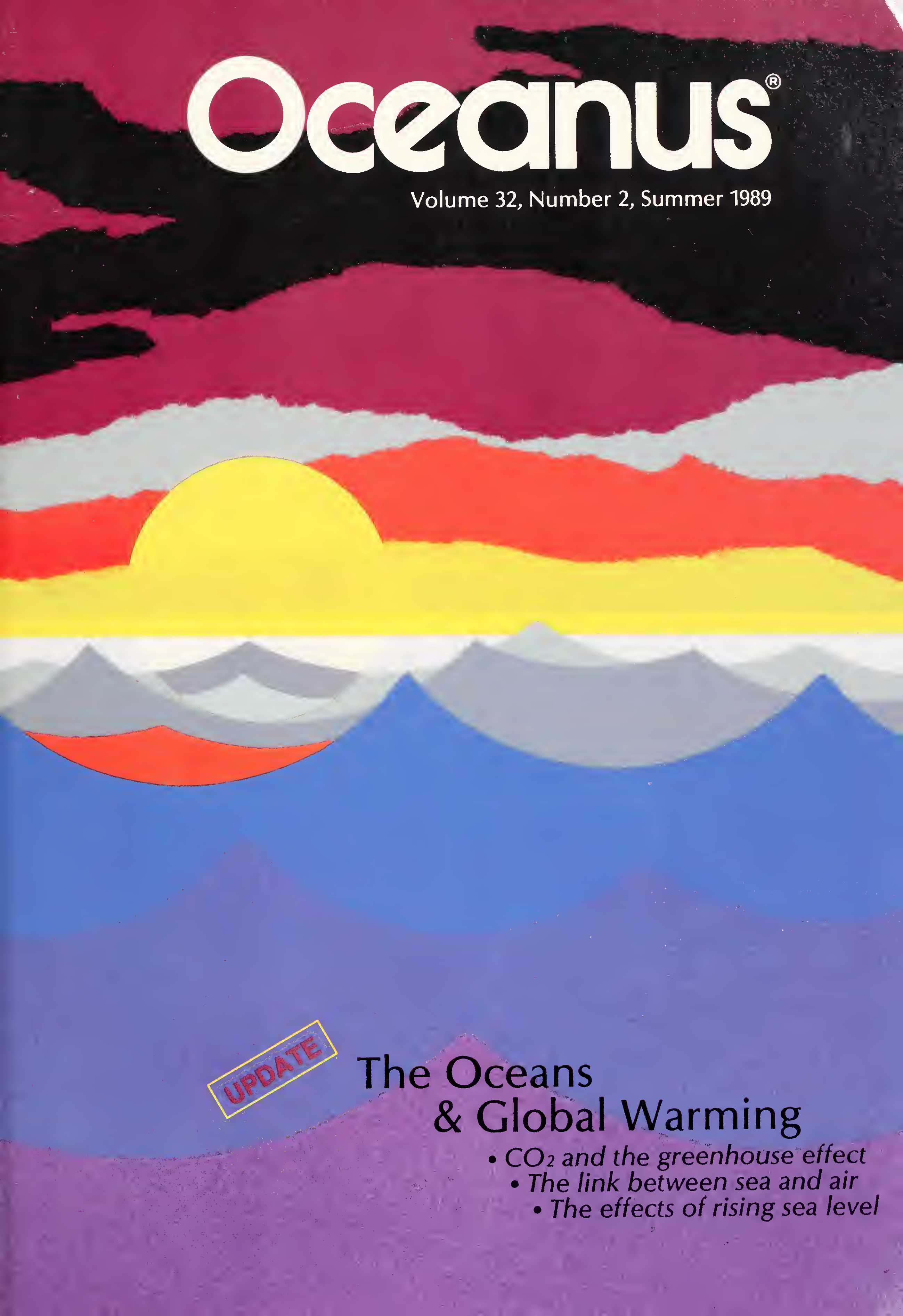

Oceanus®

Volume 32, Number 2, Summer 1989

UPDATE

The Oceans & Global Warming

- CO_2 and the greenhouse effect
- The link between sea and air
- The effects of rising sea level

Oceanus®

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Volume 32, Number 2, Summer 1989

Frederic Golden, *Acting Editor*
T. M. Hawley, *Assistant Editor*
Sara L. Ellis, *Editorial Assistant*

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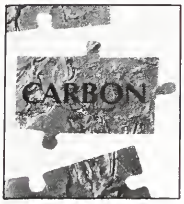

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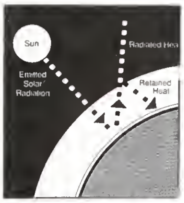

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Introduction

The Role of the Seas in the Planetary Hothouse

Everybody talks about the weather, says the old saw, but nobody does anything about it.* Actually, that's no longer true. Something *is* being done about the weather, not tomorrow's or even next week's, but that in the long haul. If eminent climatologists are to be believed, our fair planet is slowly warming, and largely because of our own folly.

The outline of the story, repeated again and again on television and in print, is painfully familiar. Ever since the beginning of the Industrial Revolution, we've been steadily pumping carbon dioxide and other gases into the atmosphere from the burning of fossil fuels—first wood and coal, now largely oil. To compound the mischief, we've sharply reduced our forests, one of nature's key mechanisms for removing carbon dioxide from the air.

The net result is that atmospheric carbon dioxide is up by an estimated 25 percent since preindustrial times, enhancing a phenomenon called the "greenhouse effect." There's irony in the name. We usually think of greenhouses as repositories of pretty flowers, yet this planetary hothouse will be anything but pleasant. According to the predictions, global temperatures will rise as much as five degrees Celsius in the next century. Rainfall patterns will be sharply realigned, accompanied by a shift in the world's agricultural breadbaskets—generally northward in our hemisphere. Still worse, sea levels will rise around the world, inundating many low-lying coastal areas.

That's the bad news.

The good news, if it can be called that, is that even the gloomiest climate prophets acknowledge that one major element has been either ignored or at the very least insufficiently examined in the various global warming scenarios. And, if we're lucky, this missing factor could possibly mitigate some of the worst consequences.

As readers of this magazine know only too well, the unsolved *X* in the climatic equation is the ocean. Accounting for nearly three-quarters of the Earth's surface, the seas obviously play a major part in maintaining the planet's heat balance, reprocessing atmospheric carbon dioxide, and interacting with the atmosphere in other ways, yet for too long they have been treated as climatology's stepchild, inconsequential components of the global weather machine.

Now that is changing. The role of the ocean in global climate has become a major priority of scientific investigation, not only among American researchers but among scientists around the world. It is also the theme of this issue, in which we offer an update on the new work involving the ocean and global change. Faithful readers will recognize it's our third foray into this subject (*Oceanus*, Vol. 21, No. 4; and Vol. 29, No. 4). And they may well wonder, why sail the same course? The answer is, so much is happening that another look is warranted.

As you read the pages that follow, you'll learn that an unprecedented number of climate-related investigations are in the planning stage or have already begun. In his comprehensive survey of these programs, oceanographer Jim Baker, the president of the Joint Oceanographic Institutions, Incorporated, lists a veritable alphabet soup of initialed undertakings (WOCE, GOFS, IGBP etc.), involving many hundreds of scientists. In one way or another, they are driven by a common goal: to learn more about how the seas, atmosphere, and land work together.

Another author draws a major message from these investigations. John Steele, the president of the Woods Hole Oceanographic Institution (WHOI) and an eminent mathematical biologist, observes that the life in the seas and the physical mechanisms of the ocean operate on vastly different scales of time and space than do their terrestrial analogs. Perhaps, he says, these differences will suggest ways of meeting the problem of global change. And maybe they can even be put to work for us.

Implicit in many of the articles, and in much of the work, are the big questions about the ocean and climate change. Will the seas moderate the global warming or make it worse? Will they dampen the anticipated swings of the climatic pendulum by soaking up excess heat or

*The saying is often attributed to Mark Twain, who had many witty comments about the weather (example: "One of the brightest gems in the New England weather is the dazzling uncertainty of it"). But in fact, it first appeared in an editorial in the *Hartford Courant* in 1897, probably written by Charles Dudley Warner, Twain's onetime collaborator.

carbon dioxide, or will they make them even greater?

No one can provide any certain answers, yet. In spite of years of investigation, the physical and chemical processes at work in the ocean are still very much a mystery. As Taro Takahashi of the Lamont-Doherty Geological Observatory points out, we don't really know—at least not in any precise way—whether the ocean has the capability of picking up the additional carbon dioxide entering the atmosphere or whether it will accelerate the buildup. That's because we're only beginning to study such basic issues as the ocean's carbon cycle—if, for instance, the phytoplankton population will expand in response to additional atmospheric carbon dioxide.

Why is it that these things remain such profound puzzles? Have scientists somehow been derelict, too compartmentalized in their own subspecialities to look at the global perspective? Until now, terrestrial and marine systems have often been considered separately, each an independent preserve overseen by its own cadre of specialists. As ocean scientists themselves admit, they've been slow getting on the climate bandwagon, letting others have it pretty much to themselves.

Indeed, some of the most interesting climate work has involved specialists in atmospheric studies. And often, as Tom Levenson points out in his essay, they've concentrated on climatic calamities: the global cold and dark that might have killed the dinosaurs 65 million years ago or that might come to haunt us in the future if there is ever an exchange of nuclear missiles. Some scientists are even looking for answers to neighboring planets like Venus, whose own primeval ocean, as Jim Kasting writes, may have vanished in a runaway greenhouse effect in the early days of the solar system. As always, what may seem like farfetched theorizing has ways of producing instructive results: in this case, an improved understanding of basic climate mechanisms.

This is evident closer to home in the recent progress made in understanding, even predicting, the climatic phenomenon called El Niño. No longer can it be viewed simply as a problem for Peruvian fishermen and farmers. The halt in the cold, fertile upwelling of water along their coast is only one small aspect of a far larger picture, which in turn has acquired a fittingly larger name, El Niño/Southern Oscillation. ENSO, as it's known for short in climate circles, involves a major flip-flop in ocean currents and winds. And as the National Oceanic and Atmospheric Administration's Ants Leetmaa writes, its effects can extend far and wide. One of them apparently was last year's drought in the American Plains. Thanks to improvements in computer modeling, even with relatively crude data, Leetmaa says, scientists can now anticipate such events months in advance.

Preparing for the climatic mayhem anticipated in the years ahead is another matter. The challenges posed by the predicted global changes are so enormous that they defy simple solutions. We could, for example, assume the worst and make major policy changes accordingly, say WHOI's Andrew Solow and James Broadus. But what if we're wrong in our assumptions? What if, as they argue, climatic catastrophe isn't really around the corner? In such a case, major changes, undertaken on a crash basis, could not only undermine scientific credibility—to say nothing of wasting a lot of money—but also jeopardize actions that may be required in the future.

If there is a single message from our authors, it's this: We need not only more research—aren't scientists always saying that?—but, equally important, research that is interdisciplinary, coordinated, and international in scope. No longer can we afford to treat the sea, land, and air as distinctly separate entities, each the fiefdom of its own specialists. We must remember that they are part and parcel of the same planet, intimately and powerfully linked, even more so than had been imagined. In ways that we are only beginning to understand, what happens on land is affected by what happens in the air and by what happens in the seas. It's a simple but critical message.

A personal note. With this issue, I am returning the helm of this very special publication—the only one I know of that writes seriously, intelligently, and passionately about the seas for nonscientists as well as scientists—to its regular editor, the very able Paul R. Ryan, who has completed nine months of profitable study in Japan as a Fulbright fellow that I'm sure he'll share with you.

My own stay here has been profitable as well. Apart from living in a delightful community by the sea, it has given me a chance to see closeup an institution I've long admired from afar and glimpse the intriguing and important work of its talented scientists. It has also brought many new friendships, which, I'm sure, I will come to cherish even more from the more distant perspective of my home in San Francisco.

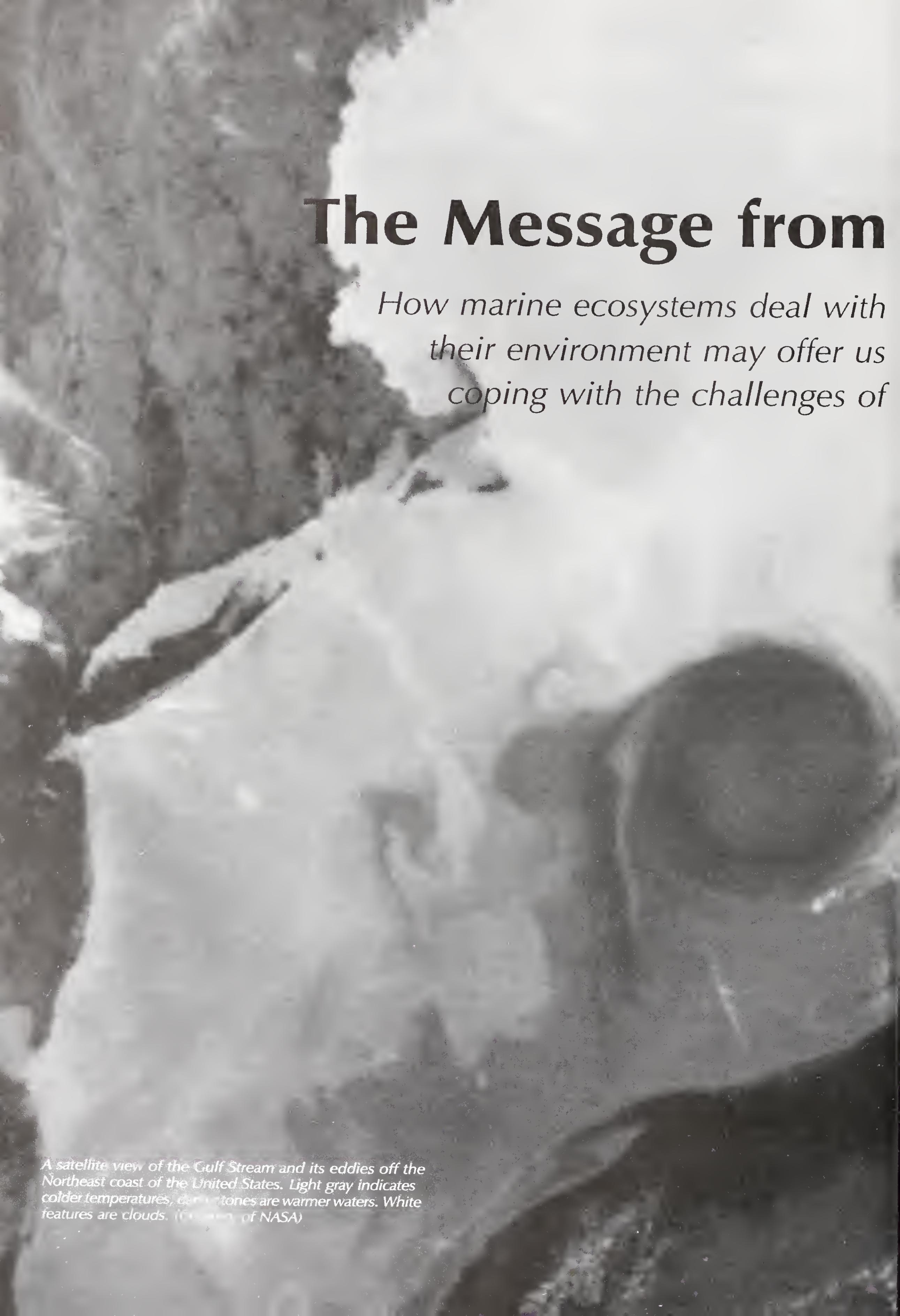
Many kindnesses were shown during my nine months here—by people within the WHOI community and without. I couldn't possibly mention them all, but I do want to single out for special thanks John Steele, who selected me for this rare opportunity; his successor, Craig Dorman, who offered cooperation and encouragement; and my colleagues, Tim Hawley and Sara Ellis, who not only cheerfully offered their skills and support but also made an outsider feel immediately at home.

