in check. Sea stars do not have a continuous skeleton made up of calcium carbonate, rather they have hundreds of tiny calcium carbonate plates embedded within their tissue.[70] These plates tend to make up a relatively small percentage of a sea star's total body weight. This may explain why sea stars appear to respond differently to increased ocean acidity than other marine calcifiers that have larger, more continuous calcium carbonate shells and skeletons, like corals and oysters.[71] Studies on sea stars have shown varied responses to increased acidity; for example, one study found that the purple sea star decreases calcification but increases its overall growth.[72] This increase in growth rate could lead to increased feeding rates, putting more pressure on preferred food sources (like mussels) and therefore causing population declines among mussels. As mussel populations are likely to have already declined because of ocean acidification, sea stars could be forced to switch to other food sources or suffer population declines themselves if they cannot find suitable substitutes. Increasing growth rates among sea stars could cause large changes through the ecosystems that sea stars have traditionally kept in balance.[73]

Another type of sea star, the sun star, has also been found to increase its growth rate in acidic conditions and was in fact found to perform better due to positive effects to its metabolism, which could decrease the time it takes for its larvae to develop.[74] The sun star is an important predator in its food web and influences how abundant many species are. Decreased larval development times could mean that larvae develop into juveniles earlier, but this new timing could be out of sync with the factors that the survival of juveniles are reliant upon, such as water temperature, food availability and lack of predators. Developing early could put juveniles in adverse conditions that prevent them from growing properly or surviving.[75] Ecosystems' exquisite balance is determined by the interconnectedness of many species relying upon each other's development and abundance. Small changes can put these systems out of balance, and while changes may appear advantageous in a lab setting they may be harmful in the natural environment.

Photo: Brandon Cole

ACIDIFICATION MAY AFFECT ANIMALS WITHOUT SHELLS OR SKELETONS

Squid

Squid are the fastest marine invertebrates, propelling themselves in speedy bursts at up to 25 miles an hour.[76] This form of high-energy jet propulsion consumes large amounts of oxygen which is sent to the tissues through the blood. Increased ocean acidity is likely to inhibit a squid's ability to transport such large amounts of oxygen,[77] which could impede these fast bursts and inhibit important activities like hunting and avoiding predators. This would inevitably affect a squid's ability to survive. While one study has suggested that cuttlefish, which are similar to squid, show resilience to changes in metabolism from high levels of carbon dioxide,[78] another study identified significant drops in metabolic rates and activity levels for jumbo squid.[79] Clearly more research is needed to better understand the impacts of acidification on these species.

If there were a loss of squid, or population reductions, this could be bad news for many of the commercial species that feed on it, such as king and coho salmon, lingcod and rockfish.[80] Declines in squid populations would also have drastic consequences for squid fisheries, which are very important to California where they are caught and exported all over the world. The fishery for market squid was the most profitable in California in 2008, providing 25 million dollars in revenue.[81]

Clownfish

Larvae of fish that live on coral reefs hatch on the reef and then leave their parents and migrate to the open ocean where they spend the next two to three weeks adrift. When the larvae are ready to return to their home reefs they use their sense of smell and sound to guide them back. Under present day conditions, clownfish can cleverly orient themselves to the smell of home using the scent of sea anemones or the vegetation characteristics of a reef.[82] Unfortunately, under the more acidic conditions predicted for the end of this century, larvae may not be able to discern between the smells of a suitable home and a hostile environment, which could result in their death.[83]

In addition, clownfish larvae also use their sense of smell to avoid predators. In carbon dioxide conditions expected around the end of this century, this smell-related predator defense system is disrupted and most returning clownfish larvae are no longer able to discern between predator and non-predator cues.[84] This disruption in the sense of smell may also result in riskier behaviors in clown fish and damselfish. Increased levels of carbon dioxide have been associated with these fish being more active, swimming further away from shelter and not responding to threats such as predators.[85] In studies, five to nine times more fish died because of their risky behavior than those not in acidified conditions.[86] As the oceans become more acidic, larval clownfish could not only be lost at sea, but the conditions may even cause them to swim right into the jaws of their predators.

