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1972-73 was the next major El Niño after 1957-58 and it contributed to the collapse of the Peruvian anchovy fishery, which at that time was the largest fishery in the world, with 10 million metric tons of fish caught per year. The collapse was caused in part by overfishing, so we can't blame it entirely on El Niño. However, the 1972-73 El Niño caught the attention of not just the oceanographic community and meteorological community, but also the public to a certain extent because it affected the price of fish meal used to feed livestock, and therefore, the price of meat products.

So in the mid to late seventies research programs were developed to help better understand El Niño. NOAA started some of these programs, and another group of investigators was funded by the National Science Foundation to work on ocean-atmosphere interactions in the tropical Pacific.

So there were groups of oceanographers and meteorologists studying aspects of the El Niño Southern Oscillation problem in the mid to late seventies. Based in part on the successes of those programs, there was a growing belief that we might be able to predict El Niño some seasons or years in advance, and that we could derive certain economic advantages from further research. For example, with accurate climate forecasts we might be able to advise farmers when to plant or what to plant, to plan for increased or reduced power generation, and reservoir levels, and to better manage a whole host of climatically sensitive economic activities.

So what started as a couple of relatively small-scale programs in the

United States soon blossomed into an international effort to develop a ten-year program to study El Niño. This program later became known as the Tropical Ocean Global Atmosphere program (TOGA). It lasted from 1985 to 1994.

In the planning stages for TOGA, the 1982-83 El Niño took place. It was not only not predicted, but it wasn't even detected until it was nearly at its peak. In some ways it was an embarrassment for the scientific community, because here they were planning this huge international ten-year program to study a phenomenon that they couldn't even observe. This riveted the community's attention on developing computer models that could forecast El Niño.

In the ten years of the TOGA program, the community put in place an observing system, one of the most important characteristics of it being that almost all the data were transmitted within hours of collection and made available to a world-wide community of research scientists and forecasters. The other major accomplishment was the development of computer models that in fact could forecast El Niño with some accuracy, as much as a year in advance.

By the time the 1997-98 El Niño came along, we had experienced something of a revolution in climate studies, with the 1982-83 and the 1997-98 El Niños being in some sense bookends on a remarkable chapter in the history of this revolution. One El Niño caught us completely off guard and we had no ability to forecast it. In 1997-98 we could observe El Niño's evolution day by day, and many

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models did predict in mid to late 1996 that 1997 was going to be a warm year.

Once the unusually warm temperatures began to develop, they rose more quickly than ever seen before. December of 1997 witnessed the largest deviations from normal on record in the eastern equatorial Pacific, which is one of the key index regions that we use to describe El Niño.

ER: What measurements does the observing system make?

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MM: There are in-ocean measurements — instruments that have been put in the water — and then there's the constellation of satellites which measure a range of important oceanographic and meteorological parameters. Probably the most important measurement system for El Niño is the Tropical Atmosphere Ocean Array which measures all the key oceanographic variables we need to know about in order to understand, to monitor, and to forecast. This array took ten years to build. It consists of about seventy deep-ocean moorings that span the width of the tropical Pacific from near the coast of South America to near the coast of New Guinea. That's about one-third of the circumference of the globe at the equator.

Each one of these buoys has an eight foot-diameter donut-shaped float on which sits a twelve foot-tall tower with different kinds of instrumentation: winds, relative humidity, air temperature, sea surface temperature. Then below is a cable with temperature sensors to a depth of one-third of a mile below the surface.

On some of these buoys we also measure ocean currents, rainfall, ocean salinity and solar radiation, but the key measurements are the surface winds, the sea surface temperatures, and the upper ocean temperatures. All the data are transmitted to shore via satellite relay within a few hours of collection.

The ENSO observing system performed spectacularly during this past El Niño. We were essentially blind in 1982 because most of the oceanographic information available then was from a few passing ships which radioed in reports from time to

time. In-ocean measurement platforms and satellites produced large amounts of data that allowed us to monitor the day by day evolution of the climate system in the tropical Pacific with high precision and accuracy.

ER: What is the consensus on El Niños?

MM: Everyone in the scientific community would agree that El Niño is associated with a warming of the eastern tropical Pacific and a weakening or collapse of the trade winds. Everyone would agree that those two things happen in tandem; in fact they rely on one another. When the water gets warm, the winds weaken, and weakened winds help the water to

The redistribution of upper ocean heat content governs the slow evolution of the climate system in the tropical Pacific.

warm even more.

Everyone would agree that the upper ocean thermal field is the flywheel of this whole system. It provides the inertia, the long three-to-four-year memory of El Niño. The redistribution of upper ocean heat content over long periods of time governs the slow evolution of the climate system in the tropical Pacific.

There are questions about why El Niño is so irregular. It doesn't happen every four years exactly. Sometimes it happens once every two years or sometimes as infrequently as every seven. Why are some stronger than others? Why do some have a different evolution in terms of how long they last? Some people think this irregularity may be due to factors external to the tropical Pacific Ocean, like the Madden-Julian Oscillation, a thirty to

sixty-day wave in the atmosphere which originates over the Indian Ocean. Some people discount those as being irrelevant and say, No, any bit of nonlinearity or chaos within the system itself will cause it to get out of sync from time to time, and we don't need external forcing factors.

ER: Can we predict monsoons in India now?