Every editor has his own style, strengths, and, yes, idiosyncracies—which attentive readers may well have detected. In any case, my editing has been guided by a view I believe many of you surely share. It's that science is so important to our well-being, so intrinsically exciting in what it tells us about our world, that we can't let it remain the secret of only an enlightened few.

—Frederic Golden
Acting Editor, *Oceanus*

The Message from

How marine ecosystems deal with their environment may offer us coping with the challenges of



A satellite view of the Gulf Stream and its eddies off the Northeast coast of the United States. Light gray indicates colder temperatures, darker tones are warmer waters. White features are clouds. (Courtesy of NASA)

the Oceans

sudden changes in some lessons in global warming.

by John H. Steele

From what we hear on television and read in the press, it seems that our present excesses—from wholesale destruction of the rain forest to widescale pollution of the atmosphere and ocean—are the sole cause of the anticipated changes in global climate. Yet, as I write this article in my office on Cape Cod, I can't help but reflect on the transitory nature of certain aspects of our planet entirely unconnected with human activities.

The Cape, for example, is nothing more than a pile of rubble—though certainly a beautiful one—left behind 10,000 years ago by a retreating glacier, the remnants of the last ice age. Similarly, as recently as a thousand years ago, during a brief warm period unconnected with any human intervention, Iceland, Greenland, and Newfoundland were sites of thriving European agricultural colonies, as well as the preferred route to the New World. Closer to our time, during the "Little Ice Age" (*Oceanus* Vol. 29, No. 4, pp. 38–39) of the 15th to the 19th centuries, George Washington's troops shivered at Valley Forge, and the Thames River in England froze over every winter.

For the last century, there has been a general warming trend but even that has proceeded at an irregular pace, with falls as well as rises in mean temperature (Figure 1). This variability raises important questions: How much of the change is natural? How much of it is of our creation? Are we still escaping from that last cold period, or do the recent changes in global temperature portend an entirely new manmade climate?

The physicists and chemists and those who create simulated worlds on computers must try to answer these questions. But for much of mankind, if the predictions are correct, the answers will appear locally or regionally in the living part of their own environment as declining forests, failing crops, and disappearing fish stocks. Again, such climate-linked changes are not new. The collapse of the Hanseatic League in the 14th century may well have been associated with the disappearance of herring from the Baltic.

More Limited in Our Flexibility

In the past, societies confronted changes in their food supply by either adapting to them or migrating—an example of the latter being the mass exodus from Ireland following the potato famine of the mid-19th century. Now, however, our flexibility is more limited.

In spite of our increased mobility as

John H. Steele is President of the Corporation of the Woods Hole Oceanographic Institution and a Senior Scientist at its Marine Policy Center, and has long studied the food-chain dynamics of ocean ecosystems.

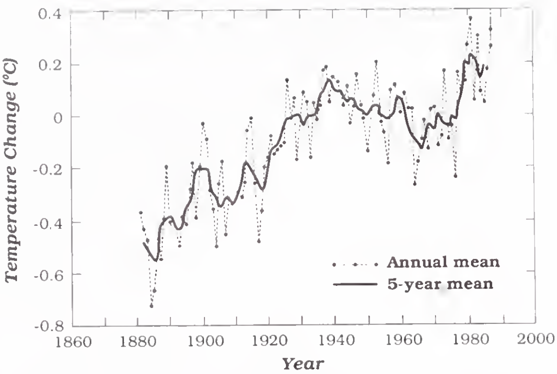


Figure 1. Variations in average temperature of the globe (land and sea) expressed as departures from the mean over the last 30 years.

individuals, thanks to the automobile and the airplane, societies are more rigid and either unwilling or unable to move; imagine, for instance, how difficult it would be to shift a major population center like metropolitan New York. Also, as a technological society that sharply alters its environment (by reshaping the land, building extensively, and releasing wastes into the atmosphere and seas), we ourselves have become a major element in its physics and biology—in effect, altering the equations.

Perhaps the most important aspect of the impending climatic change, if we are to accept the predictions, is its speed. We're told that it will occur so rapidly as to make technical solutions or cultural adaptation all but impossible. In this respect, our situation differs radically from that which confronted societies in the past.

Time is the new, and in my view critical, factor in global climate change. We need to know how rapidly the changes will occur on land, in the sea and air, and, of course, in human behavior. What's more, in extracting these rates from the complexity of environmental processes, we must take into account their spatial dimensions—that is, how large a region will be affected by a particular change. This approach allows us to use what I like to call space-time diagrams to compare diverse parts of our environment and help explain how they interact. Possibly this approach can help teach us how to cope with our changing world.

Let's consider weather. As we study our space-time diagram (Figure 2), we can see the progression from intense local short-lived disturbances, such as tornadoes, up to the circumglobal fronts (long waves, like the jet stream) that undulate across North America and bring changes in weather over almost the entire country. Yet even on a global scale, weather changes rapidly from week to week. Because of this variability, prediction becomes virtually impossible for periods beyond about two weeks (except, of course, for seasonal changes).

How have terrestrial plants and animals managed to survive the large variability in climate? Plants have worked out a simple solution for themselves. Generally, they have much longer life spans than animals—on the order of centuries or more in the case of some trees—so they can bridge the short-term fluctuations. Even the perennial grasses create a soil environment that takes a long time to develop but can then withstand year-to-year changes.

In the past, animals (including our ancestors) were closely linked to these longer time scales through the availability of food supplies. They flourished in times of feast, and foundered in years of famine. To protect themselves against the vagaries of weather, most higher animals evolved certain defensive strategies, such as warm-bloodedness, living in burrows (or air-conditioned houses), and producing fewer offspring but nurturing them longer to ensure their survival.

In either case, the general solution to the ecological problem of coping with short-term but large-scale variability in weather was to live longer—a Pritikin strategy, if you will—so that over a lifetime these unpredictable elements can be smoothed out. In my space and time scale diagram, this is seen as the "distance" between the physical regime and the biological response: days to weeks for the former, years to centuries for the latter.

But is longevity the only solution? Also, where does climate enter into these relations? The oceans offer some answers. First, consider their physics. Although they are fluid like the atmosphere with all the turbulent features we see in the air, they operate on very different time scales because water is much denser and more viscous than air. The ocean's eddies—rings of motion—correspond to cyclonic features in the atmosphere, but whereas tropical storms have lifetimes of days or at most weeks, eddies last for many months. The great ocean gyres, like the circulation of the North Atlantic, are similarly

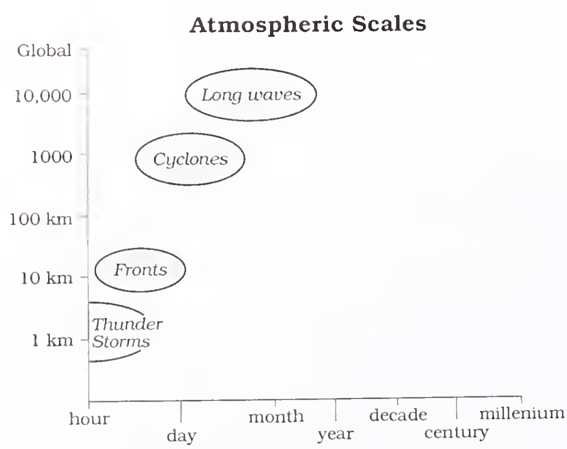


Figure 2. The space and time scales for weather events and for the dominant aspects of terrestrial ecosystems.

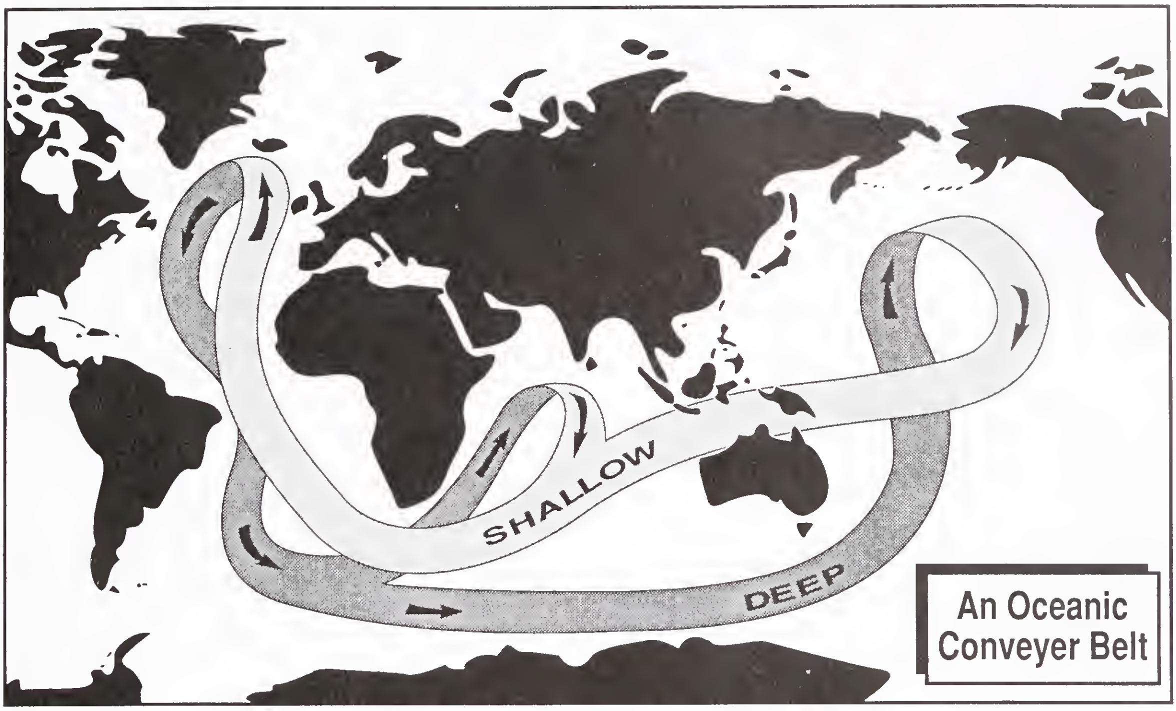


Figure 3. The long-term (centuries) circulation of water through the deep oceans returning as surface movements. (After Broecker et al., 1985)

long-lived. They take about a decade to circumnavigate an ocean basin.

Finally, there is the exchange of the ocean's warm surface layers with the cold deep ocean a mile or more down. This has been pictured as a global conveyor belt, driven by cooling in the polar regions (Figure 3). The time scale for this vertical exchange and circulation is between a century and a millennium.

Thus, with their ranges of years, decades, and even centuries, oceanic processes involve time scales we now call "climate" (Figure 4a). It's no wonder that life originated, not on land but in the much more stable sea. Indeed, as our reconnaissance of the solar system seems to show, only the Earth has life. Dry planets are not habitable; oceans are needed because they are the dominant reservoirs for water and carbon, the major components of living organisms.

Irregularities in the Oceanic Flywheel

Certainly, the oceans smooth out the daily and seasonal cycles so that, in the shorter term, we find coastal areas the most desirable habitats. But the tremendous heat capacity of the ocean and its slow dynamics also mean that its movements, both horizontal and vertical, act like a huge flywheel driving the world's climate at a relatively steady pace. Even so, this flywheel develops irregularities.

During the last ice age, the conveyor belt was generally slowed down and certainly was stopped in the Arctic. And even at much shorter, year-to-year scales, we're beginning to see that natural phenomena like El Niño* can change the circulation of the tropical Pacific with dramatic consequences for climate and food production in Asia and the Americas. An El Niño event is now considered responsible for the 1988 drought in the Midwest. Eventually we'll probably be able to predict such events six months ahead, but this is still far short of making useful forecasts for the next few decades.

Research is now under way to determine the underlying ocean processes and the feasibility of such long-term predictions. But even with our best scientific efforts, it's possible that, as with weather prediction, there may well be an ultimate limit—of a few years rather than decades—to our forecasting ability.

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*A warmer and more southerly flow of water along the Peru and Chile coast that acts almost like a blanket, sharply curtailing the nutrient-rich upwelling there, and dramatically reducing the highly productive anchovy fishery. Because the warmer current often seemed to appear around Christmastime, local fishermen named it El Niño, Spanish for "the [Christ] Child." More recently, it has been linked to a wider phenomenon called the Southern Oscillation: a change in the prevailing westerly trade winds across the Pacific, characterized first by a buildup in their strength, then a decline. As the winds diminish, water that they propeled westward "sloshes" back toward the west coast of South America, causing an El Niño event. The El Niño/Southern Oscillation process can create climatic effects all around the Pacific rim, not just in Peru and Chile (*Oceanus* Vol. 27, No. 2).