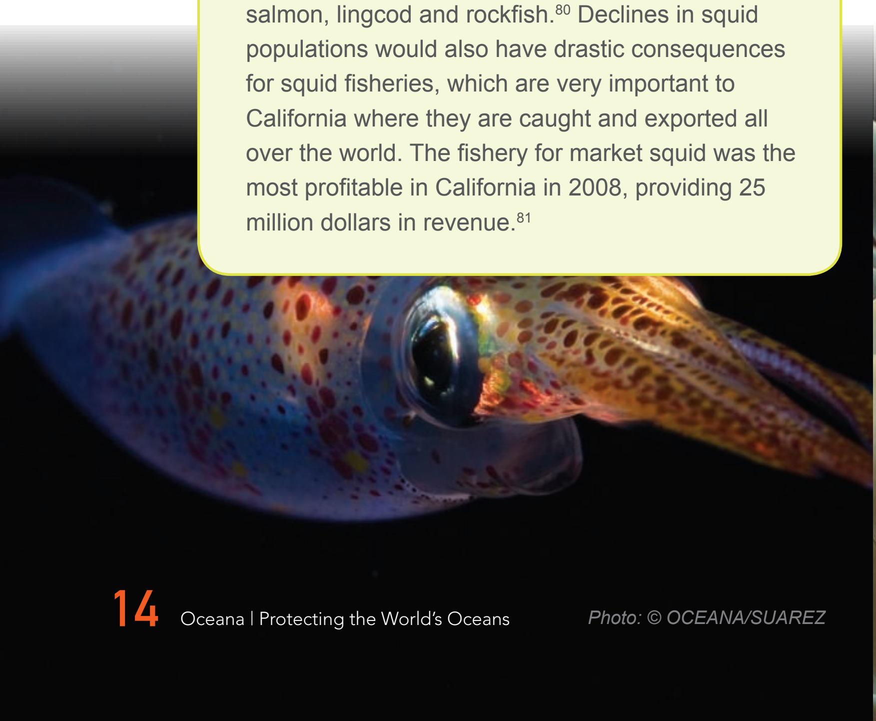


Photo: © OCEANA/SUAREZ

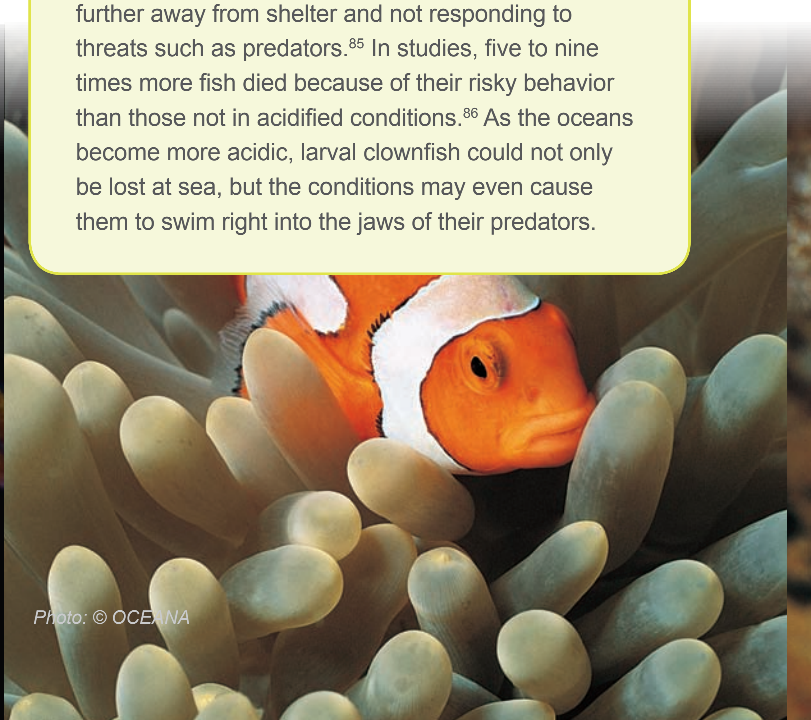


Photo: © OCEANA

> **If acidification continues unabated, the impairment of sensory ability will reduce population sustainability of many marine species, with potentially profound consequences for marine diversity.**
>
> *– Dr. Philip Munday, Australian Research Council Centre of Excellence for Coral Reef Studies*

Damselfish

In addition to smell, some reef fish like the damselfish rely on hearing to find their way back to their home reef.[87] They listen to the noises of a reef using otoliths, which are calcium carbonate structures similar to human ear bones. Using their otoliths, fish larvae can separate the low frequency sounds of breaking waves, currents, and surface winds of the open ocean from the high frequency sounds of gurgling, cracking, and snapping of a coral reef. Damselfish larvae use these distinct noises to navigate back to their home reef and away from the open ocean.[88] Carbon dioxide concentrations expected around the end of this century have been observed to alter the normal development of otoliths in the larvae of an open ocean fish, white sea bass.[89] If ocean acidification also causes malformation of otoliths in the larvae of reef fishes, such as zebrafish or damselfish, the enhanced otolith growth could make it difficult for the fish to locate appropriate reef habitats and result in population declines. Larger than normal otoliths in damselfish have been shown to decrease their ability to recognize sounds and return to a coral reef.[90] These larger otoliths may cause damselfish larvae to take longer to find the reef and even result in fewer larvae successfully returning to the reef at all.[91] Similarly, in zebrafish abnormal otolith growth has been shown to create serious disruptions in locomotion and balance.[92]

Cardinalfish

Increased levels of carbon dioxide in sea water may decrease the ability of some fish to breathe. Cardinalfish have been found to be particularly vulnerable to increasingly acidic conditions. The ability to take up oxygen decreased by as much as 47 percent in one species of cardinalfish when exposed to carbon dioxide levels similar to those expected by the end of this century.[93] Increasing amounts of carbon dioxide can cause acidification of the blood and tissue, which can lead to death.[94] The cardinalfish may have to divert energy towards mechanisms that balance their internal acidity, leaving less energy for other activities necessary for survival, such as breathing.[95] The reduced ability to breathe will likely have wide-ranging impacts on these fish, including decreased ability to feed, grow and reproduce, which could result in adverse consequences for the sustainability of cardinalfish populations.

As the acidity of the ocean increases, they are simultaneously getting warmer due to climate change. These factors, when combined, may create even more problems than either would create on its own. For example, increased temperature combined with the acidity levels expected by the end of this century proved lethal for one species of cardinalfish tested in the laboratory.[96] These results are particularly concerning, especially if they are found to apply to other marine species, since they show that while individuals might be able to survive one threat, they are less able to endure the simultaneous threats of increasing temperatures and ocean acidification.