MM: Well, it turns out that the Indian monsoon rainfalls are a better predictor of the Southern Oscillation than vice versa. Walker never achieved his goal of developing a successful predictor for monsoon rainfall, because the Southern Oscillation actually lags the monsoon rather than leads it. During an El Niño year monsoon, rainfalls are generally lower. But peak El Niño warming in the eastern Pacific generally occurs in the December, January, February season, while the weak monsoon generally

occurs the summer before in June, July, August.

But we found with the 1997-98 El Niño that the Indian monsoon was near normal. Why, when we had the El Niño of the century and when the relationship between El Niño and monsoon rainfall has generally been pretty good in terms of El Niño/low rainfall, La Niña/high rainfall? The argument that some are invoking is that the Indian Ocean was much warmer than usual in 1997, reflecting in part, a warming trend over the past twenty years.

This gets us into another level of discussion about El Niño and climate, which is, not surprisingly of course that El Niño is not the only game in town in terms of climate. We know that there are certain seasons and

certain places of the world where, if an El Niño or a La Niña are in progress, you can expect with some degree of reliability an alteration in the usual weather patterns. Or, you might expect an alteration in the ecosystems along the Pacific coast of North and South America, and in the tropics.

However, there are other factors involved in climate, and sometimes those factors can amplify the effects of an El Niño, neutralize or override it completely. We're beginning to understand that some of the weather anomalies that we expected that didn't come about may have been masked by other physical processes at work in the climate system.

For example, we expected a devastating drought in Australia. In 1997 it started out dry, but then the drought broke and Australia got the rains. They got enough rain at just the right time that agricultural output was not drastically affected.

We expected a drought in Zimbabwe. But the rains came on time and actually were even a little heavy. These events in the Indian Ocean sector we think might be related to unusually warm Indian Ocean sea surface temperatures. There are other examples like this where the expected did not occur, like the Indian monsoon, where a normal year in 1997 was considered unusual.

ER: Are there any other oscillations as large as the ENSO?

MM: ENSO is the largest global climate signal outside of the normal seasonal cycle. There are other climate-scale oscillations that are

reasonably well documented and have regional impacts, one of them being the North Atlantic Oscillation (NAO). This is a seesaw in atmospheric pressure between the Icelandic low and the Azores high. It affects the position of the jet stream and the storm tracks over the eastern U.S., Atlantic Ocean, Eurasia and Northern Africa. The NAO tends to oscillate on time scales longer than El Niño. El Niño is year to year; the NAO occurs on a decadal timescale. This past winter, unusually cold weather in Europe this year and some of the warm weather along the East Coast of the U.S. were associated with the NAO, which changed phase a couple of years ago to favor these sorts of weather patterns. The NAO's effects are usually most pronounced in the winter season, as are the effects of the

northeast Brazil they can spell the difference between life and death.

ER: Would these other oscillations influence the severity of ENSO?

MM: This is an area of research that we are just beginning to explore. The likelihood is that if there is some physical interaction between various climate signals, they're not completely independent.

This is probably true of global warming and El Niño. We know that El Niño results in a mini-global warming. The record warm temperatures in 1997-98 were in part due to the fact that we had a record El Niño. There's a loss of heat from the tropical Pacific Ocean to the overlying atmosphere, and that heat and moisture gets transported around the globe. So in

1997-98 when we had global mean temperatures 1.2 degrees Fahrenheit above normal, some percentage of that was due to the El Niño.

And then the question is of course, why did we have this major El

Niño? It may not be independent of global warming trends. Some might argue we had a major El Niño because global warming is taking place. This is a chicken and egg argument that hasn't been sorted out completely. There are a number of lines of investigation, some of the most promising of which involve computer models of global warming and El Niño-type variations together. Some of these models indicate that global warming might push the tropical Pacific into a quasi-permanent El Niño state. In fact, tropical Pacific temperatures have been elevated over the past twenty-five years, and some claim this is a fingerprint of global warming. Then if

We know that El Niño results in a mini-global warming. The record warm temperatures in 1997-98 were in part due to the fact that we had a record El Niño.

El Niño Southern Oscillation.

There are important climate signals originating in the tropical Atlantic as well, which affect the rainfall over the Sahel in northeastern Brazil. Interestingly, both the tropical Atlantic and the tropical Pacific affect the rainfall over northeast Brazil, so you've got to keep track of both if you want to make a skillful long range weather forecast there. Northeast Brazil is also a part of the world where people depend on subsistence agriculture for food. So unlike in the developed nations such as the U.S. where climate variations translate primarily into economic losses, in places like

you take these elevated temperatures and you add on to them El Niño dynamics, you can get a blockbuster like we experienced in 1997-98.

This El Niño has indicated that we may need to broaden our perspective of what we mean by El Niño. We define it as a phenomenon that occurs year to year. However, factors that influence the oscillation may not be confined to year-to-year time scales.

There is the possibility that the intraseasonal Madden-Julian oscillations originating over the Indian Ocean, many give a kick to the climate system at just the right time to initiate an El Niño. There is also the possibility that on the century-long time scales, global warming trends are affecting the background state on which El Niño anomalies grow.

ER: The fact that the trade winds stop is astounding.

MM: That is one of the hallmark characteristics of El Niño. In the early part of 1997 the trade winds started to relax, but not in a smooth and uniform way. The relaxation was episodic with strong pulses of westerly winds occurring every sixty days or so.