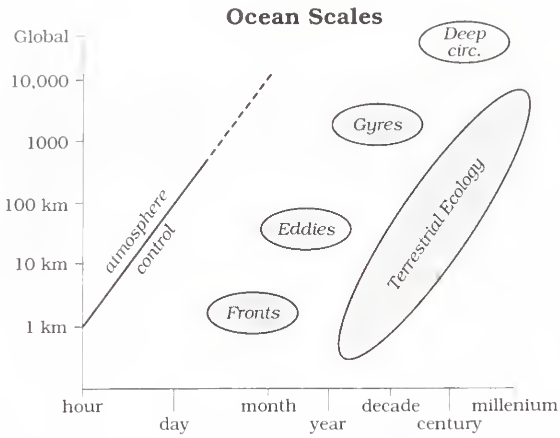

Figure 4a.

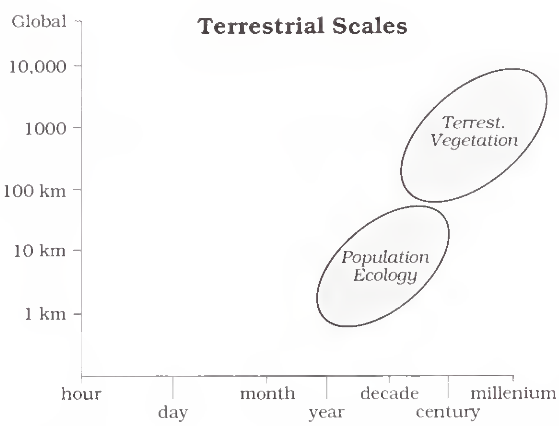

Figure 4b.

In the meantime, what can we say about the response of living systems to this kind of variability in the sea? The oceans provide a fascinating example of a completely different "solution" to the problem of living with uncertainty. Consider the planktonic plants in the open sea, the basic units of production at the bottom of the food chain. Microscopic in size, they have lifetimes of hours or days (compared to centuries for forests). Many of the dominant herbivores, the small crustaceans that graze on these tiny plants, live for a few months, about the lifetime of the eddies; and the pelagic fish, such as herring or tuna, which feed on these smaller creatures, live for several years or even decades and make use of the local or ocean gyres for their migration patterns. Thus, the space and time scales for organisms living in the open sea correspond closely to those of their physical environment (Figure 4a)—the greater the area they occupy in their lifetime, the longer they live.

Furthermore, their modes of reproduction are generally very different from land animals. Most open-ocean animals expend their energy on producing a large number of eggs—thousands to millions—but once released and fertilized, these are at the mercy of the environment and must be dispersed or carried by currents to favorable areas for feeding, growth, and survival.

There are many reasons for these alternatives to the life processes on land. Changes in sea temperature, for example, are much more predictable and less variable on time scales of weeks and months compared to the changes in temperatures over land. Oceanic life-forms don't have to work against gravity the way terrestrial ones do since the ocean's viscosity is greater than air's, and passive movement with the currents is less energetically demanding than directed movement through the water. For such reasons, life in the sea has evolved a quite different response to the problem of dealing with environmental uncertainty.

It's intriguing to use these space-time diagrams to illustrate the two quite different ways that marine and terrestrial life-forms meet the challenge. When you compare Figures 2 and 4b, you see that land organisms separate the time scales as much as possible to avoid the variable physical effects on land, while marine organisms couple the scales closely to utilize the dynamics of the marine system.

Enlarged Impacts, Speeded Up Change

What has humanity done from the perspective of space and time scales? Until the last century, our presence lay well within the context of the "natural" world, as depicted in Figure 2. But as this century has progressed, we have enlarged the scale of our impacts and speeded up the process of change. The most pervasive and best known changes are in the increased concentrations of the "greenhouse" gases, especially carbon dioxide. Changes in carbon dioxide levels are, to be sure, not a new phenomenon. We know from ice cores and other studies that concentrations of this gas were low during the last ice age. What may be new is the faster rate of change resulting from our burning of fossil carbon accumulated over millions of years.

Plowing the soil, although hallowed by custom, is the most unnatural act we perform on our environment. It always disturbs, and can quickly destroy, the work of nature over centuries. Acceptable in moderation, disruption of this organic matrix is now altering the appearance of the globe in tropical forests and at the edge of deserts. The latter process—desertification—is affecting a whole region of Africa called the Sahel. We can see these changes from space but cannot yet decide how much of this change is "climate" and how much is the immediate impact of expanding human populations.

And then, of course there is the multitude of new industrial processes that alter the world in multifarious ways. The chlorofluorocarbons (CFCs) are just one example of our capability to create a new global impact—an attack on atmosphere's protective ozone shield, which screens out lethal x-rays. The damage was done within one or two decades but will probably last a century.

If we take these diverse human activities at their present levels, we can define new positions for the scales at which we are interacting with our world (Figure 5). This is merely one way of expressing our general perception that we are playing an increasing role in changing the Earth. But the method of presentation also permits us to compare these rates with those of the atmosphere and the ocean (Figure 6). I have simplified the earlier discussion to present "weather" as the short-term control by the atmosphere, and "climate" as the consequence of long-period variability dominated by changes in the oceans. El Niño is included as our best known and understood phenomenon, occurring irregularly at intervals of 5 to 10 years and apparently affecting a large part of the world.

But what this approach allows us to portray is the consequences of our recent activities. Those that stem from industrial innovation, like the introduction of new chemicals such as CFCs, may occur rapidly, but others, like effects of expanded farming, grow out of the increase in scale (examples: the many acres of rain forest taken under cultivation daily through clear-cutting and slash-and-burn agriculture). By this reckoning, increasing spatial scale and more rapid change are additive factors in shifting to the left or upwards the place of human activities in the space-time graph. They have now moved into the region we have defined as ocean climate.

Apparently, we are creating not merely a quantitative change in our environment, but a qualitatively different relationship as well. Instead of a social and ecological system that can absorb the variability of shorter climate scales, we now have a system where the scales overlap. We're now closely coupled to our environment by many different processes.

Can we manage such a relationship? Can we slow it down? There is much to be said for doing all we can to decrease the rate of our advance (if that is the appropriate word). But "back to nature" is not practicable in the context of my space-time diagram. Small, and slow, may be beautiful; and parts of the highly cultivated European countryside are examples of this philosophy at work. But the rapidly expanding cities on every continent are not going to disappear. And so we must learn how to survive, closely coupled to an unpredictable world.

The analogy with marine communities is far-fetched, to be sure, but at least they offer examples of ecosystems that absorb and utilize the variability and unpredictable elements in their environment. We have yet to learn how to accept not merely the good surprises such as the "green revolution" but also the droughts and even the Chernobyls. We ought to try to look ahead to the next century, even if we can't expect a clear picture. And we must keep in mind that a critical part of the story will lie in the oceans. □

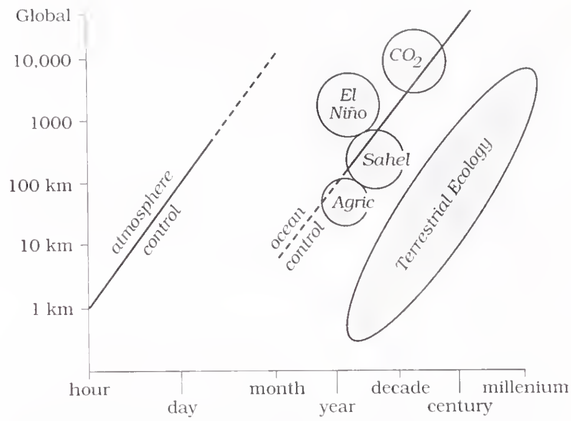

Figure 6. A comparison of the space and time scales for land, sea, and human processes.

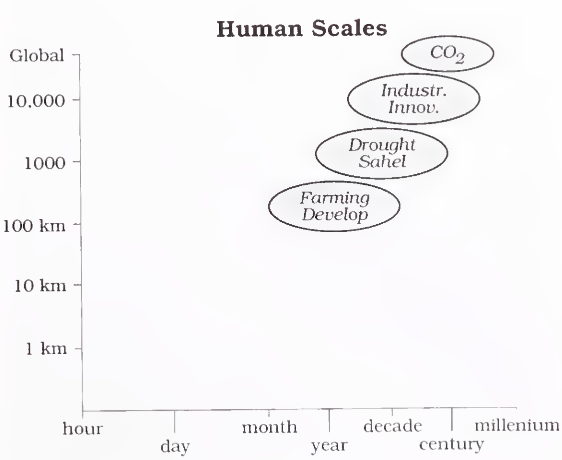

Figure 5. Present scales of human activity.

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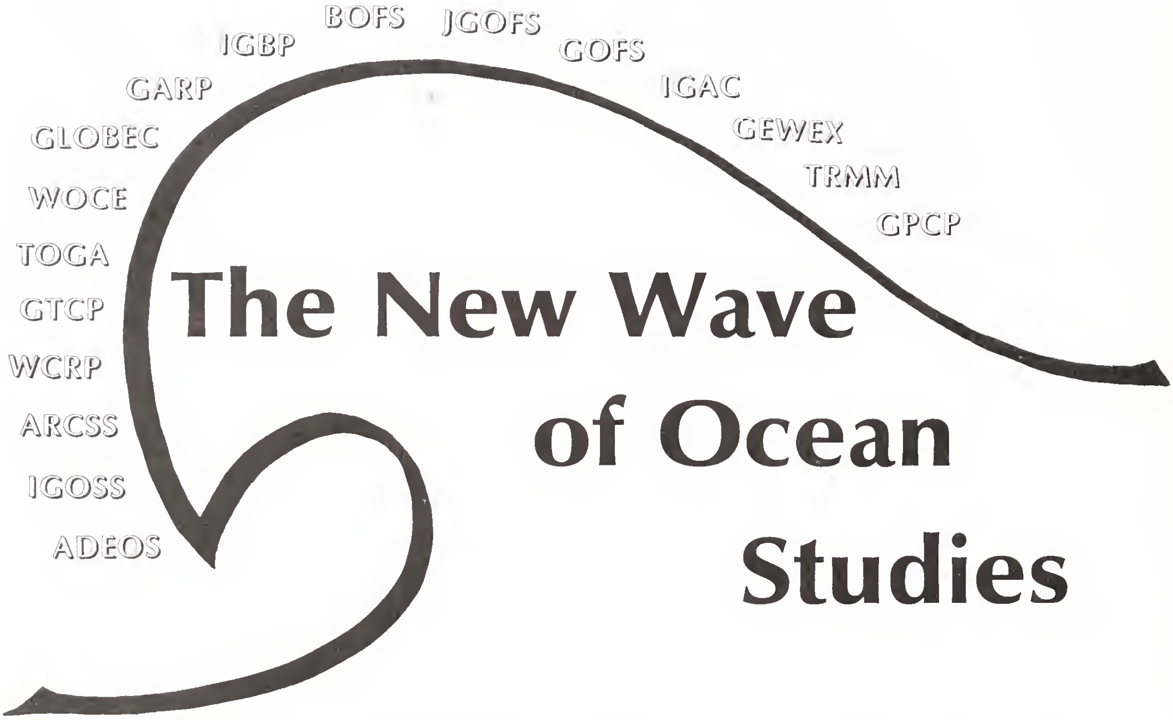


The New Wave of Ocean Studies

In the face of global climate change, oceanographers are intensifying their efforts to understand how the air and sea interact using a host of large, cooperative programs.

by D. James Baker

Although there have been substantial advances in our understanding of how the ocean interacts with the atmosphere to change climates, many of the easiest questions to frame remain the hardest to answer. Some examples: Does the Gulf Stream warm Europe? How much heat is transported by the ocean as part of the Earth's heat budget? How do the ocean and the atmosphere work together to produce the phenomenon known as El Niño? How does ocean circulation affect the uptake of carbon dioxide and other "greenhouse" gases linked to global warming? How do biological processes in the ocean influence global change?

The beginning of any answers to such basic questions lies in the efforts of many researchers who have worked diligently to understand how the ocean works on many scales. As they have gathered knowledge of the global ocean, they have also learned that an essential element of progress is the coordinated program. That's not to say that all progress lies in such programs, because research by talented individual scientists provides much of the stimulus and many of the new ideas for scientific advancement. But global-scale measurements encompassing the operation of large facilities and multiship observations require a degree of coordination beyond the reach of only a few scientists, working alone or in small groups. Only if they join forces in a large cooperative effort can a global data set be collected, usable by all for a greater understanding of the ocean at work.

Today there are a number of coordinated ocean programs aimed at different aspects of the general problem of global environmental change. What follows is a summary of those that are either primarily designed and carried out by the oceanographic community or that are of relevance and interest to ocean science. The programs are based in three disciplines—physical oceanography, geochemistry, and ecosystem dynamics—and also include geology.

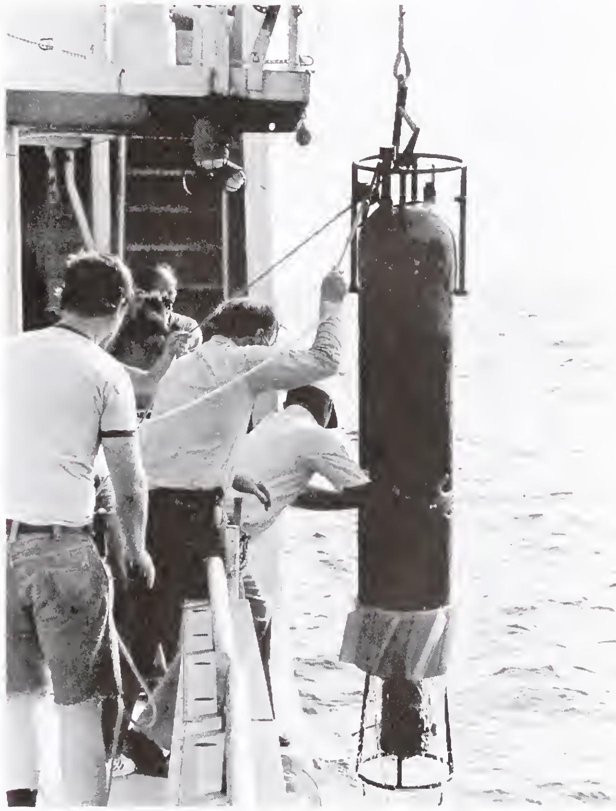
Launched with the Space Age

The recent history of global climate programs began with the space age and continued through the International Decade of Ocean Exploration (IDOE) of the 1970s. With the advent of operational weather satellites, the atmospheric science community recognized that major advances in weather prediction could be made with global data sets of atmospheric temperature, clouds, and surface boundary conditions. So it devised the Global Atmospheric Research Program (GARP), which had two goals: to improve weather prediction and to understand the physical basis of climate. After the successful Global Weather Experiment in 1979, which involved a full set of satellite observations of the atmosphere as well as major field studies, the World Climate Research Program (WCRP) was begun. Its focus was on clearing up two major areas of uncertainty in models of climate: the role of clouds and radiation, and of the ocean.