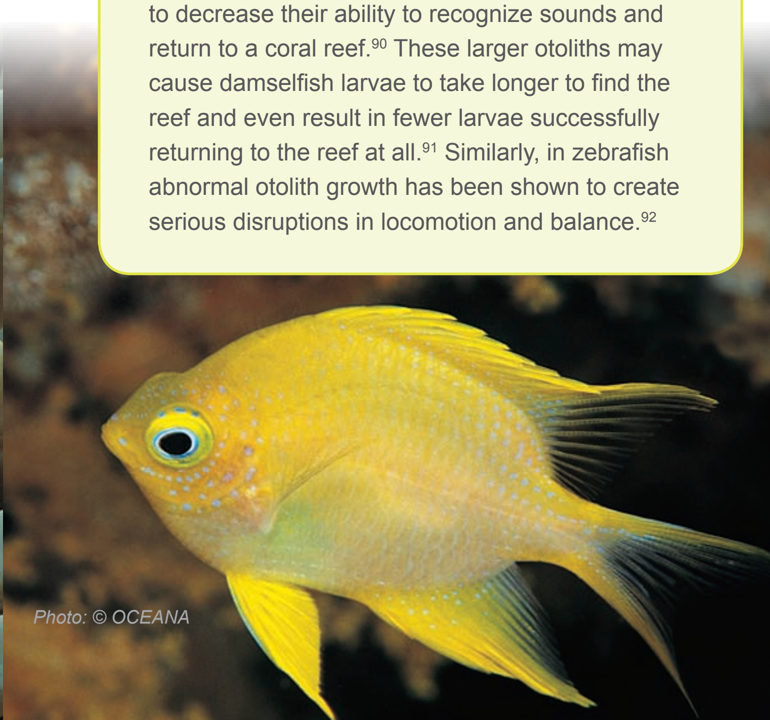


Photo: © OCEANA

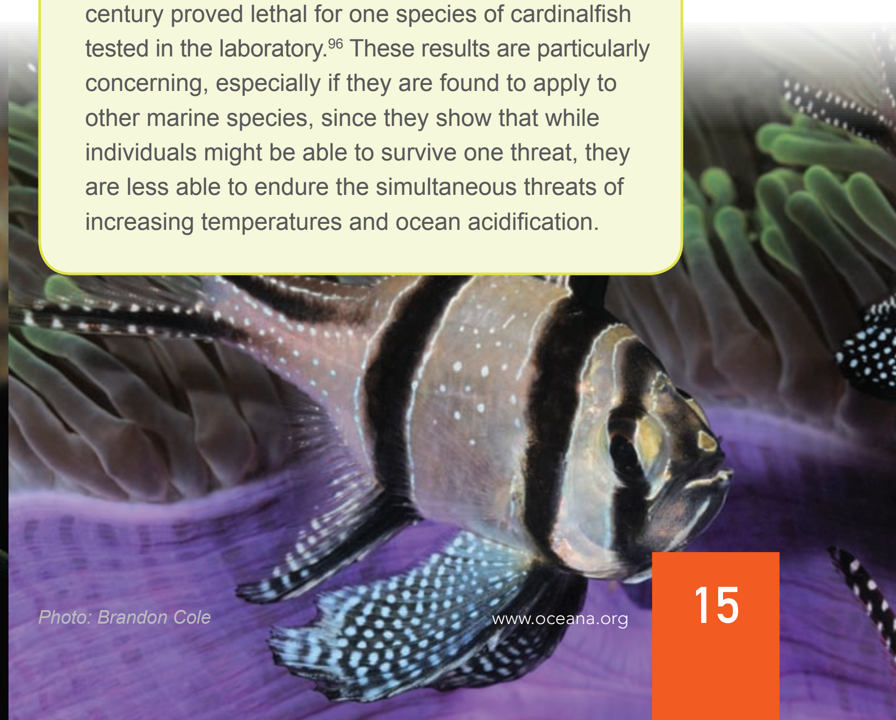


Photo: Brandon Cole

> "We're pushing the oceans back to the dawn of evolution, a half-billion years ago when the oceans were ruled by jellyfish and bacteria."
>
> *– Dr. Jeremy Jackson, Scripps Institution of Oceanography*

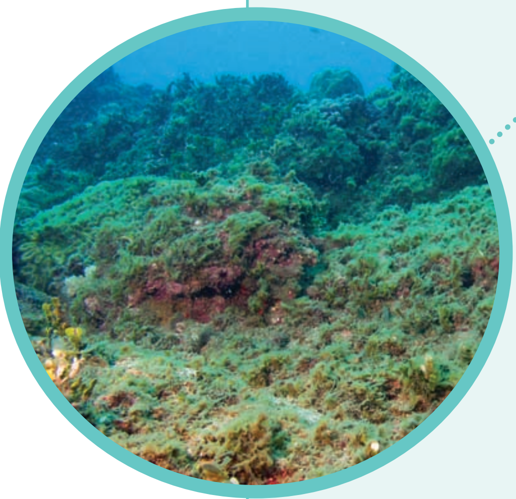
ECOLOGICAL WINNERS – ALGAE, JELLIES AND INVASIVES MAY DOMINATE

There will likely be some species that are able to flourish in an acidified ocean, either because increased carbon dioxide levels benefit them directly or because their competitors are directly harmed by it. The only problem is that the species that appear to be best suited to prosper in high-carbon dioxide conditions are those that we currently see as nuisance, or weedy species. These species are unable to provide adequate habitat and food for the species that we love, and as a result the oceans will look very different if acidification worsens.

Jellies

Jellyfish may be one of the "winners" in a more acidic ocean. It's unclear whether increasing acidity is directly related to the recent increases in jellyfish prevalence,[97] but it does appear that ocean acidification does not harm jellyfish reproduction or the formation of their internal structures, as it does for many other forms of marine life.[98] It is likely that even if acidification is not directly responsible for their recent increased prevalence, it may be creating ocean conditions that are ripe for jellyfish to flourish.

Jellyfish blooms could have disastrous impacts, especially if past disruptions from these creatures are replicated. Previous outbreaks have been responsible for decreasing commercial fish stocks due to competition and predation, as well as harboring various fish parasites.[99] In addition, they also represent a threat to beach-goers and can harm economies that depend on coastal tourism.[100]



Sea Plants

Algae and sea grasses are likely do well in an acidified ocean. These species take up carbon dioxide and sometimes directly compete with calcifiers. So as acidity increases, conditions will likely shift in their favor and they may be able to move into areas where they have not previously flourished.

Observations at natural carbon dioxide vents can give us a glimpse into what the future oceans may look like. These visions show marine communities dominated by green algae and sea grasses. One study of naturally occurring carbon dioxide vents off the coast of Italy found 30 percent lower species diversity, especially of calcifiers, close to the vents compared to the surrounding areas.[101] Some of the calcifiers near the vents had weakened and dissolving shells. The areas near the vents also had higher levels of invasive algal species, including some that are already recognized as stubborn invasives in other marine systems.[102] These vents may serve as an example of how future oceans may look after acidification sets in—our oceans may be dominated by algae and invasives.

Photos: David Burdick

Photo: David Burdick

OUR FUTURE OCEANS

We are currently conducting an uncontrolled experiment on our oceans, forcing marine species to live in unusual conditions unlike any that have existed for many millions of years. We do not know the full extent of this global experiment, but we do know that for some species the changes we are forcing on them will be too great and they will likely be pushed into extinction.