In 1997 there were six or seven pulses of strong westerly winds that lasted in each case for one to three weeks. Those surface wind pulses were related to the Madden-Julian oscillation that originated over the Indian Ocean and propagated into the Pacific. These oscillations apparently gave the ocean a healthy kick at just the right time to set off an incredibly fast warming. This Madden-Julian oscillation occurs every year over the Indian Ocean; every year it tends to

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amplify during the northern hemisphere winter season. Beginning in winter 1996 and early spring of 1997 though, it amplified even more for reasons that are not quite clear now.

It is true that the tropical Pacific had been preconditioned for an El Niño to occur. Twelve to eighteen months before the onset of the event, there had been a build up of warm water in the Western Pacific Ocean, which is viewed as a precursor of El Niño events. That build up of warm water is what many of the forecast models, one way or another, were keying in on in terms of predicting that 1997 was going to be warm.

But when this series of atmospheric waves came over from the Indian Ocean, they launched the system off towards warming at a rate that we've never seen before. It may be that it was the combination of being preconditioned and hitting the ocean at just the right time that produced this huge El Niño. The hypothetical difference between this El Niño with and without episodic wind forcing is probably the difference between a garden variety El Niño and the strongest on record.

So although there is a basic governor to the system, which is the interior ocean heat content in the

Pacific, these energetic atmospheric waves and other weather disturbances may be able to push it more quickly in a particular direction, or knock it off course.

During normal conditions there is a well-developed trade wind system that's piling up warm water in the Western Pacific, because water is flowing from east to west along the equator. During an El Niño, when the winds weaken and collapse, that warm water pool can slide back eastward. The amount of water movement involved is enormous. The difference between water moving from east to west during normal conditions, and then going back from west to east during El Niño conditions is the same amount of water that's flowing in the Gulf Stream. So moving water around during El Niño is like taking the Gulf Stream, which is one of the strongest ocean flows on the planet, and shutting it off.

ER: The thermocline changes too.

MM: Right. The thermocline is the boundary between the warm surface layer and the cold interior ocean. It generally slopes down towards the west because you're pushing warm water to the west under the action of

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the trade winds. When the trades relax, the thermocline flattens out as warm water migrates eastward over the course of a few months.

ER: Are there any other hallmarks of El Niño?

MM: Another hallmark is the shift in tropical rainfall patterns. You generally get the strongest rains in the tropics over the warmest water. When the warm water moves eastward, so does the rainfall. That's why during El Niño you get droughts in Australia and Indonesia and the Philippines, typically, and heavy rains over the island states of the Central Pacific and along the West Coast of South America.

When its raining, moisture is condensing and releasing heat into the atmosphere. That heat release is a major energy source for driving the global atmospheric circulation. It is like throwing a rock in a stream, setting off wave patterns that ripple downstream. These shifts in tropical Pacific rainfall generate atmospheric waves that affect the position of the jet streams at higher latitudes. Storms are formed within, and steered by the jet streams, so if you alter the path of these air flows, you also alter weather patterns.

So the warm water in the tropical Pacific affects precipitation, which affects not only the climate of countries bordering the tropical Pacific, but also global climate. That's how for

example, in the Pacific Northwest our weather is affected, and how it is influenced along the coast of California and the southern tier of the United States, and so on.

ER: How does it affect marine life?

MM: When the trade winds relax, it allows the warm water that's been confined to the Western Pacific to move eastward. That is the main reason why the Central Pacific becomes unusually warm during El Niño. This eastward movement of warm water also pushes the thermocline down in the eastern Pacific. A deep thermocline means it's that much harder to bring cold water up to the

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surface through the process of equatorial upwelling.

That cold water is also high in nutrients, the fertilizer that allows the one-celled plants called phytoplankton to grow in the equatorial region and in the coastal zones of North and South America. So when El Niño pushes the thermocline down, it not only shuts off the upwelling of cold water; it shuts off the source of plant fertilizer, which reduces the phytoplankton growth.

This reduction in primary productivity in turn affects all the higher levels of the food chain. Zooplankton and small fish don't thrive, and then the bigger fish that feed on these don't thrive, and then the sea birds and the mammals that feed on the bigger fish begin to be affected, both in terms of their mortality and in their ability to reproduce. As a result, along the coast of California sea lions and fur seals, which are near the top of the food chain, were dying by the thousands of starvation during the 1997-98 El Niño.

Also, Peruvian fishermen have long known that, aside from the heavy rains that El Niño brings, there was a great reduction in and a die-off of sea birds that fed on them along the coast. The anchovies in this case migrated south to colder, more nutrient rich waters.

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Effects of Increased Atmospheric Carbon Dioxide on Coral Reefs

Introduction:

Coral reefs are called the rainforests of the oceans because they provide habitat for a wide variety of marine plants and animals. The rock-like substrate of a coral reef is an accumulation of calcium carbonate, a building material used by humans in limestone and concrete. Calcium carbonate is secreted by tiny reef building animals and plants layer by layer to form coral reefs. These reef building organisms obtain their building materials from sea water in the form of calcium and carbonate ions.