Just before the Global Weather Experiment, in 1978, NASA's Seasat satellite demonstrated that it was possible, using new radar techniques, to measure from space a number of parameters of importance to the ocean. These include wind forcing (or stress) at the sea surface, waves, and broader-scale ocean surface topography. From the topography measurements, oceanographers can estimate horizontal pressure forces at the surface and determine geostrophic currents (those that balance the Coriolis force with pressure gradients).

In Seasat's brief life, cut short by a power failure, oceanographers saw the possibility of long-term global measurements of circulation. Out of this insight and the understanding of circulation gained from in situ studies during the IDOE came the analog of the Global Weather Experiment, the World Ocean Circulation Experiment (WOCE, *Oceanus*, Vol. 29, No. 4, page 25). NASA's Nimbus-7 satellite, also launched in 1978, showed that ocean color could be measured on a global scale. The data have been used to provide information about chlorophyll's regional and basin-wide concentrations for study of biogeochemical processes. Such studies provide clues to the growth and distribution of phytoplankton, which plays a key role in the absorption of carbon dioxide.

At about the same time, we began seeing results from a number of studies aimed at understanding tropical oceans and their role in the anomalous ocean temperature changes and associated atmospheric pressure patterns known as El Niño and the Southern Oscillation. WCRP provided a useful framework for these programs, which were amalgamated into a global study, called the Tropical Ocean/Global Atmosphere (TOGA) program.



Scientists launch an absolute velocity profiler, which measures horizontal forces as it is hoisted up from the ocean floor. Such techniques are used to track currents. (Courtesy of Woods Hole Oceanographic Institution)

Involving both oceanographers and atmospheric scientists, TOGA was launched in 1985 as the first major project of WCRP and is expected to last 10 years. TOGA will measure changes in the tropical oceans and global atmosphere over an extended period to see if predictions can be made on time scales of months to years. It also seeks to understand the basic physical processes underlying its predictability; to study the feasibility of modeling the coupled ocean-atmosphere system for

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purposes of predicting its variations on the same time scales; and to help design observational and data transmission systems for operational prediction.

TOGA has established a quasi-operational monitoring network of drifting and moored buoys, sea-level gauges, and upper-layer and meteorological measurements from volunteer observing ships in the tropical Pacific, Atlantic, and Indian Oceans. In 1986 and '87, the value of the TOGA program was demonstrated as experimental predictions by TOGA scientists at the Lamont-Doherty Geological Observatory and data from the TOGA observing system made it clear that a warm event was under way. The Peruvian government used this information to help Peru's farmers make the right decision about which crops to grow. The models used at Lamont and other institutions, including Florida State University, the National Oceanic and Atmospheric Administration's (NOAA) Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, and the National Center for Atmospheric Research in Boulder, Colorado, are based on an understanding of the ocean developed over the years by oceanographers interested in the equatorial regions and their interactions with the atmosphere.

The models are far from perfect, but they do show some skill in forecasting at lead times out to a year or more. The results from 1986 and '87 are important as a demonstration that forecasts of El Niño and associated events are possible many months ahead, in spite of the poor quality of the data and the relative simplicity of the models used. Much work remains to be done with the forecasting models so that we'll know how far to trust their predictions.

TOGA has also been useful in the study of the atmospheric interactions between the tropical and temperate regions. El Niño warming in the equatorial Pacific Ocean has been observed to alternate with a periodic cooling, called La Niña (article, pp. 30–34). The cold cycle may have played a major role in the drought of 1988. The cold water along the equator appears to have caused a displacement of warm water farther north, leading to changes in the jet stream. Although the links between the tropical and temperate atmosphere are poorly understood, it is possible that these changes were at least partially responsible for the large, rainless high-pressure system that brought on the drought. The links between the tropics and midlatitudes uncovered by TOGA will help in the development of climate prediction schemes. By focusing on the tropical system, we are beginning to learn how that critical system works.

Testing the Predictions

The second major ocean part of WCRP is the World Ocean Circulation Experiment. Its primary goals are to develop models useful for predicting climate change and to collect data necessary to test them; to determine the representativeness of the specific WOCE data sets for the long-term behavior of the ocean; and to find methods for determining long-term changes in ocean circulation. Specific parts of the program will include efforts to determine and understand on a global basis, the divergences over five years in the large-scale flows of heat and freshwater, and their annual and interannual variability. In addition, the WOCE investigators will probe the dynamical balance of global circulation and its response to changing surface conditions of winds, temperature, and rainfall. They will seek to identify the components of ocean variability on temporal scales of months to years, and spatial scales of thousands of kilometers to global, as well as examine the statistics on smaller scales. They will also investigate the rates and nature of water-mass formation and circulation that influence climate over periods from 10 years to a century.

A second goal of WOCE focuses on long time scales. The object is to identify those oceanographic parameters, indices, and fields essential for continuing measurements in a climate-observing system on a time scale of decades, and to develop cost-effective techniques suitable for deployment in an ongoing system.

WOCE has as its central element a global observing network that would provide precise

This buoy carries meteorological instruments that record data as it floats in the sea. (Courtesy of the Woods Hole Oceanographic Institution) satellite measurements of sea-surface topography, currents, temperature, salinity, and various chemicals. It will begin its field phase in 1990. In early 1991, these programs will be supported by the launch of the European Space Agency's ocean satellite ERS-1. It will provide global wind measurements by scatterometer (a device that probes the surface with radar and uses the scattered radiation to determine the state of the surface), and surface-topography measurements by altimeter.

In 1992, the joint U.S./French precision altimeter mission TOPEX/POSEIDON will begin to provide accurate measurements of surface topography. With these various global data sets, modelers should finally be able to shed light on ocean circulation and its interaction with the atmosphere on a global scale. A NASA scatterometer, also for global wind measurements, is scheduled for flight on the Japanese Advance Earth Observation Satellite (ADEOS) in early 1995.

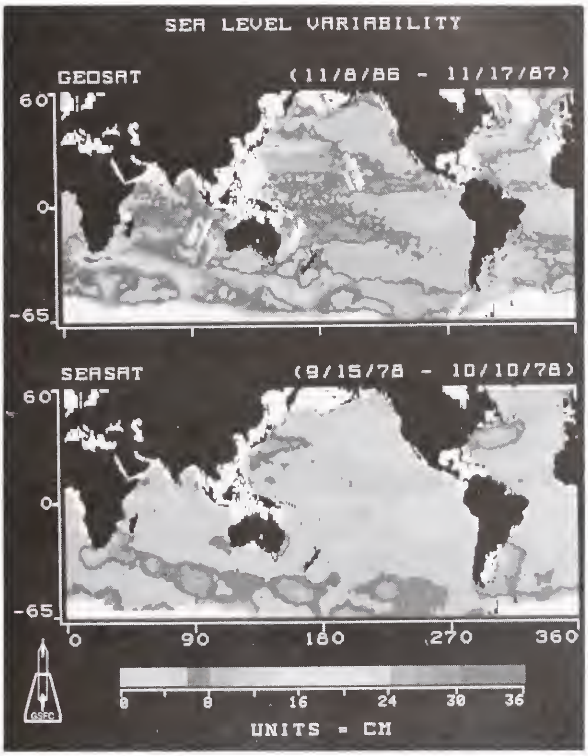
A new global energy and water cycle study proposed by WCRP is aimed at the large uncertainties in the amounts and rates at which water moves through its various phases on Earth: freshwater, seawater, water vapor, and ice. Consequently, light will be shed on global atmospheric and oceanic energy budgets. The major new initiative is called the Global Energy and Water Cycle Experiment (GEWEX) and is planned for the late 1990s. GEWEX will model the global hydrological cycle and its impacts in the atmosphere and the ocean; and it will develop the ability to predict the variations of global and regional hydrological processes and the response of water resources to environmental change. The overall objective is to foster the creation of observing techniques, data management, and assimilation systems suitable for operational application to long-range weather forecasts, hydrology, and climate predictions.

But global change is not limited to physical climate. During the late 1970s, atmospheric chemists recognized that other trace chemicals in the atmosphere, including methane, nitrous oxide, and chlorofluorocarbons can have a cumulative effect on climate equal to that of carbon dioxide. The Global Tropospheric Chemistry Program (GTCP) and the International Global Atmospheric Chemistry program (IGAC) have been proposed to study these issues.

GTCP will measure and model concentrations and distributions of gases and aerosols in the lower atmosphere, or troposphere; the chemical reactions among atmospheric chemicals; sources and sinks of important trace gases and aerosols; and the exchange of gases and aerosols between the troposphere, the biosphere, the Earth's surface—including the ocean—and the stratosphere. GTCP will include field, laboratory, and modeling studies designed to improve understanding of the chemical reactions in the lower atmosphere and to develop new instruments for measuring trace atmospheric constituents. GTCP will take place in the context of IGAC, which is an initiative of the Commission of Atmospheric Chemistry and Global Pollution, of the International Association of Meteorology and Atmospheric Physics, of the International Council of Scientific Unions.

The Importance of Tiny Dust Particles

A potentially important mechanism for chemical influences on climate may occur through the tiny dust particles, or aerosols, formed over the



Sea-level variability as measured by altimeters. A precision version of the altimeter on an accurately tracked satellite, TOPEX/POSEIDON, will be used in WOCE for global measurements of circulation. Above, from Navy's Geodetic Satellite (Geosat); below, from NASA's Seasat. (Courtesy of C. Koblinsky, NASA Goddard Space Flight Center)

ocean from the oxidation products of dimethyl sulfide (DMS), a gas emitted by marine phytoplankton. Many of the physical properties of low-level clouds are dependent on the properties and distribution of the aerosols upon which the cloud droplets are formed. In turn, these affect the reflectivity, lifetime, and precipitation properties of these clouds. Because climatic factors may affect the activity of the marine phytoplankton, there is the possibility of a climate feedback loop through the formation of aerosols. The relationship between phytoplankton activity, DMS emissions, and aerosols needs to be clarified, including how they are affected by climate changes.

The linkage between ocean chemistry, biology, atmospheric chemistry, and climate is just one reason why, if we are to understand the cycles of the chemical elements, we must first understand their uptake and reactions with the ocean and its ecosystems. Technical advances in the 1970s and '80s enabled us to make global measurements of ocean color by satellite-borne instruments, and infer the ocean's biological productivity from the data. Also developed were in situ techniques for direct measurement of fluxes of biogenic material in the water column by sediment traps as well as high-precision methods for detecting trace species.

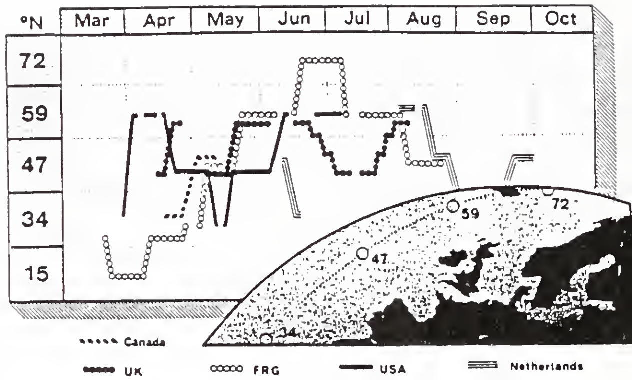
The need to understand biogeochemical cycles and the capabilities provided by the new techniques led to the development of the U.S. Global Ocean Flux Study (GOFS) and its international counterpart, the Joint Global Ocean Flux Study (JGOFS). The U.S. program also has its counterparts in other nations—the Biogeochemical Ocean Flux Study (BOFS) in Great Britain, for example. The goal of JGOFS is to determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor, and continental boundaries.

The JGOFS organizers have identified the special importance of carbon dioxide studies and the need for satellite observations of ocean color to determine the biological productivity of the ocean. To carry out a global survey of carbon dioxide, measurements of dissolved carbon dioxide will be made during the WOCE global survey by JGOFS scientists. The required satellite measurements stem from a large accumulation of data from the Coastal Zone Color Scanner aboard NASA's Nimbus-7 satellite instrument. JGOFS' first field experiment began this last spring; scientists hope that a new satellite ocean-color instrument will be available in the early 1990s. Such an instrument has been proposed by NASA to fly on the next Landsat satellite, Landsat-6, in 1991. However, present funding difficulties make that launch date uncertain. Without Landsat-6, the next scheduled satellite ocean-color instrument will be on the Japanese ADEOS satellite in early 1995.

Chemical and Biological Aspects

If we are to understand the Earth's overall climatic system, we must include the chemical and biological aspects in our studies. Recognizing this need, scientists are showing an increased interest in a comprehensive study that would integrate physical, chemical, and biological aspects of their present investigations. In response, the International Council of Scientific Unions has established the International Geosphere-Biosphere Program (IGBP), which has as its subtitle: a program for understanding global change.

IGBP, building on the basic physical framework provided by WCRP, is currently



JGOFS pilot study in the Northeast Atlantic, 1989. Cruise transects and stations around 20 degrees West (except Canada, 55-40 degrees West) and NASA aircraft overflights at 34, 47, and 59 degrees North between late April and early June. (Courtesy of Peter Brewer, Woods Hole Oceanographic Institution)

focusing on biological and chemical processes and the interface between these and the physical system. Of specific interest to IGBP are five key areas: biogeochemical cycles, ecological systems and dynamics, climate and hydrological systems, solid Earth dynamics, and studies of the human and social impacts of global environment change.

IGBP will seek to describe and understand the interactive physical, chemical, and biological processes that regulate the total Earth system, the unique environment that it provides for life, the changes occurring in this system, and the manner in which these changes are influenced by the environmental impacts of increased human population and industrial activity. The atmospheric chemistry program, IGAC, will be an important contributor to the goals of the IGBP. Also, JGOFS has been identified as a core program of the IGBP, in recognition of the key role of biogeochemical cycles in the ocean.