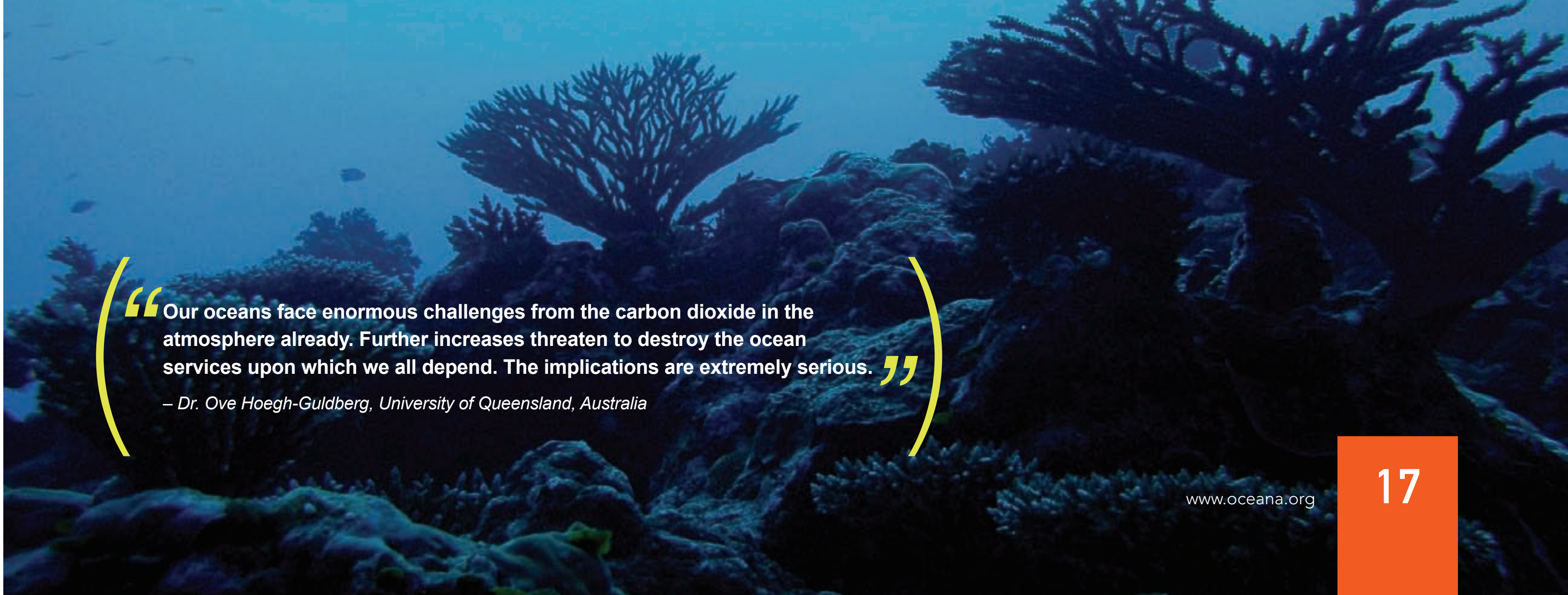
There will be ecological winners and losers, but overall, marine ecosystems will change for the worse. They will become less vibrant and diverse, devoid of the animals we love and depend upon and full of those that have less value. Undesirable species are likely to be among the winners as declines in their direct competitors and predators will allow them to flourish. Some species will even increase their growth rates and abundance because of increasing carbon dioxide.[103] The problem lies in that these resilient communities do not mirror a healthy ocean; rather, they reflect an overall decline in biodiversity and signify an ocean out of balance. From a whole ocean perspective, ocean acidification can never be a good thing.[104,105]

The results from this global experiment are starting to come in, and they are confirming our worst fears—that rising acidity will have widespread impacts on many types of marine life. Results suggest that species will respond negatively to rising acidity by decreasing calcification and in other more surprising ways, including increasing shell growth and decreasing muscle mass. Non-calcifiers have also exhibited responses that will likely decrease their ability to survive in an acidified future.

By directly impacting many important habitat and food providers, increasing acidity may change entire ocean ecosystems and cause collapses in food webs. Ocean acidification is rapidly changing the conditions to which marine species have adapted to for millions of years, threatening to push species that can not adapt beyond their limits of survival. Some species are already challenged by current conditions, but these changes are just the tip of the iceberg. If ocean acidification continues unabated, many more species will be pushed to the edge.

As the oceans become less vibrant and diverse, the many goods and services they provide will dwindle, forcing millions of people to find new food sources, new homes and new sources of income. Some of the most vulnerable communities will not have alternatives available to make up for the loss of marine goods and services. Adapting to these losses will take huge resources from the global community and in some cases adaptation will not be possible.

A smarter future is one where we reduce carbon dioxide emissions, transition to cleaner, renewable sources of energy and prevent the need for large-scale adaptation. Transitioning to a new energy economy is not only the best and most cost effective way forward, it is also the only way to protect the oceans. This transition will not be easy, but with current and emerging alternative technologies and improvements in energy efficiency and conservation it is possible, and for the sake of the oceans and ourselves it is a necessity.



"Our oceans face enormous challenges from the carbon dioxide in the atmosphere already. Further increases threaten to destroy the ocean services upon which we all depend. The implications are extremely serious."

– Dr. Ove Hoegh-Guldberg, University of Queensland, Australia

> "If there's no action before 2012, that's too late. What we do in the next two to three years will determine our future. This is the defining moment."
>
> *– Dr. Rajendra Pachauri, Chair of the IPCC*

RECOMMENDATIONS

Adopt a Policy of Stabilizing Atmospheric Carbon Dioxide at 350 ppm or Below

In order to best protect the oceans and the goods and services they provide, we must strive to return the level of carbon dioxide in the atmosphere to 350 parts per million (ppm) from the current level of 390 ppm. This will be a monumental task, one that will require emissions to peak and begin to be drastically reduced within the decade. Industrialized nations will have to reduce their emission 25 to 40 percent below 1990 levels by 2020 and 80 to 95 percent by 2050, and global emissions will need to be reduced at least 85 percent below 2000 levels by 2050.