Increased carbon dioxide in the atmosphere, the same phenomenon that brings us global warming, is also changing sea water chemistry with respect to carbonate, thereby decreas-

ing the ability of reef building organisms to secrete calcium carbonate. Many reefs around the world are in decline from overuse and destruction, from warmer sea water temperatures, diseases, eutrophication and bleaching. [*Eutrophication is the term used for excess plant production in water leading to, in worst cases, deoxygenated water. Ed.*]

Decreasing corals' ability to build reefs means they are less likely to survive environmental insults and slower to recover if they do survive.

We spoke with Joan A. Kleypas about her work on reef communities and the effects of environmental changes on them.

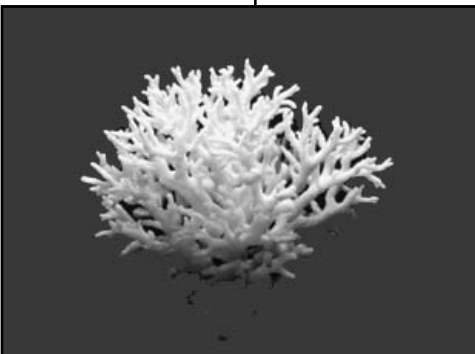
ER: Dr. Kleypas, what is your scientific training?

JK: I have a Ph.D. in tropical marine studies from James Cook University in

north Queensland, Australia, which is located adjacent to the Great Barrier Reef. Most of my work since my Ph.D. has focused on what controls the distribution of reefs around the world. To that end I've developed a simple diagnostic computer model which uses environmental data as inputs to predict where reefs should occur. As we develop this model we hope to use it to examine how environmental changes might affect where reefs will occur.

Right now I'm assisting Dr. Scott Doney in various projects associated with the US Joint Global Ocean Flux Survey. One of the main goals of this project is to examine the ocean's role in the global carbon

cycle. Recently, there has been extensive work on how much carbon dioxide the ocean can sequester from the atmosphere, but there has not been much research on how changing



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atmospheric carbon dioxide may affect marine biological communities, particularly those on the continental shelves. Some of these shallow water communities such as coral reef communities and mangroves are quite important both economically and biologically. In terms of how coral reefs will be affected by global change, the effect of increasing sea water temperature is currently a prime research area, mainly because of the alarming episodes of coral bleaching. But investigations into how increased atmospheric carbon dioxide might directly affect these marine communities has only just begun.

ER: What are corals ?

JK: Corals are invertebrate animals that secrete calcium carbonate, lime, to form their skeletons. Most reef-building corals consist of a colony of anemone-like animals, all interconnected, which precipitate calcium carbonate at the base of their tissues. The live part of a coral exists only on the outer surface. As the colony grows, it periodically lays down a layer of calcium carbonate, so that in cross-section a coral skeleton has a banded appearance, analogous to tree rings. Corals skeletons exhibit a great variety of shapes, from the typical brain and branching

corals, to platy and encrusting forms. Some forms can grow up to several meters in diameter, but still, the live coral tissue on even very large corals is typically only millimeters thick.

ER: That's why tourists are asked not to walk on or drop anchor on coral reefs.

JK: Precisely. Trampling on the individual polyps can damage them, and if that doesn't kill them outright, they may be weakened and then susceptible to disease.

In experiments which simulate these seawater chemistry changes, corals show a decrease in calcification.

ER: Don't corals have algae living inside them?

JK: Yes. Living within the tissues of many corals are unicellular algae. These algae can photosynthesize and produce carbohydrates and other nutrients that the coral can use. In turn, the coral can provide the algae with its own waste products. This is a classic example of what ecologists call symbiosis, a relationship between two organisms where both benefit. All corals that build reefs have symbiotic algae. Apparently these algae enhance the growth rate of the corals.

ER: Like fungi growing on tree roots.

JK: Yes, exactly. Corals grow much better with the algae present. Coral bleaching occurs when a coral loses its algae; this usually happens

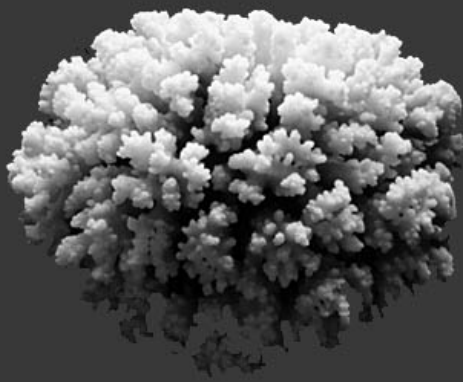
when the coral becomes stressed. The reason it's called bleaching is because the algae provide much of the color in the coral tissue, and once they are gone, the coral tissue becomes transparent, and the white skeleton beneath becomes visible. Whether a coral dies from bleaching depends on the severity and duration of the stress. Corals can re-establish their algae if environmental conditions return to normal, but in the meantime they are weakened and more susceptible to disease.

Bleaching can be caused by quite a variety of stresses, such as temperatures that are too hot or too cold, increases in solar radiation, and rapid changes in salinity, but over the last decade, the increase in coral bleaching worldwide has been attributed

mainly to increases in sea surface temperature. Increases in the average maximum temperature by as little as one degree Celsius can induce bleaching.

ER: What is the connection between atmospheric carbon dioxide and corals?