Other potential programs of relevance include the Global Ocean Ecosystem Dynamics (GLOBEC) program, aimed at understanding the response of marine plant and animal populations to environmentally driven changes in ocean circulation and chemistry. GLOBEC is now in the initial planning stages; it is expected to lead to the development of new ecosystem models to quantify the complex interactions responsible for the changing populations of ecosystems.

Oceanographers concerned with large-scale ocean-atmosphere interactions are interested in the role of rainfall over the ocean. It has long been recognized that the difference between precipitation and evaporation—the flux of freshwater—is one of the factors that influences ocean circulation. Although evaporation can be estimated, with some difficulty, from sea-surface temperature and surface wind (surface humidity is also required but difficult to measure at sea), precipitation cannot be, except at islands and from ships at sea.

The Global Precipitation Climatology Project (GPCP) is an effort to provide such data from operational satellites. Sponsored by WCRP, GPCP incorporates conventional rain-gauge measurements for continental areas; geostationary satellite infrared images for estimating the monthly convective-type precipitation in the belt between 40 degrees North latitude to 40 degrees South; and radiation in the microwave frequency range (which is sensitive to the presence of water) as detected by polar-orbiting satellites for estimating frontal-type precipitation in extratropical oceanic regions. GPCP began operations in 1987 and will provide global precipitation patterns for the period 1986–1995.

The new, water-sensitive, microwave techniques available with satellites promise to give global distributions of rainfall over both ocean and land. The first scheduled application of the techniques on a global scale over the oceans will be the Tropical Rainfall Measurement Mission (TRMM), a joint U.S./Japan satellite mission planned for the mid-1990s. TRMM measurements will be an important aspect of GEWEX. Operational satellite measurements of water vapor in the atmosphere have also recently been used to estimate surface humidity, with a promise of providing global determinations of evaporation from the ocean.

Our list of programs must also include the initial planning for Arctic System Science (ARCSS), aimed at understanding the natural interactions that link the Arctic environment to global climate, as well as to geological and oceanic processes. If successful, ARCSS will provide improved information and predictive modeling capabilities of physical and biological conditions and changes in the planet's environmentally sensitive polar regions. Using data from ice and sediment cores, ARCSS should help expand the understanding of Arctic paleoenvironments.

The Ocean Drilling Program (ODP) is an international effort that obtains cores of the Earth's crust beneath the oceans to reveal its composition, structure, and history. The program includes geophysical and geochemical studies, development of new techniques, and exploration of potential drilling regions by geophysical field studies. ODP contributes to global change studies primarily by accumulating and studying paleoclimate data from sediment cores.

Thus there are several large research programs either in progress or planned for the early 1990s to study the role of the ocean in climate change. Moreover, the technology necessary for improving the speed of computers to handle global ocean prediction models is also developing rapidly. It appears that the next generation of supercomputers, relying on high-speed parallel processors and other developments, will provide the number-crunching capability needed to incorporate the oceans in long-term studies of climate in a physically realistic way.

The list of research programs is long and impressive, but a major piece is still missing: a routine, global operational ocean-observing system. For the atmosphere, we have the World Weather Watch (WWW), which consists of a combination of satellite and in situ measurements in the atmosphere. Each nation participating has a national weather service that provides local data for transmission on the Global Telecommunications System (GTS). The world-wide satellite network, consisting of five geostationary satellites operated by the U.S., the European Space Agency, Japan, and India, and polar-orbiting satellites operated by the U.S. and the Soviet Union, also provides its data through GTS. This operational system is the basis for WWW and is driven by the needs of weather forecasting and civil aviation.

Heroic Efforts by NOAA

But there is no analogous World Ocean Watch, primarily because the same level of customer interest isn't there. Most countries don't have the ocean equivalent of a weather bureau, and those that do, like the U.S., don't provide the necessary money to make it viable. In the U.S., the National Ocean Service of NOAA has this charge, but in spite of heroic efforts by NOAA administrators and the Ocean Service's directors, there has never been sufficient federal funding to make it work. The international framework is in place, with the existence of the International Global Ocean Station System (IGOSS), sponsored jointly by the Intergovernmental Oceanographic Commission and the World Meteorological Organization.

IGOSS supports a global system of expendable bathythermographs (XBTS)—devices for taking the temperature of the upper ocean—and related ocean measurements by volunteer observing ships; these data are transmitted to data centers by GTS. But in the main, the funds for the XBTs come from research programs like TOGA and WOCE. If we are to see a long-term operational system, we must find a way to provide such instruments on a regular basis outside the usual sources of research funding.

Understanding global change requires global measurements in both the atmosphere and the ocean; for the long haul, we will need operational measurements. This transition from research to operations will be a focus for oceanography in the 1990s and into the 21st century. □

Supercomputers like this Cray XMP are the "crystal balls" of the scientific seers looking into the Earth's future climate. (All photographs in this article, except those noted, are courtesy of the National Center for Atmospheric Research)

The Model Makers

Scientists are now seeking a single model of the Earth's complex systems, including the oceans, to predict climate change

by Arthur Fisher

The world of modern science and engineering is filled with models, thanks to advances in both mathematics and computers. Specialists in many disciplines regularly employ models, which are attempts to reduce the myriad complexities of a system, natural or otherwise, to a mathematical formulation, or collection of algorithms, that can serve as instructions for a computer. Some models are grandly inclusive, some are exquisitely specific. Many are capable not only of emulating the system but also of making predictions about its future behavior.

There are models covering, for example, the spread of sulfur dioxide emissions from power plants; traffic on New York's Long Island Expressway; spruce budworm infestations; fluctuations in the Earth's magnetic field; tidal variations in the Bay of Fundy; rhythms of the human heart; the salmon run on the Columbia River; and even the socialized hunting behavior of African lions.

More ambitious in scope, and more demanding in their construction, are the regional weather/climate models—which any global model must mimic, incorporate, and far surpass. All models such as these must include, in part, one

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or more of the basic laws of classical, or Newtonian, mechanics—laws that encompass causal relationships and are therefore predictive. These fundamental precepts include Newton's laws of motion; the conservation laws for mass, energy, and momentum; the first and second laws of thermodynamics; and laws governing the radiation and transfer of electromagnetic energy. Modern models for weather prediction can be traced back to pioneers in the field: Vilhelm Bjerknes, Lewis Fry Richardson, and the computer genius John von Neumann (who contributed much of the computational vigor needed to treat such problems).

Today, scientists are pursuing numerous broad-scope models that are critical to the study of large-scale changes in climate. Many of these models involve the oceans, partners with the atmosphere in determining temperature and rainfall. Examples include an international program to model ocean circulation on a global scale, based on the World Ocean Circulation Experiment, to begin in 1990 with the launch of a European remote-sensing satellite; the Joint Global Ocean Flux Study, an international program that has as one of its components the Biogeochemical Ocean Flux Study, which will develop models of chemical and biological recycling processes in the oceans and of the way these are modified by climatic variations; and the Fine Resolution Antarctic Model, a simulation of the Antarctic Circumpolar Current (*Oceanus* Vol. 31, No. 2, pp. 53–58).

Contrasting Approaches

Weather/climate models are based on atmospheric physics. To be reliable, however, these models must take into account the interaction of the atmosphere and the surface layers of the oceans. For the last 20 years, scientists at the National Center for Atmospheric Research (NCAR) and at the Geophysics Fluid Dynamics Laboratory at Princeton University have been developing three-dimensional models of global atmospheric circulation, variously called General Circulation Models. In Boulder, NCAR has developed a similar model, the Community Climate Model.

What is the basis for constructing such a model? Intuitively, there may seem to be two contrasting approaches. One is to start from first principles—the laws of physics—and to assemble a group of equations describing them, feed in some initial conditions, and then see what comes out. In this approach, data from the real world are gathered mainly to serve as a check, to validate the model. The other approach is to gather as much real data as possible over a succession of narrow time intervals and then draw up a model that fits the data.

The distinction between the two approaches is that one is derived as far as possible from basic physical principles and the other is derived from purely empirical descriptions of present behavior with no basis for generalization to other circumstances.

Robert E. Dickinson, a senior scientist at NCAR, has explored this distinction in depth. He has been working on assembling three-dimensional atmospheric circulation models on a global scale for 20 years, using a process that essentially follows the first approach.

"There are basic physical equations that we believe govern the system," he says. Atmospheric motions, for example, are determined by the laws of hydrodynamics, expressed in the Navier-Stokes equations [equations governing the motions of simple fluids and gases]. "But we run into the problem

Veteran modeler Robert E. Dickinson creates three-dimensional atmospheric models based on first principles rather than collected data.

right away that these motions occur on all spatial scales." In global modeling, Dickinson explains, motions can be described only down to a scale of a few hundred kilometers; nothing finer can be described directly in terms of solutions to the Navier-Stokes equations. So modelers have to find simple, approximate ways to represent the effects of these subgrid-scale motions. "The classical approach," says Dickinson, "is to cook up so-called eddy-diffusion approximations, to argue that these small-scale motions diffuse things to the larger scale. That's approximately true in some cases, and in others not very realistic."

Besides the Navier-Stokes equations governing hydrodynamics, says Dickinson, modelers need to be concerned about the

This computer display shows the variations between two models of projected global-temperature increase over a three-year period. The models are identical except that one assumes the presence of twice as much carbon dioxide. The numbers in the contour lines indicate the difference in the predicted temperatures.

thermodynamics of the atmosphere and its details. Solar radiation drives the atmosphere. However, so much energy is reflected that it is necessary to examine the mechanisms involved: reflection either by the atmosphere itself—by way of clouds and aerosols—or by snow and ice at the earth's surface. Then modelers must account for the way the system responds to the outgoing longwave radiation that cools the system overall.

Nobody searches for a new model anymore and attempts to put one together from scratch, says Dickinson. Rather, researchers borrow from existing models and put in their own ideas. One example at NCAR has been the creation by Dickinson, Raymond G. Roble, and their colleague Cecily Ridley of NCAR's High Altitude Observatory of a numerical model of the dynamics of the thermosphere, an outer region of the atmosphere 80 to 500 kilometers up. Begun in 1978, the task was achieved by beginning with a global circulation model and then stripping out all the mountains, clouds, and radiation processes that were in the original. Then the NCAR team added the auroral processes, ionospheric interactions, and chemical reactions that occur in the upper atmosphere.

Modeling the Thermosphere

This kind of cobbling may not meet the present challenge, however. "Now we have to put new pieces into the existing model," says Dickinson. The motivation for writing new pieces, he says, is that the existing model does not reproduce observations as well as might be desired, and it may not correspond to the scientists' perception of the appropriate description of the physics. "We are trying to produce models that are derived as much as possible from basic physical principles and as little as possible from empiricism," he says, "because of the concern that empiricism might not extrapolate very well into the future."

Dickinson adds, "These models are usually quite different from those of the social scientist or the economist, for example, which are largely based on some simple relationships and a lot of data that determines the coefficients. Our models do not depend on the accumulation of vast amounts of data."

But Dickinson and his colleagues still depend on data for model validation. "When you put the model together," says Dickinson, "you have to have some data to convince yourself that you did it right—if nothing else, to turn up errors in programming or misunderstandings of the physics. Gathering data for validation is a never-ending job—I don't think we'll ever be finished."

There is also value in making predictions about some constrained part of the system and checking those predictions against independent data sets not used in setting up a model. "That is a process by which we systematically establish confidence in our models," says Francis Bretherton, formerly of NCAR and now Director of the Space Science and Engineering Center at the University of Wisconsin-Madison. "Every experienced modeler is acutely aware of the possibilities for producing numerical garbage—and the more complex the model, the messier the garbage."

"Oceanographers," says Bretherton, "have not had the benefit of the weather services of the world taking measurements for them over the last 100 years. In fact, we know much less about the dynamics of oceans than we do about the dynamics of the atmosphere." So oceanographers are more likely to rely on the other main approach to model building: the collecting of data that describe a system, not merely for validation but for assembling a first attempt at a realistic picture. (Actually, Bretherton says, all model building is a blend of the two.)

Part of the problem is the difference in important scales. Whereas atmospheric modelers work with weather systems having spatial scales of 500 to 1,000 kilometers, the analogue in the ocean is more like 25 to 50 kilometers. The difference is attributable to the higher density of water, but also to such details as the disparate speeds of currents in air and water.

Given those differences, says Bretherton, oceanographers need to simulate these so-called mesoscale eddies—the 25-to-50-kilometer phenomena—to get more plausible large-scale dynamics. But to do that, to really get a complete data set comparable to the ones that exist for large-scale systems in the atmosphere, there would have to be an observation grid over the ocean every 25 kilometers.

"We're beginning to get such observations from the surface via satellite," says Bretherton, "but God help us in terms of the traditional methods of measuring the ocean." So the oceanographers have built a general description of the ocean's circulation from what data they have. "They've put much more reliance on tracers," Bretherton explains, "to say that it looks like the water has gone from here to there and mixed in a way that we can't quite quantify—but we think there is a current in that general direction—the sort of thing meterologists would have to throw their hands up at."

In a Bind with Ocean Circulation

Another problem is that the atmosphere has an intrinsic time scale measured in days or weeks, not years. So an atmospheric model would need to be run through only a few annual cycles to get a very good idea of what the world would be like with, say, twice as much carbon dioxide as the present levels. But the intrinsic time scale in the ocean is measured in centuries, because that is how long it takes the ocean to respond to changes in external conditions.

"So we are really in a bind with ocean circulation," says Bretherton. "We have to run the model far longer, because the ocean time scale is measured in centuries; we also have to have higher resolution, because the key dynamical scales are smaller. Put those together, and we have to have much more number crunching to simulate the ocean circulation with the same degree of fidelity that we do for the atmosphere. The difference is a greater reliance on empirical data for the ocean than for the atmosphere. Our confidence that we can build models a priori and that they'll be of reasonable faithfulness is much higher for the atmosphere than for the oceans."

One measure of "reasonable faithfulness" is whether a model closely matches the current state of a system, and then whether it can predict the future of that system when given its initial conditions. Berrien Moore III, director of the University of New Hampshire's Institute for the Study of Earth, Oceans, and Space, describes model building as occupying a continuum ranging from what he calls diagnostic to prognostic. With diagnostic models, he explains,

Francis Bretherton wants more data from the oceans.

the researcher is not seeking to predict, he is simply asking, "To what extent can I describe the extant behavior in the system?"