Conserve Energy and Shift to Alternative Energy Sources

Energy should be conserved at every opportunity by adopting widespread energy efficiency standards for homes, businesses and transportation. The energy needs that remain should be met by alternative energy sources, such as offshore wind. Governments should implement programs that curtail subsidies to fossil fuel production and redirect those funds towards alternative energy production and energy efficiency programs. Alternative energy can be viable and effective and when it is put on a level playing field with fossil fuels, alternative energy sources show that they are not only safer and cleaner but also more cost effective.

Photo Credits (clockwise):
Wikimedia Commons, NOAA, © OCEANA, © OCEANA/CORNAX, U.S. Air Force

Stop Offshore Drilling

To combat ocean acidification and climate change, destructive practices such as offshore drilling need to be stopped. Not only is oil pollution damaging to marine life and ecosystems, but the emissions from the continued use of oil are driving acidification and climate change. To both protect our oceans and to reduce carbon dioxide emissions, new offshore drilling should be banned, and we must transition from oil to alternative energy.

Promote Offshore Wind Energy

An essential way to transition to clean energy is to support offshore wind development. Offshore wind utilizes the oceans in a cleaner and safer way than offshore drilling. To facilitate the growth of wind energy, federal subsidies for fossil fuels should be redirected to renewable energies. Tax credits for investment in wind technology should be extended, and policy mechanisms that increase the long-term demand for and supply of renewable energies should be developed and used. Finally, the electrification of the transportation fleet must be accelerated and infrastructure should be established to allow maximal use of this new technology.

Preserve Natural Resilience

The natural resilience of marine ecosystems should be maintained by curtailing other human-caused threats, such as offshore drilling and overfishing that decrease the ability of the oceans to cope with rising acidity. Ocean acidification and climate change are not isolated threats, but act in concert with others. Ocean ecosystems will have the best chance of surviving the pressures of ocean acidification if they are not simultaneously struggling to overcome other threats.

ENDNOTES

1 Orr, J.C., *et al.* (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437:681-686

2 Orr, J.C., *et al.* (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437:681-686

3 Orr, J.C., *et al.* (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437:681-686

4 De'ath, G., J.M. Lough, and K.E. Fabricius, K.E. (2009) Declining Coral Calcification on the Great Barrier Reef. *Science,* 323:116-119

5 Turley, C., J. Blackford, S. Widdicombe, D. Lowe, P.D. Nightingale and A.P. Rees (2006) Reviewing the impact of Increased atmospheric CO_2 on oceanic pH and the marine ecosystem. In: H.J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe (eds) Avoiding dangerous climate change. *Cambridge University Press*, Cambridge, pp. 65–70

6 Kerr, R.A. (2010) Ocean acidification unprecedented, unsettling. *Science*, 328: 1500-1501.

7 Hauri, C., *et al.* (2009) Ocean Acidification in the California Current System. *Oceanography*, 22(4):60-71

8 Oysters in deep trouble: Is Pacific Ocean's chemistry killing sea life? *Seattle Times*, 14 June, 2009. Reported by Craig Welch, http://seattletimes.nwsource.com/html/localnews/2009336458_oysters14m.html

9 Gazeau, F., C. Quiblier, J.M. Jansen, J.P. Gattuso, J.J. Middelburg and C.H.R. Heip (2007) Impact of elevated CO_2 on shellfish calcification. *Geophysical Research Letters*, 34, L07603

10 Cooley, S.R. and S.C. Doney (2009) Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*, 4024007

11 De'ath, G., J.M. Lough, and K.E. Fabricius, K.E. (2009) Declining Coral Calcification on the Great Barrier Reef. *Science*, 323:116-119

12 Veron, J.E.N. (2008) Mass extinctions and ocean acidification: biological constraints on geological dilemmas. *Coral Reefs*¸ 27:459-472

13 Veron, J.E.N., O. Hoegh-Guldberg, T.M. Lenton, J.M. Lough, D.O. Obura, P. Pearce-Kelly, C.R.C. Sheppard, M. Spalding, M.G. Stafford-Smith and A.D. Rogers (2009) The Coral Reef Crisis: The critical importance of <350 ppm CO_2. *Marine Pollution Bulletin,* 58:1428-1436

14 Wilkinson, C. (2008) Status of the Coral Reefs of the World: 2008. *Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre*, Townsville, Australia

15 TEEB (2010) The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of *Nature*: A synthesis of the approach, conclusions and recommendations of TEEB

16 U.S. EPA; Region 9; Water Program; Ocean, Coasts and estuaries; Coral Reefs, www.epa.gov/region09/water/oce/coralreefs.html

17 Wilkinson, C. (2008) Status of the Coral Reefs of the World: 2008. *Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre*, Townsville, Australia

18 Bryant, D., L. Burke, J. McManus, and M. Spalding (1998) Reefs at Risk: A Map Based Indicator of Threats to the World's Coral Reefs. *World Resources Institute*, Washington D.C.

19 Knowlton, N., R.E. Brainard, R. Fisher, M. Moews, and L. Plaisance (2010) Coral Reef Biodiversity. In: A.D. McIntyre (Ed.) Life in the World's Oceans: Diversity Distribution and Abundance, pp. 65-74

20 Silverman, J., B. Lazar, L. Cao, K. Caldeira and J. Erez (2009) Coral Reef May Start Dissolving when Atmospheric CO_2 Doubles. *Geophysical Research Letters*, 36:L05606

21 Hoegh-Guldberg, O., *et al.* (2007) Coral reefs under rapid climate change and ocean acidification. *Science*, 318(5857):1737-1742

22 Veron, J.E.N., O. Hoegh-Guldberg, T.M. Lenton, J.M. Lough, D.O. Obura, P. Pearce-Kelly, C.R.C. Sheppard, M. Spalding, M.G. Stafford-Smith and A.D. Rogers (2009) The Coral Reef Crisis: The critical importance of <350 ppm CO_2. *Marine Pollution Bulletin*, 58:1428-1436

23 Munday, P., G.P. Jones, M.S. Pratchett, and A.J. Williams (2008) Climate change and the future of coral reef fishes. *Fish and Fisheries,* 9(3):261-285.