JK: Carbon dioxide has increased in the atmosphere by some 30 percent since the year 1880, and is expected to double by around 2065. As excess carbon dioxide in the atmosphere is absorbed into the surface ocean, seawater chemistry is altered. In experiments which simulate these seawater chemistry changes, corals and reef-building algae — often called coralline algae because they resemble corals — both show a decrease in calcification. The rate at which these organisms secrete calcium carbonate is correlated with how many calcium and carbonate ions are available in the water. There is a



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balance in seawater carbonate chemistry so that the concentrations of carbonate and bicarbonate ions are continually shifting in response to changes in carbon dioxide. If less carbonate ion is available, then saturation state is lowered, and it is more difficult for those organisms to secrete calcium carbonate. So adding carbon dioxide to seawater lowers the saturation state, and taking it up raises it.

Typically, the surface oceans are supersaturated with calcium carbonate, but the ions do not precipitate out directly. Instead, most of the precipitation is done through calcification by organisms. As more carbon dioxide is dissolved in seawater, saturation state decreases. We're predicting that because of the drop in saturation state, calcification by reef building organisms will also decline. Since calcium carbonate is the building block of reefs, this decline in calcification may affect the status of entire reef ecosystems.

ER: What takes up carbon dioxide from seawater?

JK: Plants. In the oceans, most plant-life are algae, both unicellular phytoplankton, and the larger macro algae. As plants photosynthesize, they take carbon dioxide out of the water. Corals and calcareous algae secrete their skeletons by extracting both calcium and carbonate ions from seawater. If one lowers the concentration of either ion, then the saturation state also declines. Aquarists know they have to maintain high calcium levels in their tanks if they want healthy coral growth. But in the open ocean, the calcium ion is very abundant and doesn't change very rapidly. We're more concerned with the carbonate ion because its concentra-

tion responds rapidly to changes in carbon dioxide.

ER: Haven't we heard something like this before?

JK: In the seventies there were several publications which predicted that increases in atmospheric carbon dioxide would cause the surface oceans to become undersaturated with respect to calcium carbonate, and that by the year 2000, many marine calcifying ecosystems could collapse. However their calculations didn't take into account the buffering capacity of the carbonate system. Later calculations showed that the surface oceans wouldn't become undersaturated with calcium carbonate until atmospheric carbon dioxide levels were ten times the preindustrial level. So assuming that calcification would continue as long as the calcium carbonate remained supersaturated, the issue was largely forgotten. What recent experiments show however, from aquaria and in the Biosphere 2, is that the degree of supersaturation is important in calcification.

ER: Can corals respond to changing ion availability?

JK: These relatively simple organisms like corals and coralline algae apparently do not have strong mechanisms for controlling their internal chemistry. They appear to be at the mercy of their environment. I would not try to extrapolate this to higher organisms like molluscs or some of the more advanced organisms which have greater control on their internal chemistry. For example, a clam

can pump water, so it may be able to sequester ions for building its shell, and it once it precipitates that shell, it can protect it from dissolution by covering it with organic layers.

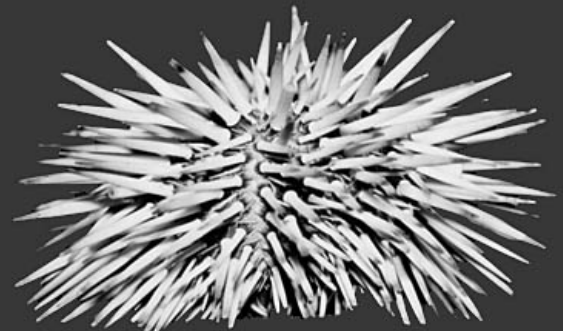
ER: Is there any reality testing? A lot of your work here involved two different computer models.

JK: Right. We do not have much field evidence from actual coral reefs that this is actually happening. Our work extrapolates from aquarium and Biosphere 2 experiments to the real world. It is time to go out and see if this is really happening.

ER: How?

JK: One of the first ways is to look at corals which have survived over the last one hundred years to see if there have been changes in their calcification. There are various ways to do this. This is analogous to the tree-ring methodologies. Scientists are already using corals extensively for paleoclimate analysis, and we need to develop the tools to look for calcification changes in the past. We also need to look at the whole system to see if there is some mechanism within reefs which can effectively buffer the carbon dioxide-driven changes in saturation state. There are many various ways to look for this evidence, and they cross many different disci-

Sea urchin: Images courtesy of NOAA



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plines, including biology, chemistry, and geology. The concern is that we currently have little reason to doubt that increasing atmospheric carbon dioxide will indeed impact coral reefs.

ER: Is there a connection between changing ocean surface chemistry and coral bleaching and disease?

JK: We don't have an answer to that question yet, but certainly the overall decline in the planet's coral reefs suggests that there could be a connection. So far, we have only addressed the direct effects of the ocean chemistry on corals. Certainly if a change in saturation state is an added stress on corals, one would expect it will have some effects. A decrease in coral calcification is something akin to osteoporosis: the live tissue of the coral may not be affected, but its supportive skeletal structure may be weakened and more susceptible to breakage.

We have a long way to go before we fully understand the implications of decreased calcification on coral reefs. But even though we don't understand how this might affect overall coral or reef health, it intuitively suggests that decreased calcification poses an additional threat to all of those other impacts reefs are facing today, such as overharvesting, dynamite fishing, cyanide fishing, pollution, and increased iron and nitrate availability.

ER: How big a problem is the change in carbon chemistry in relation to all of the other insults that corals face?