For example, Moore cites two basic lines of attack in modeling the ocean at the ocean-basin or global scale. One is prognostic, paralleling the global climate modeling work for the atmosphere, and not surprisingly, is typical of institutions like NCAR and the Geophysics Fluid Dynamics Laboratory with a history of interest in such modeling. The other is an outgrowth of what are termed box models, and rests upon advances made in what are called inverse methods.

"What we do [in this second approach]," says Moore, "is take observed distributions of chemical constituents—salt, carbon, phosphorus, alkalinity, etc.—that have been measured on oceanographic expeditions. Then we ask: What is the best set of flows—turbulent mixing terms, biological activity, carbon fixation, or decomposition—that would give you such a distribution? That doesn't mean it necessarily corresponds with reality. It's just a description of flows consistent with the observations. There may be more than one such set, maybe an infinite number of consistent descriptions—or there may be none." Such a description is purely diagnostic; prediction is still off in the future. However, says Moore, "for terrestrial modeling, we are beginning to write down what we could call the rules."

Trouble in the Biosphere

Moore has been concerned for a long time with the global carbon cycle. In the earth's biosphere, the flow of carbon to and from the atmosphere is controlled primarily by photosynthetic activity for carbon fixation and by the oxidation of material—respiration. The fixation term, Moore says, can be controlled by what is present in the environment—type of vegetation, light, moisture, temperature, and nutrient availability. With a record of these variables, it is possible to describe the time course of carbon dioxide uptake.

There is now a model consisting of a system of partial differential equations that describes the rate of carbon fixation in terms of those variables. "We have photosynthetic equations, equations of state," Moore says. "We know what form the equations have, and if we change the variables, we assume we can predict what's going to happen to the carbon cycle. Actually, that model is only on the verge of being prognostic."

One reason is that Moore and his colleagues do not really have the kind of first principles from which to derive equations with sufficient confidence. "With biology," says Bretherton, "we are largely in the empirical business. Any person trying to model terrestrial ecosystems who strays very far from the present level is in trouble. And that level is 'Hey, I got these trends from these data sets, and if my model doesn't fit them, throw the model out and start from scratch.' "

Another difficulty stems from the system being tightly coupled. Moisture in the soil, for example, depends on temperature, precipitation, soil type, and in fact, on type of vegetation. So the growth of vegetation—carbon fixation—depends on soil moisture, but soil moisture depends on vegetation—some of the moisture is being absorbed by the vegetation—which may also be responsible for preventing runoff.

"So," says Moore, "not only are we dealing with partial differentials with multiple variables but the variables themselves are functions of other multivariables—they're tightly coupled. There are feedback loops all over the place." Moore refers to the middle ground, between purely diagnostic models and fully reliable prognostic ones, as agnostic, "because I wonder what the hell we're doing." Such middle-ground models are a blend of first principles and of purely deduced phenomena.

Berrien Moore III follows the carbon cycle. (Courtesy of the University of New Hampshire)

There is a further confounding factor—human intervention—that must be built into any model to gain prognostic ability. This factor involves manifold activities, ranging from deforestation to changes in farming practices to increases in the burning of fossil fuels to the manufacture and use in aerosols and refrigerants of chlorofluorocarbons.

Deforestation is a salient example of the nested nature—loop within loop—of variations in the biosphere. Cutting down huge swaths of trees obviously has an impact on the carbon cycle, but it can also produce temperature changes—and temperature, of course, is one of those multivariables involved in the carbon cycle.

NCAR's Dickinson has calculated that future large-scale clearing of tracts of tropical forest in South America (primarily to create grazing land for cattle ranches and for small-scale agriculture) would cause a significant decrease in the evaporation of moisture. This would raise temperatures in the region by an average of three to five degrees Celsius, which would produce extended periods of dry soil conditions inimical to the goals of deforestation.

Deforestation also has contributed to the striking increase in methane levels in the atmosphere, especially in the last decade. Methane levels today are twice what they were 200 years ago and are up more than 10 percent in the past decade. Methane is one of the "greenhouse" gases, so it too enters the temperature loop.

If there is so much complexity in modeling the effects of just one variable moderated by human activity, what happens to the attempt to link all the feedback loops into one overarching model of the entire global system, encompassing all physical, chemical, and biological processes from the top of the atmosphere to the depths of the ocean? A first attempt at that grand design is the representation fondly known as "the wiring diagram." It was the product of a small panel on modeling—chaired by John Dutton of Pennsylvania State University and attended by, among others, Bretherton, Dickinson, and Moore—that met in Jackson Hole, Wyoming, in 1985.

"We didn't have a screen," Bretherton recalls, "so we just projected view-graphs onto the wall and kept running up to make changes right on the wall, which got pretty messy. In fact we had to pay for repainting it. It's become known as the wiring diagram because that's how the global system is wired up, and it's got lots of feedback loops in it."

The diagram, a conceptual model of Earth processes operating on scales of decades to centuries, was conceived as an architecture for a numerical computer. A given process was included if it seemed to be extensive or influential enough to produce a global impact on temperature or precipitation, on the biogeochemical cycles, or on the distribution of living organisms. The direct impacts of human activities on natural systems were treated as inputs.

Functions of Space and Time

The compartments in the wiring diagram represent computer subroutines—algorithms—that define subsystems and work on the global state variables. The state variables (generally physical, chemical, or biological quantities such as pressure or ozone concentration), are functions of both space and time.

Each block of subroutines, Bretherton says, assumes something about global state variables in other subsystems. For example, the atmospheric scientists assume something about the ocean surface temperature, which is an internal state variable in the dynamic oceanography model, and that information must be passed between the subsystems. There are many arguments about precisely which algorithms go into an atmospheric model, or into an ocean-system model. However, it turns out that there is a general consensus about what seem to be most of the global state variables and about the general nature of what has to pass among the various subsystems.

What the wiring diagram does is put together what Bretherton calls a "consensus picture" of that large-scale architecture. "The real issues of just what algorithms you use in the models are glibly subsumed in those boxes," he says.

And as far as realizing the system is concerned, says Bretherton, "we don't have a concrete idea of when such a global model can actually be implemented. There is an active effort to glue together some of the parts of the system, such as the physical atmospheric circulation and the physical ocean circulation, but the further you get into the biological part of the system, the fuzzier everything gets.

"There are a few individuals who are thinking hard about putting the whole thing together. It will take guts. It has to be someone who is not too concerned about his professional reputation, because he will have to oversimplify to a ridiculous extent to get it within the compass of a Vax [computer]. If the model takes a larger machine, it will be too complex to understand and to experiment with. At our present level of knowledge, experimentation is more important than realism. Eventually, the model will require a massively parallel supercomputer."

The limited global atmospheric model now being used routinely in the research community occupies a significant part of the capacity of a Cray XMP 4800, one of today's most powerful supercomputers. "We never actually solve these equations, we just beat them down with numerical routines," Moore says. "Even in something as simple as ocean chemistry, to calculate the partial pressure of carbon dioxide in the ocean, you have to solve a fifth-order polynomial. Now there is no closed-form solution for polynomials of degree five, so you use numerical routines, and they take up a lot of computer time."

There is no present global model, says Bretherton, able to deal simultaneously with mesoscale phenomena and with the world ocean circulation. All the present models arbitrarily take the mesoscale eddies and convert them into one bulk eddy diffusivity that "demonstrably destroys any usefulness in terms of the circulation of the deep ocean." One limit, says Bretherton, is the lack of a computer powerful enough to deal with the data. Further, he says, "it almost doesn't matter how big and powerful our computers will be in 10, 20, 30 years' time. I guarantee that this community will saturate them."

What are the prospects of developing the strongly predictive global model the climate community is aiming for? The whole Global Change Program is based on a working hypothesis that for major trends and in terms of the 50 to 80 major, large-scale state variables being considered, the global system is basically predictable. But there are strong qualifiers.

Bretherton, for example, accepts the possibility that the system may not be predictable but may in fact, for various reasons, be chaotic. "It's one of the sobering things that people like me have to be reminded of," he says. "It's possible that random fluctuations will come to dominate the whole system. So what we do is an article of faith."

However, Bretherton adds,"I'm one who regards the idea of total chaos as a cry of despair from scientists. The very act of trying to understand something says there is more there than total chaos." In which case, the effort may ultimately succeed. □

Only half as much CO_2 as expected from

in the atmosphere. Could the oceans be

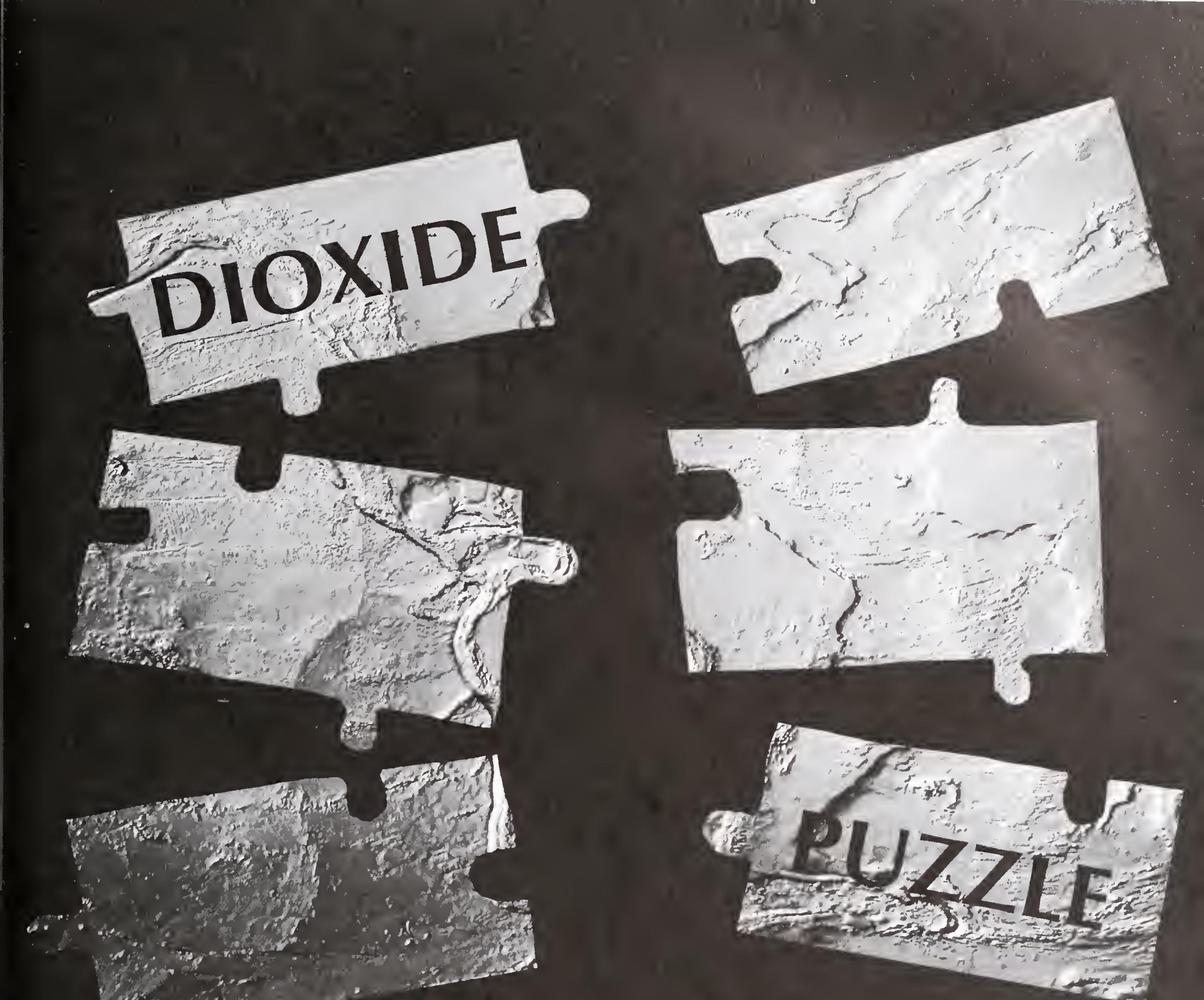
Even before the dawn of modern science, man recognized the moderating effect of the oceans on climate. The effect is due mainly to the special characteristics of water: its large heat-carrying capacity allows ocean currents like the Gulf Stream to transport a large amount of heat from the tropics to high latitude areas; the cooling that occurs when water evaporates from the tropical oceans; and the warming that accompanies the condensation of water vapor in cooler areas.

An additional role of the oceans, more chemical in nature, has recently been recognized as an equally important factor for the future course of the Earth's climate. Carbon dioxide is one of the most important "greenhouse" gases in the atmosphere—perhaps the most important. Along with methane, chlorofluorocarbons (CFCs), nitrogen oxides, and some other atmospheric gases, it absorbs infrared (heat) radiation, thereby contributing to the so-called greenhouse warming of the Earth.

As it happens, the oceans are a huge reservoir for CO_2, containing 50 times more than the atmosphere and 20 times more than the biosphere. What's more, this changing reservoir plays an important role in regulating the levels of atmospheric CO_2, and hence global climate.

The concentration of CO_2 in the

Taro Takahashi, Associate Director and Doherty Senior Scientist at Columbia University's Lamont-Doherty Geological Observatory, is a member of the National Academy of Sciences' Ocean CO_2 Panel.



The puzzle was created from a global relief map prepared by the Goddard Space Flight Center from data compiled by NOAA's National Geophysical Center.

industrial emissions is accumulating

the storehouse for the missing gas?

atmosphere has been measured with high precision under the direction of Charles David Keeling of the Scripps Institution of Oceanography since the International Geophysical Year of 1958, first at the Mauna Loa Observatory, Hawaii, and then at the South Pole. At present, it is being monitored at more than 45 locations around the world by a number of investigators. Keeling and his associates have found that atmospheric CO_2 has been increasing at an annual rate of about 0.35 percent in recent years and has reached a concentration of about 350 parts per million (ppm), or 0.035 percent by volume, as a result of releases from such industrial activities as the combustion of fossil fuels and the production of cement. This represents an increase of 25 percent since preindustrial times; and the level is expected to reach twice the preindustrial value of about 280 ppm by the second half of the 21st century. These estimates, however, contain a major puzzle; the concentration of CO_2 in the atmosphere has been increasing annually at only about half the rate expected from the yearly emissions of industrial CO_2—and thus the Earth's atmosphere has experienced only half the impact that might have been expected from the Industrial Revolution. Which of the major CO_2 reservoirs—the biosphere, or the ocean—has taken up this missing CO_2?