23 Hoegh-Guldberg, O., *et al.* (2007) Coral reefs under rapid climate change and ocean acidification. *Science*, 318(5857):1737-1742

25 Stone, R. (2007) A world without corals? *Science*, 316(5825):678-681.

26 Munday, P., G.P. Jones, M.S. Prachett and A.J. Williams (2008) Climate Change and the Future for Coral Reef Fishes. *Fish and Fisheries*, 9(3): 261-285

27 Jones, G.P., M.I. McCormick, M. Srinivasan, and J.W. Eagle (2004) Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences of the United States of America*, 101(21):8251-8253

28 Bonin, F., B. Devaux, B., and A. Dupre (2006) Turtles of the World, *John Hopkins University Press*, Baltimore, MD

29 Fuentes, M.M.P.B., J.L. Dawson, S.G. Smithers, M. Hamann and C.J. Limpus (2010) Sedimentological characteristics of key sea turtle rookeries: potential implications under projected climate change. *Marine and Freshwater Research*, 61:464-473

30 Fuentes, M.M.P.B., J.L. Dawson, S.G. Smithers, M. Hamann and C.J. Limpus (2010) Sedimentological characteristics of key sea turtle rookeries: potential implications under projected climate change. *Marine and Freshwater Research*, 61:464-473

31 Doney, S., Fabry, V., Feely, R., Kleypas, J. (2009) Ocean Acidification: The Other CO_2 Problem. A*nnual Review of Marine Science*, 1:169-92

32 Hunt, B.P., E.A. Pakhomov, G.W. Hosie, V. Seigel, and P. Ward (2008) Pteropods in southern ocean ecosystems. *Progress in Oceanography*, 78:193-221

33 Willette, T.M., R.T. Cooney, V. Patrick, D.M. Mason, and G.L. Thomas (2001) Ecological processes influencing mortality of juvenile pink salmon (Oncorhynchus gorbuscha) in Prince William Sound, Alaska. *Fisheries Oceanography*, 10:14-41

34 Chen, W., J.J. Govoni, and S.M. Wavlen (1992) Comparison of feeding and growth of larval round herring (Etrumeus teres) and gulf menhaden (Brevoortia patronus). *Fishery Bulletin*, 90(1):183-189

35 Karnovsky, N.J., K.A. Hobson, S. Iverson, and G.L. Hunt Jr. (2008) Seasonal changes in diets of seabirds in the North Water Polynya: a multiple-indicator approach. *Marine Ecology Progress Series*, 357:291-299

36 Weslawski, J.M., L. Hacquebord, L. Stempniewicz and M. Malinga (2000) Greenland whales and walruses in the Svalbard food web before and after exploitation. *Oceanologia*, 42:37-56

37 Orr, J.C., *et al.* (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437:681-686

38 Doney, S., Fabry, V., Feely, R., Kleypas, J. (2009) Ocean Acidification: The Other CO_2 Problem. *Annual Review of Marine Science*, 1:169-92

39 Fabry, V.J., J.B. Mcclintock, J.T. Mathis and J.M. Grebmeier (2009) Ocean Acidification at High Latitudes: The Bellwether. *Oceanography*, 22(4):160-171

40 Aydin, K.Y., *et al.* (2005) Linking ocean food webs to coastal production and growth rates of Pacific Salmon (Oncorhynchus spp.), using models on three scales. *Deep Sea Research Part II: tropical studies in Oceanography*, 52(5-6):757-780.

41 The Research Group (2009) North Pacific Salmon Fisheries Economic Measurement Estimates version 1.2. *Wild Salmon Center,* Portland, Oregon

42 Orr, J.C., *et al.* (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437:681-686

43 Seibel, B.A. and H.M. Dierssen (2003) Cascading trophic impacts of reduced biomass in the Ross Sea, Antarctica: Just the tip of the iceberg? *The Biological Bulletin*, 205:93-97

44 Fabry, V.J., J.B. Mcclintock, J.T. Mathis and J.M. Grebmeier (2009) Ocean Acidification at High Latitudes: The Bellwether. *Oceanography*, 22(4):160-171

45 Feely, R.A., S.C. Doney and S.R. Cooley (2009) Ocean Acidification: Present Conditions and Future Changes in a High-CO_2 World. *Oceanography*, 22(4):37-47

46 Ford, J.K.B., *et al.* (1998) Dietary specialization in two sympatric populations of killer whales (Orcinus orca) in coastal British Columbia and adjacent waters. *Canadian Journal of Zoology*, 76(8):1456-1471.

47 Ogden, J.C. and P.S. Lobel (1978) The role of herbivorous fishes and urchins in coral reef communities. *Environmental Biology of Fishes*, 3(1):49-63

48 Department of Marine Resources for the State of Maine; Historical Maine Fisheries Landings Data: Urchins, www.maine.gov/dmr/commercialfishing/historicaldata.html

49 Reuter, K.E., K.E. Lotterhos, R.N. Crim, C.A. Thompson, and C.D.G. Harley (2010) Elevated pCO_2 increases sperm limitations and risk of polyspermy in the red sea urchin *Strongylocentrotus franciscanus*. *Global Change Biology*, 10:1365-2486

50 Havenhand J.N., F.R. Buttler, M.C. Throndyke, and J.E. Williamson (2008) Near-future levels of ocean acidification reduce fertilization success in a sea urchin. *Current Biology*, 18:651-652

51 Kurihara, H. (2008) Effects of CO_2-driven ocean acidification on the early developmental stages of invertbrates. *Marine Ecology Progress Series*, 373:275-283

52 Reuter, K.E., K.E. Lotterhos, R.N. Crim, C.A. Thompson, and C.D.G. Harley (2010) Elevated pCO_2 increases sperm limitations and risk of polyspermy in the red sea urchin *Strongylocentrotus franciscanus. Global Change Biology*, 10:1365-2486