JK: It's significant, and because the entire surface ocean is in contact with the atmosphere, the carbon chemistry changes are global. However, compared to some of the other impacts to reefs, which are often lethal to reef organisms, we do not suspect that reduced calcification will be lethal. The corals will probably survive, but their capacity to build reefs will decline. A reef is the accumulation of calcium carbonate, so more calcium carbonate must be produced than is removed. If carbonate production is lowered and rates of erosion are not, the accumulation rates are going to decline.

Corals apparently do not have strong mechanisms for controlling their internal chemistry. They appear to be at the mercy of their environment.

This build-up of calcium carbonate creates space for other organisms; it allows a reef to keep up with sea level change; and the buildups provide protection for many coastlines. Carbonate production is a valued part of the ecosystem and if it decreases, the reef structures themselves will weaken. We saw that in the Galapagos during the 1982-83 El Niño. Ninety-eight percent of the corals died. With carbonate production halted, those reefs underwent phenomenal rates of erosion for several years. Fortunately, once the reef was recolonized by corals and coralline algae, the process reversed.

In the case of atmospherically-driven reductions in reef calcification, we do not expect the process to be reversed. So if you think of this as a chronic problem of not being able to

secrete calcium carbonate, you can see what's going to happen.

We have some reefs that live near the edge of a reef's environmental limits, and they are just barely reefs in the sense of accumulating much calcium carbonate. If we lower the calcium carbonate production on those reefs, what's going to happen? And if the coral skeletons are weaker, then how will individual corals hold up to storms? They're more likely to break up.

And we can expect community changes, where some of the corals that we see today will decline and perhaps others will increase. There is tremendous competition for space on coral reefs; there's a pecking order out there. There have been large community shifts in the Caribbean as the staghorn coral, *Acropora*, has died off,

and other species have come in and taken over the newly available space. A classic example was in Belize where large tracts of *Acropora* were killed by disease. Another species, *Agaricia*, colonized the empty space and became the predominant coral there. But very recently, and only a few years after this species became dominant, it experienced massive bleaching and died. We haven't seen these kinds of community structure changes for thousands of years.

Further Reading:

Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs. JA Kleypas, RW Buddemeier, D Archer, JP Gattusso, C Langdon, BN Opdyke 1999 *Science* 284:118-120



How Big Do Marine Reserves Need To Be?

Introduction:

The Florida Keys National Marine Sanctuary encompasses about 2,800 square miles off the south coast of Florida. The sanctuary was established to minimize human impacts to particularly high risk habitats, promote scientific research, and maintain natural assemblages of living resources. In a letter to *Science* magazine, Craig Dahlgren pointed out that the reserves in the sanctuary were being evaluated for a hoped for benefit, replenishing fish stocks, a purpose for which they were not designed¹. We spoke with him about conservation in the Keys and about how large reserves would need to be to replenish fish stocks.

ER: Dr. Dahlgren, what's your training and your current job?

CD: I received my Ph.D. from North Carolina State University in the summer of 1998. I did my dissertation research at the Caribbean Marine Research Center in the Bahamas where I studied population dynamics of Nassau grouper. I've also done work on community ecology and population ecology of some other species as well, mostly in the Caribbean and South Atlantic area.

Now, I'm a postdoctoral scientist working on marine protected areas, marine reserves, and marine sanctuaries as a part of the Center for Marine Conservation's ecosystem program.

ER: What prompted you to write a letter to *Science*?

CD: Well, since the time I started here I've been involved with the work we're doing in the Florida Keys National Marine Sanctuary, specifically thinking about what a marine reserve in the Dry Tortugas should look like: what type of habitat should be included, what it should be designed to do, and how big it should be.

Last November there was a big symposium on marine reserves at a Marine Lab in Florida and I gave a talk about design considerations for the Dry Tortugas reserve. I spoke about how big it should be to achieve certain objectives such as protecting species at risk of local extinction, or enhancing fisheries. I was not saying which of those objectives we should do, just if we want to achieve a particular objective we need a reserve that's big enough to do the job.

One of the biggest problems is that fish stocks have been drastically reduced, below sustainable levels in many cases.

In reading *Science* I saw the note in the Random Sample section talking about the progress they've seen on the existing no-take areas in the Keys, which are all very small. The short article said that the reserves were building biomass of some species, like spiny lobster, which is true, and may eventually provide the hoped for benefit of enhancing fisheries.

As I said in my letter, these areas weren't necessarily designed to provide any kind of benefits to the fishery at all. Because these areas were so small, they probably aren't capable of making a substantial contribution to replenishing fish stocks

outside of their own boundaries. They might be great at protecting what's in them, but not necessarily enhancing the fishery outside of them.

ER: What is the sanctuary intended to do?

CD: The National Marine Sanctuary program was designed to provide a higher degree of protection for marine resources in specific areas, in addition to allowing some traditional uses within their boundaries. The Florida Keys Marine Sanctuary is one of the newer National Marine Sanctuaries; however, there have been marine sanctuaries in the Keys for a while. There was a small sanctuary in the Looe Key area, and another one up at Key Largo. Around 1997 they combined these two sanctuaries and incorporated a large area extending all the way from the upper keys, the Key Largo area, to the Dry Tortugas and Tortugas Bank into the Florida Keys National Marine Sanctuary.

So the Florida Keys National Marine Sanctuary incorporated areas that were previously

under different jurisdictions in order to manage the entire Keys ecosystem rather than just an individual geographic region.