Because each of these reservoirs responds differently to temperature change, we are unable to predict with any reasonable expectation of accuracy the course of global warming unless we know the answer. Biologists have been studying the biosphere's uptake and release of CO_2. My own investigations have concentrated on the role of the oceans—in particular, how fast they take up industrial CO_2 and what natural processes are important in the accumulation of CO_2 by the oceans.

The Nature of the Oceanic Reservoir

Three major factors govern the ocean's capacity to hold CO_2: 1) the unique chemical properties of CO_2 in seawater; 2) the presence of a biological "pump" that transports CO_2 from the surface to the deep ocean; and 3) the rate and pattern of ocean water circulation.

The solubility of CO_2 in seawater is considerably greater than that of the atmosphere's major components, oxygen and nitrogen. These don't react chemically with water. By contrast, CO_2 reacts with water to form carbonic acid (H_2CO_3), bicarbonate ions (HCO_3^-), and carbonate ions (CO_3^{-2}). Figure 1 shows the total distribution of these three species (that is, chemical varieties) of CO_2 at various depths.

The figure also shows that the total amount of CO_2 dissolved in seawater increases rapidly to about 1,000 meters, and below this level, it increases more slowly. This downward increase in CO_2 is a result of oceanographic processes, which are collectively called a "biological carbon pump." This pump transports carbon from the upper layers to the deep ocean via the gravitational settling of the biogenic debris produced in the photic (or Sun-illuminated) zone of the oceans. The biogenic debris consists of three components: 1) the soft, made of organic compounds; 2) the hard calcareous, consisting of skeletal calcium carbonate ($CaCO_3$), such as foraminifera shells; and 3) the hard silicic component, consisting mainly of skeletal opaline silica from marine organisms such as diatoms.

Carbon is a major constituent of the first two components. The organic component is oxidized and decomposed during its descent through the water column, releasing CO_2 and nutrient salts to the surrounding waters. This chemical scenario is supported by observations that the concentration of oxygen dissolved in seawater decreases with depth and that the concentrations of nutrient salts (nitrate and phosphate) increase with depth nearly in parallel with the total CO_2 concentration. This oxidation occurs mostly in the upper 1,000 meters. Only a small portion of the surface debris ever reaches the deep-sea floor, as shown by the low concentration of organic carbon (less than one percent by weight) in deep-sea sediments. About 75 percent of the observed increase in the total CO_2 concentration in the deep waters may be accounted for by the oxidation of organic debris, and the remaining 25 percent by the dissolution of $CaCO_3$ in the deep oceans. This is borne out by the observed increase of alkalinity in deep water.

Alkalinity is a measure of the amount of

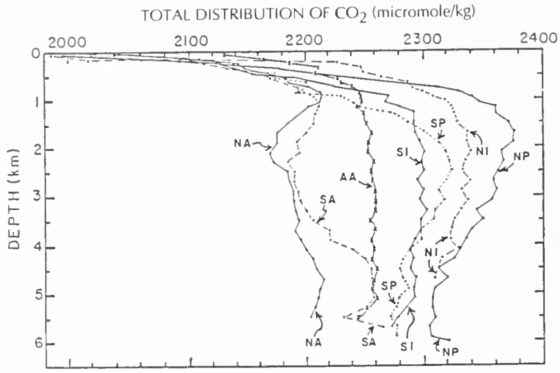


Figure 1. Depth distribution of the total CO_2 concentration in the global oceans. NA & SA = North & South Atlantic; NP and SP = North and South Pacific; NI and SI = North and South Indian Oceans; and AA = Antarctic ocean.

excess cations (positively charged ions such as Ca^{+2}) dissolved in seawater. It can be determined precisely by means of an acid titration, a chemical measure that tells the amount of excess positive ions available for the reaction with negative ions, such as the hydroxyl (OH^-), HCO_3^- and CO_3^{-2} ions.

Thus seawater of greater alkalinity has a higher pH (a measure of alkalinity), with the pH of seawater governed mainly by the amount of CO_2 dissolved in it. A change in the alkalinity of seawater reflects the change in the concentration of calcium ions (Ca^{+2}). Figure 2 shows the distribution of alkalinity in the global oceans. At increasing depths, alkalinity (or Ca^{+2}) increases, though less rapidly than the total CO_2 concentration. This suggests that while the oxidation of organic debris takes place preferentially in water depths above 1,000 meters, the dissolution of skeletal $CaCO_3$ occurs only in deeper waters. The reason is that the solubility of $CaCO_3$ increases with depth, doubling with each 4,300 meters (or 430

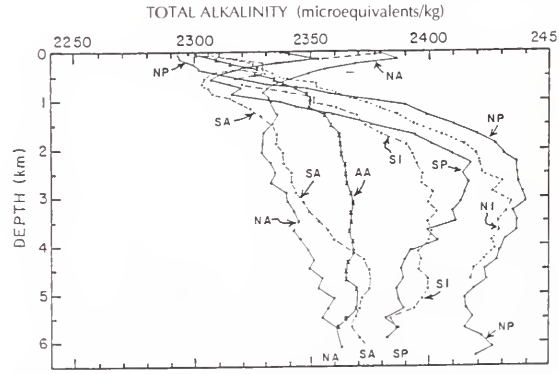


Figure 2. Depth distribution of the alkalinity in the global oceans. NA & SA = North and South Atlantic; NP & SP = North and South Pacific; NI & SI = North and South Indian Oceans; AA = Antarctic Ocean.

atmospheres of pressure).

We also see in Figures 1 and 2 that the depth distribution of CO_2 differs geographically: the concentrations in the North Pacific deep water (marked NP) are among the highest, whereas those in the North Atlantic deep water (NA) are among the lowest in the oceans. This difference may be attributed to the rate and pattern of ocean circulation. In the 1920s, oceanographers learned that the deep waters in the western Atlantic basin (west of the Mid-Atlantic Ridge system) are supplied by waters from the high-latitude oceans of both the Northern and Southern Hemispheres. This flow is caused by the sinking action of dense surface waters produced by severe winter cooling of these waters in high-latitude areas. The deep waters in the Atlantic basin are replaced rapidly by the flow from both the north and south. Measurements of the concentration of the radioactive isotope carbon-14 (^{14}C) below 4,000 meters give about 80 years as a travel time for seawater from the sea surface in high latitude areas through the length of the Atlantic Ocean. During this relatively short journey, the Atlantic deep waters receive only a small amount of biological pump products. On the other hand, since the Pacific Ocean does not extend far enough north to produce very dense waters, the Pacific deep waters are only supplied from southern high-latitude areas, and hence are replaced at much slower rates than those in the Atlantic. As indicated by the ^{14}C concentration, the travel time of the Pacific deep waters is about 1,000 years. This long travel time means that the deep waters of the Pacific accumulate a large quantity of biological pump products during their northward journey.

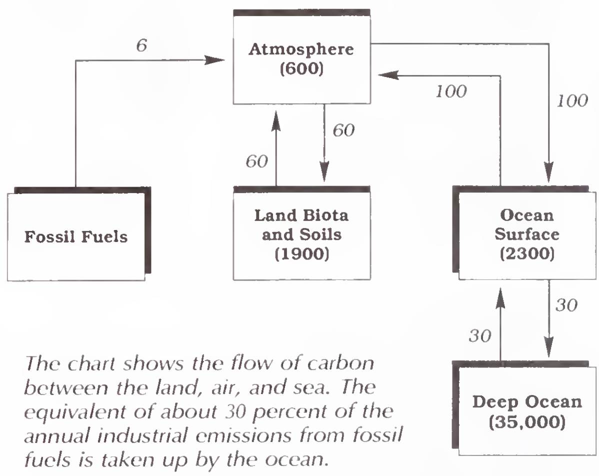
A Question of Supersaturation

One question often asked is, "Are the oceans supersaturated with CO_2?" Supersaturation implies that the oceans can no longer take up additional CO_2. To answer the question, we need to know the partial pressure of CO_2 (that is, the pressure it would exert if it were by itself) in the global deep ocean water, since it determines the direction of CO_2 flow between the seawater and the overlying air. When the partial pressure of CO_2 in the sea is greater than that in the overlying air, CO_2 should escape into the air. When it is smaller, the sea should take up CO_2 from the air.

The CO_2 partial pressure for the global deep water (water below 1,200 meters) may be computed using the mean alkalinity and total CO_2 concentration values obtained from Figures 1 and 2. It turns out to be 437 microatmospheres (or 437 millionths of normal atmospheric pressure at sea level) at the mean deep water temperature of 1.5 degrees Celsius and 913 microatmospheres at the mean surface water temperature of 19.2 degrees. These values are considerably greater than the present atmospheric value of 340 microatmospheres. This means that the deep ocean water (at 1.5 degrees) is supersaturated by about 30 percent (437/340 = 1.3) with respect to the present atmosphere. If the deep seawater were warmed up to the present sea surface temperature and allowed to exchange CO_2 gas with the air, the atmospheric CO_2 concentration would be increased about two and a half times. Thus, the unique feature of the oceans is that a large body of deep water highly supersaturated with CO_2 is capped with a thin layer of warm and less dense water that prevents the rapid transfer of CO_2 from the deep ocean CO_2 reservior to the atmosphere.

So the answer to the question—Are the seas supersaturated with CO_2?—is that supersaturation isn't the whole issue. The ocean's capacity to take up CO_2 is not simply governed by the degree of CO_2 saturation in the deep oceans. Rather, it depends very much on

Global Carbon Cycle (billion tons)



The chart shows the flow of carbon between the land, air, and sea. The equivalent of about 30 percent of the annual industrial emissions from fossil fuels is taken up by the ocean.

the dynamics of ocean circulation and on the effect of the biological pump. The biological pump, however, cannot function without a supply of nutrient salts. Since these come primarily from the upward mixing of nutrient-rich deep water, the intensity of the biological pump is intimately coupled with the rate of ocean circulation. Both processes are known to be highly variable in time and space, and are neither thoroughly documented nor completely understood. Two recently launched global-scale projects, the Gobal Ocean Flux Studies (GOFS) and the World Ocean Circulation Experiment (WOCE, *Oceanus*, Vol. 29, No. 4, page 25, and article pp. 10–15, this issue), are aimed at improving our understanding of the rate and distribution of the biological pump in the oceans and the global circulation of ocean water, respectively. The results could greatly enhance our predictive capabilities concerning the amount of CO_2 the oceans can store, and hence help us predict climatic changes.

Oceanic Sinks and Atmospheric Sources

The direction of CO_2 transfer between air and water may be determined by the difference between the partial pressure of CO_2 in the two reservoirs. Since partial pressure (pCO_2) in the atmosphere varies by no more than five percent over the globe at any given time (excluding the areas affected by local industrial emissions), and since the pCO_2 in the surface waters of the open seas varies from about one half to twice the atmospheric value, any variation in the difference is due mainly to changes to pCO_2 in seawater. It in turn is governed primarily by water temperature, the total CO_2 concentration, and the alkalinity of seawater.

Water temperature changes geographically —from -1.9 degrees in the polar seas to 30 degrees in the equatorial oceans—and also seasonally by as much as 15 degrees at a given location. CO_2 concentration may be reduced by the photosynthetic utilization of carbon, and increased by the release of CO_2 due to respiration and oxidation of organic debris. To a lesser extent, it is also affected by the CO_2 gas exchange with the atmosphere. As for alkalinity, it is also affected by the formation and dissolution of calcareous shells.

Therefore, the pCO_2 in seawater depends on a complex web of interactions involving physical, chemical, and biological processes occurring in the surface layers of the oceans.

Figure 3 shows the mean annual distribution of the sea/air CO_2 partial pressure difference (ΔpCO_2) over the oceans during non-El Niño years (article, pp. 30-34). It has been compiled from several thousand measurements obtained during more than 90 oceanographic expeditions since 1972. These have been conducted by our group at the Lamont-Doherty Geological Observatory and investigators from the University of Alaska (who worked in the Arctic Ocean), Scripps Oceanographic Institution (North and South Pacific), and the National Oceanic and Atmospheric Administration (North Pacific), as well as by scientists from France (equatorial Atlantic), West Germany (North Atlantic), Japan (western Pacific), and the People's Republic of China (western Pacific). The positive values in the hatched areas indicate regions where the surface ocean is a source of atmospheric CO_2, while the negative values show those parts of the ocean where it is a "sink" for atmospheric CO_2. The map also shows that the atmosphere is out of equilibrium with the surface ocean CO_2 because the ΔpCO_2 values are not zero. The ocean water exhibits a large pCO_2 difference from the air because the gas transfer rate of CO_2 to and from the atmosphere is much slower than the rates of temperature change and of the biological processes, both of which are finely linked to the pCO_2 in seawater. Furthermore, the figure shows that the equatorial waters of the Pacific and Atlantic are supersaturated with CO_2 and hence are strong CO_2 source areas. On the other hand, the northern North Atlantic and the Southern Ocean are large CO_2 sinks.

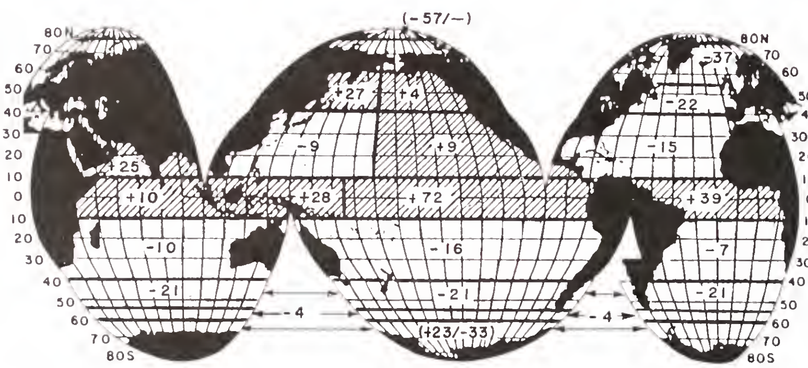


Figure 3. Mean annual differences of the CO_2 partial pressures between surface ocean water and overlying air (ΔpCO_2). The values are in microatmospheres, or a millionth of an atmosphere at sea level. The positive values (and the hatched areas) indicate that the ocean is a source of atmospheric CO_2, and the negative values indicate that the ocean is a CO_2 sink.