53 Hoegh-Guldberg, O., *et al.* (2007) Coral reefs under rapid climate change and ocean acidification. *Science*, 318(5857):1737-1742

54 Hunt, B.P., E.A. Pakhomov, G.W. Hosie, V. Siegel, P. Ward and K. Bernard (2008) Pteropods in southern ocean ecosystems. *Progress in Oceanography*, 78:193-221

55 Gazeau, F., C. Quiblier, J.M. Jansen, J.P. Gattuso, J.J. Middelburg and C.H.R. Heip (2007) Impact of elevated CO_2 on shellfish calcification, *Geophysical Research Letters*, 34, L07603

56 Brennand H.S., N. Soars, S.A. Dworjanyn, A.R. Davis, and M. Byrne (2010) Impact of ocean warming and ocean acidification on larval development and calcification in the sea urchin *Tripneustes gratilla*. *PLoS ONE*, 5(6):e11372

57 Brennand H.S., N. Soars, S.A. Dworjanyn, A.R. Davis, and M. Byrne (2010) Impact of ocean warming and ocean acidification on larval development and calcification in the sea urchin *Tripneustes gratilla*. *PLoS ONE*, 5(6):e11372

58 Arnold, K.E., H.S. Findlay, J.I. Spicer, C.L. Daniels and D. Boothroyd (2009) Effect of CO_2 related acidification on aspects of the larval development of the European lobster *Humarus gammarus, Biogeosciences Discussions*, 6:3087-3107

59 Al-Sawalmh, A., *et al.* (2008) Microtexture and chitin/calcite orientation relationship in the mineralized exoskeleton of the American lobster. *Advanced Functional Materials*, 18:3307-3314

60 Evans, L., J. Jones, and J. Brock (2208) Diseases of Spiny Lobsters. In: B. Phillips and J. Kittaka (Eds) Spiny Lobsters: Fisheries and Culture, Second Edition. *Blackwell Science*, Oxford, U.K.

61 Ries, J.B., A.L. Cohen and D.C. McCormick (2009) Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. *Geology*, 37(12):1131-1134

62 National Oceanic and Atmospheric Administration National Marine Fisheries Service; FishWatch; American Lobster. www.nmfs.noaa.gov/fishwatch/species/amer_lobster.html

63 Maryland Department of Natural Resources; Maryland Fish Facts; Bluecrab. www.dnr.state.md.us/fisheries/fishfacts/bluecrab.asp

64 Cavey M.J, K. Markel (1994) Echinoidea. In: F.W. Harrison and F.S. Chia (Eds), Microscopic Anatomy of Invertebrates: Echinodermata. *Wiley-Liss*, New York, pp 247–344

65 Gooding, R.A., C.D.G. Harley and T. Emily (2009) Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm, *Proceedings of the National Academy of Sciences of the United States of America*, 106:9316–9321

66 Gooding, R.A., C.D.G. Harley and T. Emily (2009) Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm, *Proceedings of the National Academy of Sciences of the United States of America*, 106:9316–9321

67 Gooding, R.A., C.D.G. Harley and T. Emily (2009) Elevated water temperature and carbon dioxide concentration increase the growth of a keystone echinoderm, *Proceedings of the National Academy of Sciences of the United States of America*, 106:9316–9321

68 Dupont, S., B. Lundve and M. Thorndyke (2010) Near Future Ocean Acidification Increases Growth Rate of the Lecithotrophic Larvae and Juveniles of the Sea Star *Crossaster papposus. Journal of Experimental Zoology (Mol. Dev. Evol.)*, 314B

69 Dupont, S., B. Lundve and M. Thorndyke (2010) Near Future Ocean Acidification Increases Growth Rate of the Lecithotrophic Larvae and Juveniles of the Sea Star *Crossaster papposus. Journal of Experimental Zoology (Mol. Dev. Evol.)*, 314B

70 Duineveld, G.C.A, and Van Noort, G.J. (1986) Observations on the population dynamics of Amphiura filiformes (ophiuridae: echinodermata) in the southern north sea and its exploitation by the dab, *Limanda limanda. Netherlands Journal of Sea Research*. 20(1):85-94

71 Vopel, K., D. Thsitle and R. Rosenberg (2003) Effect of the brittle star *Amphiura filiformes* on oxygen flux into the sediment. *Limnology and Oceanography*, 48(5):2034-2045

72 Nilsson, H.C., and M. Skold (1996) Arm regeneration and spawning in the brittle star *Amphiura filiformes* during hypoxia. *Journal of Experimental Marine Biology and Ecology*, 199(2):193-206.

73 Wood, H.L., J.I. Spicer and S. Widdicombe (2008) Ocean acidification may increase calcification rates, but at a cost. *Proceedings of The Royal Society B*

74 Wood, H.L., J.I. Spicer and S. Widdicombe (2008) Ocean acidification may increase calcification rates, but at a cost. *Proceedings of The Royal Society B*

75 Dupont, S., Havenhand, J., Thorndyke, W., Peck, L., and Thorndyke, M. (2008) Near-future level of CO_2-driven ocean acidification radically affects larval survival and development in brittlestar *Ophiothrix fragilis. Mar. Ecol. Prog. Ser.*, 373:285-294.

76 Smithsonian National Zoological Park, Invertebrates, Cephalopods, http://nationalzoo.si.edu/Animals/Invertebrates/Facts/cephalopods/locomotion.cfm

77 Rosa, R., and B. Seibel (2008) Synergistic effects of climate-related variables suggest future physiological impairment in a top oceanic predator. *Proceedings of the National Academy of Sciences of the United States of America*, 105(52):20776-20780

78 Gutowska, M.A., Portner, H.O., and Melzner, F. (2008) Growth and calcification in the cephalopod Sepia officinalis under elevated seawater pCO_2. *Mar Ecol Prog Ser.* 373:303-309

79 Rosa, R., and B. Seibel (2008) Synergistic effects of climate-related variables suggest future physiological impairment in a top oceanic predator. *Proceedings of the National Academy of Sciences of the United States of America*, 105(52):20776-20780

80 National Oceanic and Atmospheric Administration National Marine Fisheries Service; FishWatch; Market Squid (Pacific Loligo). www.nmfs.noaa.gov/fishwatch/species/market.squid.html

81 California Department of Fish and Game (2009) Review of selected California fisheries for 2008: coastal pelagic finfish, market squid, ocean salmon, groundfish, California spiny lobster, spot prawn, white seabass, kelp bass, thresher shark, skates and rays, kellet's whelk, and sea cucumber. *CalCOFI Rep.*, 50:14-42

82 Munday, P.L., Crawley, N.E., Nilsson, G.E. (2009) Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. *Proceedings of the National Academy of Sciences of the United States of America*, 105:20776-20780.