When they developed the management plan for the Florida Keys Sanctuary it was a pretty new approach to marine management in terms of zoning different areas with different levels of protection. Other countries have zoned marine areas for specific uses, but this approach to marine management has not really been done much in the United States.

There are areas where you're not allowed to fish but you're allowed to dive, or areas where even divers aren't

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allowed to go and you're only allowed to go there to do scientific research. Zones that prohibit fishing are the type of areas that the Science article that I commented on was talking about.

ER: How big is the overall sanctuary?

CD: It's about 2,800 square nautical miles.

ER: How is that broken down into zones?

CD: Most of the sanctuary is regulated under one set of rules, but within it they've set aside some pretty small areas actually, with a higher degree of protection in them. The main areas have just general, not very prohibitive rules about what kind of fishing is allowed. For example, there is no trapping of fish allowed in the sanctuary.

ER: What about commercial fisheries?

CD: Commercial fishing is allowed within the sanctuary, as is recreational fishing. There are some gear restrictions on what you can and can't do in the sanctuary, but in general most things are allowed. So most of the sanctuary provides the lowest level of protection.

ER: How much of the sanctuary is under these permissive regulations?

CD: It's on the order of 99 percent. The largest of the zones where they have increased protection is about one half of one percent of the total sanctuary. The largest of these zones is an ecological reserve. It's the Western

Sambos Ecological Reserve, about thirty-one square kilometers. It works out to be about 0.5 percent of the total sanctuary area. It is basically a band that extends from land off the lower Keys towards the shelf edge. It protects a variety of habitats, shallow water nursery habits that many fish and lobsters use, and extends out to where the adults live as well. It's meant to integrate habitats required by all the different life stages of an animal into one area that will protect them all the time.

ER: Is this a scientific study site?

CD: Yes. It went into effect in 1997, and it's being monitored now to see what changes occur over time. The article I commented on mentioned some of the changes they are seeing: an increase in the average size of lobsters and some other effects, but it's still a very early stage in the game and you wouldn't expect to see too many changes after just two years of protection. Over three, four, five, ten years you should start seeing more significant changes.

So that's the largest area. There are also several areas called Sanctuary

The burden of proof should be shifted to show that fishing doesn't have a negative impact on the natural community.

Preservation Areas (SPAs) and special use areas which are very small. Those are on the order of a single square kilometer in size, and are designed to protect some of the shallow coral reefs that are most damaged or most at risk to damage by boats that might ground on them.

The Western Sambos reserve is a no-take area, no fishing is allowed in

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there at all. Some of these small SPAs are even more restricted where no diving is allowed or you need a research permit to dive in them.

ER: What led to the reserves being put in?

CD: Well, they were put in place in response to a number of things actually. One of the biggest problems, not just in the Florida Keys but in other places as well, is that fish stocks have been drastically reduced, below sustainable levels in many cases.

Last year a paper came out by Jerry Ault, who is at the University of Miami and Jim Bonesack, who works at Marine Fishery Service². They have been doing stock assessments of snapper and grouper species, a major part of the fishery, and they found that the majority of them were below federally defined levels for being

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overfished. The fish stocks are depleted, and that's one of the reasons why they wanted to have these areas that were no-take and restricted, to see if fish stocks would rebound within those areas.

Some of the Sanctuary Preservation Areas were made even more restrictive because those are the ones that are most at risk. There have been a number of ship groundings on the Florida reef track within the Keys within what is the sanctuary now, so they wanted to provide an additional level of protection to them.

ER: What have government agencies done to address overfishing in the Keys?

CD: Everything from the shoreline out to three miles is regulated by the state. Everything on the Atlantic coast of Florida and on the southern side of the Keys from that three miles out to 200 miles is under the jurisdiction of the South Atlantic Fishery Management Council. And on the Gulf, basically the north side of the Keys and into the Gulf of Mexico outside of state waters, is the Gulf of Mexico Fishery Management Council.

Not all of those three organizations are necessarily on the same page. There hasn't been any plan to do a buyout or that kind of thing, but each of those three organizations have taken steps in some way or another. Depending on the fishery, the fish species in question, they have taken steps to reduce fishing effort on the stocks, whether that's setting some sort of quotas or limiting the type or amount of gear that could be used, but haven't bought up boats or anything like that to ease the fishing pressure.

ER: How are the commercial fishers doing?

CD: When the sanctuary was first proposed with a number of different no-take reserves in it, fishermen protested it heavily and got a number of no take areas knocked off the proposed management plan and others cut down in size. So they were effective from the start at minimizing the potential impact it would have on them.

Since the existing management plan has been in place over the past few years, I'm not sure if there have been many changes in the fishery. And if there have, I'm not sure if you'd be able to determine if it was due to the change in protection of certain areas or not. So the short answer to your question is I don't know. The long answer is I'm not sure if you'd be able to tell yet, simply because the areas that are closed to fishing are pretty small and it's been such a short time. A positive indica-

To produce fisheries benefits using a no-take reserve, it requires a reserve size of at least 30 percent of the area to bring stocks up above the overfished level for the entire region...

tion that fishermen are not being hurt too badly is that they have, to this point, supported the creation of a fairly large no-take area in the Dry Tortugas region.

ER: Here in the Pacific Northwest the response to depletion of salmon or halibut or cod is pretty easy to gauge because most of the fishermen have gotten out of the business. Has it come to that in the Keys?