83 Dixson, D.L., Munday, P.L., Jones, G.P. (2010) Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. *Ecology Letters*, 13:68-75

84 Munday, P., *et al.* (2010) Replenishment of fish populations is threatened by ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, 107(29):12930-12934

85 Munday, P., *et al.* (2010) Replenishment of fish populations is threatened by ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, 107(29):12930-12934

86 Munday, P., *et al.* (2010) Replenishment of fish populations is threatened by ocean acidification. *Proceedings of the National Academy of Sciences of the United States of America*, 107(29):12930-12934

87 Gagliano, M., M. Depczynski, S.D. Simpson, and J.A.Y. Moore (2008) Dispersal without errors: symmetrical ears tune into the right frequency for survival. *Proceedings of the Royal Society; Biological Sciences*, 275:527-534

88 Gagliano, M., M. Depczynski, S.D. Simpson, and J.A.Y. Moore (2008) Dispersal without errors: symmetrical ears tune into the right frequency for survival. *Proceedings of the Royal Society; Biological Sciences*, 275:527-534

89 Checkley Jr., D.M., A.G, Dickson, M. Takahashi, J.A. Radich, N. Eisenkolb, and R. Asch (2009) Elevated CO_2 enhances otolith growth in young fish. *Science*, 324:1683

90 Gagliano, M., M. Depczynski, S.D. Simpson, and J.A.Y. Moore (2008) Dispersal without errors: symmetrical ears tune into the right frequency for survival. *Proceedings of the Royal Society; Biological Sciences*, 275:527-534

91 Gagliano, M., M. Depczynski, S.D. Simpson, and J.A.Y. Moore (2008) Dispersal without errors: symmetrical ears tune into the right frequency for survival. *Proceedings of the Royal Society; Biological Sciences*, 275:527-534

92 Riley, B.B., and S.J. Moorman (2000) Development of utricular otoliths, but not saccular otoliths is necessary for vestibular function and survival in zebrafish. *Journal of Neurobiology*, 43 (4):329-337

93 Munday, PL, N.E. Crawley and G.E. Nilsson (2009) Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. *Marine Ecology Progress Series*, 388:235-242

94 Ishimatsu, A., M. Hayashi and T. Kikkawa (2008) Fishes in high-CO_2 acidified oceans. *Marine Ecology Progress Series*, 373:295–302

95 Munday, P.L., N.E. Crawley and G.E. Nilsson (2009) Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. *Marine Ecology Progress Series*, 388:235-242

96 Munday, P.L., N.E. Crawley and G.E. Nilsson (2009) Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. *Marine Ecology Progress Series*, 388:235-242

97 Richardson, A.J., and M.J. Gibbons (2008) Are jellyfish increasing in response to ocean acidification? *Limnology and Oceanography*, 53(5):2040-2045 AND Attrill, J.M., J. Wright, and M. Edwards (2007) Climate-related increases in jellyfish frequency suggest a more gelatinous future for the North Sea. *Limnology and Oceanography*, 52(1):480-485 AND Haddock, S.H.D., *et al.*, (2008) Reconsidering evidence for potential climate-related increases in jellyfish. *Limnology and Oceanography*, 53(6):2759-2762 AND Tucker, A. (2010) "Jellyfish: The Next King of the Sea." *Smithsonian Magazine*, August

98 Winanas, A.K., and J.E. Purcell (2010) Effects of pH on asexual reproduction and statolith formation of the scyphozoan, Aurelia labiata. *Hydrobiologia*, 645:39-52

99 Stenevik, E.K., and S. Sundby (2006) Impacts of climate change on commercial fish stocks in Norwegian waters. *Marine Policy*, 31(1):19-31

100 Purcell, J.E., S.I. Uye, and W.T. Lo (2007) Anthropogenic causes of jellyfish blooms and their direct consequences for humans: a review. *Marine Ecology Progress Series*, 350:153-174

101 Hall-Spencer, J.M., *et al.* (2008) Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*, 454:96-99

102 Hall-Spencer, J.M., *et al.* (2008) Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*, 454:96-99

103 Connell, S.D. and B.D. Russell (2010) The direct effects of increasing CO_2 and temperature on non-calcifying organisms: Increasing the potential for phase shifts in kelp forests, *Proceedings of the Royal Society B*, 277:1409-1415

104 Hall-Spencer, J.M., *et al.* (2008) Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*, 454:96-99

105 J.E.N. Veron (2008) A Reef in Time: The Great Barrier Reef from beginning to end. *The Belknap Press of Harvard University Press*, Cambridge, Massachusetts

Photo: Adrienne McCracken

Oceana campaigns to protect and restore the world's oceans. Our team of marine scientists, economists, lawyers and advocates win specific and concrete policy changes to reduce pollution and to prevent the irreversible collapse of fish populations, marine mammals and other sea life. Global in scope and dedicated to conservation, Oceana has campaigners based in North America, Europe, and South America. More than 500,000 members and e-activists in over 150 countries have already joined Oceana. For more information, please visit www.Oceana.org.

FSC
Mixed Sources
Product group from well-managed forests, controlled sources and recycled wood or fiber
Cert no. SW-COC-002557
www.fsc.org
© 1996 Forest Stewardship Council

OCEANA Protecting the World's Oceans
www.oceana.org/climate

1350 Connecticut Ave., NW, 5th Floor
Washington, DC 20036 USA

100% green power wind & solar