CD: Not yet at least. Most fish stocks in the Keys probably aren't as bad as most of the salmon stocks of the Pacific Northwest. This may be due to differing life history characteristics of fish in each area. Another thing that the Keys have going for them that the Pacific Northwest doesn't is simply the sheer number of species that are fished for. They are not depending on salmon or very few species, there's a pretty wide range. Because there are a number of different species in the Keys, if you fish one stock down you just switch and go to another stock.

Also, the problem with the salmon has largely to do with the fact that the fish are returning to the same streams where they were spawned, which may or may not be in any condition to support them in the future. In the Keys there are mechanisms that retain larvae; that is, fish spawned in the Keys will be retained in there. However, there also is a large potential for fish larvae that are

spawned elsewhere to come into the Keys. This is particularly important for spiny lobster. Lobster have a larval stage that lasts up to a year, so the lobster that are being caught in the Keys may be coming from somewhere else in the

Caribbean or Gulf of Mexico to start with, so the Keys may not be dependent on their own stocks for replenishment.

ER: You said these highly restricted no-take areas are being praised for something for which they weren't set up to do. Were they set up for scientific research?

CD: Yes, mostly for scientific research but also for other reasons.

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Again, protection against the catastrophic effect of, say, a ship grounding. They were also set up to let a natural community develop over time. This effect has been shown in other places where fishing is prohibited.

In other countries — throughout the Caribbean, Australia, New Zealand, Philippines — where they have much more experience with this type of no-take reserve than we do, setting aside a given section of reef or of whatever bottom type has, in most cases, resulted in a number of large changes, such as increase in fish (and invertebrate) abundance, increase in the number of species you'll find in an area, increase in fish size in an area, and even changes in the life history characteristics of protected species.

ER: Do fish seek out sanctuaries?

CD: We don't really know. It's likely that any increases in fish abundances inside the no-take areas are simply due to the fact that fish are not being captured in these areas, but there probably is some degree of movement into or out of an area based on an increase in prey or predators. That's something that a number of different scientists are looking into right now.

ER: So the United States is learning fisheries recovery from Third World Countries.

CD: Yes, and even learning from countries like the Philippines that have a pretty dismal record when it comes to marine conservation. Some of these small no-take preserves that they have set up have been shown to do an excellent job of preserving natural coral reef communities, as well as enhancing fisheries outside of them.

ER: What do you think would be the best thing for the Florida Keys?

CD: In general beyond the Florida Keys, when we think about fishing and setting up no-take areas, the way it's approached by policy makers now is that fishing should be allowed and it should be proven that a no-take reserve is going to produce benefits before it's established.

The thinking has to be shifted to the perspective that the ecological community that exists in the absence of fishing is the natural state of things. The burden of proof should be shifted to show that the fishing doesn't have a negative impact on that natural community. If we were to do that in the Florida Keys it would probably not be a place where 0.5 percent is set aside as no fishing, but a place where the majority of it would be no-take and areas where you are allowed to fish would be the smaller part.

ER: Is that an aesthetic vision or a synthesis of what you think is sustainable?

CD: It's a little of both. It is an aesthetic vision in that I'm placing a high value on natural communities, but there is a lot of scientific work to show how big a reserve has to be to produce fishing benefits. In cases where stocks are severely overfished, like in the Florida Keys, reducing catch hasn't been able to prevent overfishing, but establishing large reserves that cover 50, 60, up to even 80 percent of the area will allow a sustainable catch at a high level in the fished areas. So reserves can serve as a fishery management tool.

In my work, specifically dealing with the Dry Tortugas, I've shown that to produce fisheries benefits using

a no-take reserve, it requires a reserve size of at least 25 to 30 percent of the area to bring stocks up above the overfished level for the entire region, and it more likely requires reserves including up to 70 percent of the area, depending on different variables. But protecting a large area will allow you to sustainably harvest high levels in other areas.

ER: How does the protected area replenish fish stocks?

CD: The main way that it can do that is either by protecting enough spawning stock that the fish that are spawned are carried by currents into the fished area and serve as a source of replenishment that way. Or juvenile and adults can leave the reserve and go into the fished area and then be caught.

My work has looked at both of those factors to see how big an area needs to be for both of those to contribute to the fishery and bring it up to a certain level. Many of the models I'm using are looking at the state that fish stocks are at right now as a percentage of what they would be under natural conditions.

Under federal guidelines that define what overfishing is, for most species you want to preserve at least 30 percent of that virgin unexploited stock so that they can replenish themselves. I've been looking at how big that reserve needs to be to bring that percentage up above the 30 percent level for an entire region.

If you have a stock that's fished down to 1 percent of its virgin level, we want to see how big a reserve we need to have to bring it up to 30 percent on average for the entire region. Assuming that the fish stock in the protected area will go up to 100 percent, we can work out the math,

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and it comes out to be we need to protect 25 percent of the area with a completely natural stock to bring the stocks in the entire region up that much on average.

Once we have that basic equation down, then we start saying, Well, what if you don't get a completely virgin stock building up in your reserve? What if fish are leaving and being caught in the fishery? How much larger does our total reserve have to be to protect enough to bring it up to 30 percent? There's nothing magic about that 30 percent number. That's been cited by other authors as a threshold level. A more reasonable target might be to be conservative and say you want to keep all your stocks at 40 percent.

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