The source character of the equatorial waters is apparently due to two major causes: the upwelling of deep water enriched in CO_2 and nutrient salts, and the warming of cold deep water to equatorial temperatures. The effect of warming on seawater pCO_2 overwhelms the lowering effect on pCO_2 caused by photosynthesis. While the Pacific equatorial belt is the single most important oceanic CO_2 source in normal years, NOAA's Richard Feely and Richard Gammon have observed that during the 1982 El Niño event, the pCO_2 of the equatorial waters in the central Pacific was reduced to nearly equal to that of the atmospheric value, and hence the CO_2 source in the equatorial Pacific vanished. The explanation given was that the high pCO_2 equatorial water of normal years was overridden by and covered with a layer of the warmer low pCO_2 water that rushed eastward from the western equatorial Pacific during the El Niño event.

In the sub-Antarctic oceans between 40 degrees and 55 degrees South latitude, there is a seasonally persistent CO_2 sink belt that nearly encircles Antarctica. This is the zone where the south-flowing warm subtropical waters meet the north-flowing sub-Antarctic waters. The subtropical waters cool rapidly as they flow toward higher southern latitudes and hence their pCO_2 quickly decreases from the cooling effect. Since the subtropical waters are nearly depleted of nutrient salts, the photosynthesis rate in these waters is generally low. On the other hand, the Antarctic surface waters, which are rich in CO_2 and nutrient salts, acquired from upwelling further south, become warm as they flow northward. However, the pCO_2 in Antarctic waters decreases rapidly during this northward trip because the increasing effect on pCO_2 by warming is far surpassed by the lowering effect by the photosynthetic utilization of CO_2. Thus a strong CO_2 sink is created in the areas where the low pCO_2 waters from the subtropical region meet with the other low pCO_2 waters from the Antarctic region.

The Atlantic north of 40 degrees North latitude and the Norwegian-Greenland Seas are also strong CO_2 sink areas. The low pCO_2 conditions in these waters are mainly attributed to the rapid cooling of the warm Gulf Stream water and its northward extension that flows into the Artic Ocean, as well as to photosynthesis that occurs in the water during the summer months. During the winter months, we have observed that the surface water pCO_2 in the northern Atlantic southwest of Iceland increases, mainly because of the convective mixing of deep waters rich in CO_2 and nutrient salts, and that the area becomes a CO_2 source. However, this weak winter CO_2 source is not strong nor widespread enough to offset the strong CO_2 sink conditions existing during most of the year. The winter upwelling of deep waters brings up nutrient salts which support photosynthesis for the following summer.

Winter Source versus Summer Sink

In contrast to these high-latitude areas, those of the north Pacific are, on a yearly average, a strong CO_2 source. We have observed that during the winter months, this area becomes a CO_2 source as strong as the equatorial Pacific. This is due partially to the fact that the North Pacific deep waters, which have upwelled to the surface, have the highest concentrations of CO_2 in the world's oceans, as shown by the curve marked NP in Figure 1. During the summer months, the surface-water pCO_2 in this area is drawn down, mainly because of the intense photosynthetic activity that occurs in the waters at that time of the year. The lowering effect of photosynthesis on the pCO_2 far surpasses the increasing effect of the summer warming. However, on an annual basis, the winter source condition wins out over summer sink condition.

The net amount of CO_2 being transferred across the sea surface may be obtained by multiplying the sea/air CO_2 partial pressure difference (ΔpCO_2) with the gas transfer coefficient (or transfer velocity) for CO_2. The former represents the chemical driving force for gas transfer, and the latter characterizes the speed at which it occurs. The magnitude of gas transfer velocity depends on the degree of turbulence in the surface layer of the oceans and the shape of waves, and hence on the wind speed above sea surface. The results of field and laboratory studies to determine the effect of wind speed on the transfer velocity (Figure 4) show a wide range of variation.

Experiments using wind tunnels of various sizes and shapes show a range of results that are indicated by the two solid curves; those obtained over the oceans using radon gas (^{222}Rn) as a tracer are indicated by the open circles; and those estimated on the basis of ^{14}C distribution in the air and oceans are shown by the open squares. Because of the complexity of the turbulent interactions between wind and water surface, the observed variations have yet to be explained.

Among these data, however, are values based on the distribution in the atmosphere and oceans of both naturally produced ^{14}C atoms and those resulting from nuclear testing. These values should represent an average value for the global oceans. Furthermore, since these ^{14}C atoms exist as CO_2, their rate of entry into the oceans must represent that of the CO_2 molecules themselves. For these reasons, I give most credence to the wind speed versus gas transfer velocity relationship indicated in Figure 4 by the dashed curve, which passes through the ^{14}C data points. This curve is nearly consistent with the upper limit of the wind tunnel results.

The mean annual flow for CO_2 transfer across the sea surface in various oceanographic regions is summarized in Figure 5. For the preparation of this map, the flux (flow) value over each two-degree-by-two-degree area was computed using the observed ΔpCO_2 values and the gas transfer velocity value estimated from the wind speed dependence shown in Figure 4. The global wind speed distribution compiled by S.K. Esbensen and Y. Koshnir of Oregon State University has been used for these computations. The flux values were summed over the oceanic regions for the summer and winter seasons, respectively, and then averaged to obtain the mean annual value for each region. The flux values shown in Figure 5 are expressed in gigatons (or billion tons) of carbon per year. They show that the equatorial Pacific is the largest oceanic CO_2 source region, accounting for about 60 percent of the total oceanic CO_2 source flux of about 1.8 gigatons carbon per year. This underscores the conclusion that the disappearance of this source during the 1982/83 El Niño event had a significant impact on the global CO_2 budget. Among the oceanic sinks, the sub-Antarctic belt is the largest sink, accounting for about 35 percent of the total oceanic CO_2 sink flux of about 3.4 gigatons of carbon per year. The global oceanic flux is given by the difference between the sink and source fluxes, and is about 1.6 gigatons of carbon annually from the atmosphere into the oceans. The accuracy of this estimate depends on the gas transfer velocity values used and will be discussed later. According to United Nations and industrial records, about 5.3 gigatons of carbon per year is presently being added as CO_2 to the atmosphere. Global atmospheric measurements show that of this amount, about 3 gigatons of carbon (or 55 percent of the annual industrial emissions) are found in the atmosphere as CO_2 and about 1.6 gigatons of carbon per year (corresponding to about 30 percent of the annual industrial emissions) are being taken up by the oceans. This leaves about 0.7 gigatons of carbon unaccounted for.

The missing CO_2 may be explained in several ways. First, the global summary presented in Figure 5 may be in error because of our limited knowledge of the oceanic pCO_2 distribution and the CO_2 gas transfer rate across the sea surface. Whereas the seasonal variability of surface water pCO_2 in some oceanic areas, including the North and South Atlantic and the North Pacific, has been extensively measured, that of other areas, including the South Pacific Ocean, the North and South Indian Oceans, and the Southern Ocean, has not been satisfactorily documented. The limited data base could introduce an error of up to ± 0.3 gigatons per year in our final estimate of the global ocean CO_2 flux. Our understanding of the CO_2 gas transfer rate across the sea surface also is incomplete, as shown in Figure 4. If the wind speed versus gas transfer velocity relationship represented by the lower solid curve (namely, the lower limit of the wind tunnel data) were used instead of the dashed line in Figure 4, the total oceanic uptake would be reduced to about 0.8 gigatons carbon per year, which corresponds to about 15 percent of the current industrial CO_2 emission rate. When models for the atmosphere/ocean CO_2 system are tuned to yield ^{14}C distributions in the oceans consistent with the observed values, these models yield an amount of CO_2 corresponding to 25 to 40 percent of the annual industrial CO_2 emissions taken up by the oceans. So, while the global ocean flux estimated on the basis of the greater gas transfer speed is supported by the model results, that obtained using the smaller gas transfer speed does not appear to be consistent with the observed ^{14}C distribution in the oceans.

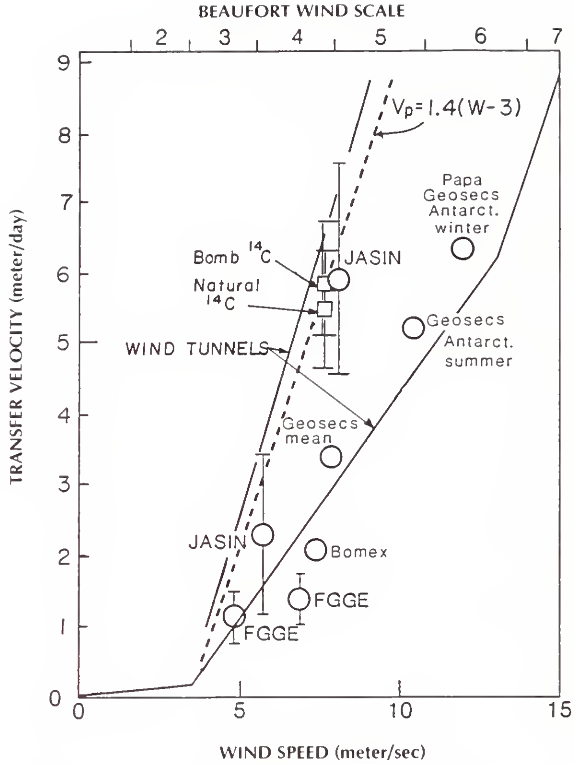


Figure 4. The effect of wind speed on gas transfer velocity across the sea surface. The circles indicate the results obtained over the oceans in a variety of studies (JASIN, Geosecs, Bomex, etc.) using the distribution of radon gas (^{222}Rn). The squares represent the global mean values estimated on the basis of the air-sea distribution of the natural and nuclear-bomb $^{14}CO_2$. All the values are corrected to those corresponding to CO_2 gas at 20 degrees Celsius. The solid curves indicate the upper and lower limits of the experimental data obtained using wind tunnels. The dashed curve indicates the relationship adopted for this study.

A Hotly Debated Question

Where then is the missing CO_2? The question has been hotly debated since Keeling first observed in the 1960s that the atmospheric CO_2 concentration has been increasing annually at about half the rate expected from the industrial emission rate. My global analysis suggests that while about 1.6 gigatons of carbon per year are being taken up by the oceanic reservoirs, about 0.7 gigatons carbon per year are being taken up by carbon reservoirs other than the oceans.

Has the land biosphere been expanding to account for this missing CO_2? As has been widely publicized, the Brazilian rain forests are being cleared and burned at a rapid rate, presumably shrinking the biosphere. And the estimates of the amount of carbon injected into the atmosphere from deforestation range between 0.4 and 1.6 gigatons annually. On the other hand, Pieter Tans and Thomas Conway of NOAA and T. Nakazawa of Tohoku University in Japan have analyzed the meridional (north-south) distribution of the atmospheric CO_2 concentrations observed at widely distributed locations from 1981 through 1985, and have found that there must be a strong CO_2 sink in the Northern Hemisphere. They observed that the annual mean of atmospheric CO_2 concentration in the Northern Hemisphere stations are much lower (several ppm) than those computed using an atmospheric circulation model that included the meridional distribution of industrial CO_2 sources. This discrepancy could not be eliminated by taking into account the oceanic CO_2 uptake. Thus, their analysis suggests that the biospheric reservoir in the Northern Hemisphere has been taking up CO_2 at a rate of two to three gigatons of carbon per year. Possibly the northern forests are sequestering more carbon in response to the climatic warming and CO_2 increase in the atmosphere. The North American boreal forests may still be rebounding from the extensive cutting that took place during pioneer days.

Future concentrations of atmospheric CO_2, so central to global climate, are hard to predict because of our incomplete understanding of how the major carbon reservoirs—the oceans and biosphere—would respond to the anticipated warming. No one is yet able to say with certainty whether the oceans will release more CO_2 to the atmosphere as a result of warming, and thus, by positive feedback, further exacerbate the climate changes. To learn more about this far-reaching global problem created by the very industrial progress that has made the 20th century a uniquely proud century, technologically speaking, the nations of the world must continue to pool their resources and wisdom. Such cooperation was demonstrated recently by the ratification of the Montreal Protocol for the global regulation of chlorofluorocarbon compounds, the main culprits in the reduction of the protective ozone layer in the upper atmosphere as well as major contributors to greenhouse warming. The accord showed that the many nations of the world could use their accumulated scientific knowledge for the safety and betterment of our living environment. The problem of CO_2, however, may be more difficult to manage. Carbon dioxide is produced mainly by the combustion of fossil fuels, not only for running factories and providing transportation, but also for such basic human needs as cooking food and warming shelters. Thus, regulating its production on a global basis appears highly impractical for now. Even if CO_2 emissions could be reduced in the near future, the atmospheric concentration would remain high for several centuries. Our society can rely more on nuclear-generated power, which does not release CO_2 into the atmosphere, but the expansion of facilities to generate power also entails a risk to the global environment.

In the absence of any easy solutions, we're left with only one course. We must hone our predictive skills, based on sound scientific principles and measurements, so we can make wise decisions that will enable to us to adjust and prepare for eventual climatic changes. If we combine our scientific knowledge with the kind of collective wisdom and dedication shown in establishing the Montreal Protocol, we may yet be able to navigate safely through the uncharted climatic waters of the 21st century. □

Acknowledgment

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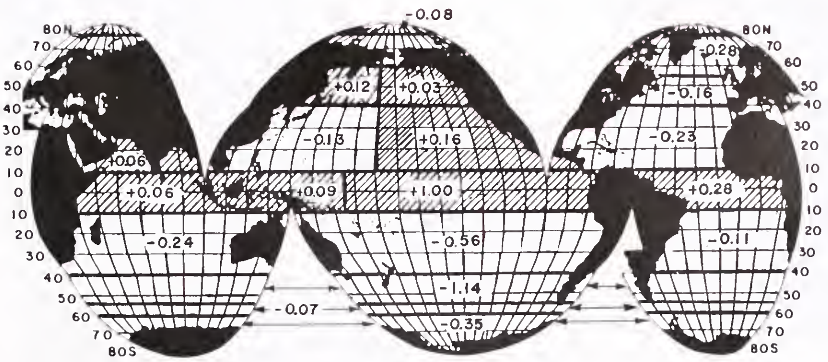

Figure 5. The mean annual net CO_2 transfer across the sea surface of gigatons of carbon per year. The equatorial Pacific is the most intense CO_2 source, whereas the subantarctic belt, 40 degrees to 55 degrees South latitude, is the most intense CO_2 sink. The global oceans take up about 1.6 gigatons carbon per year, about 30 percent of the annual industrial CO_2 emissions.

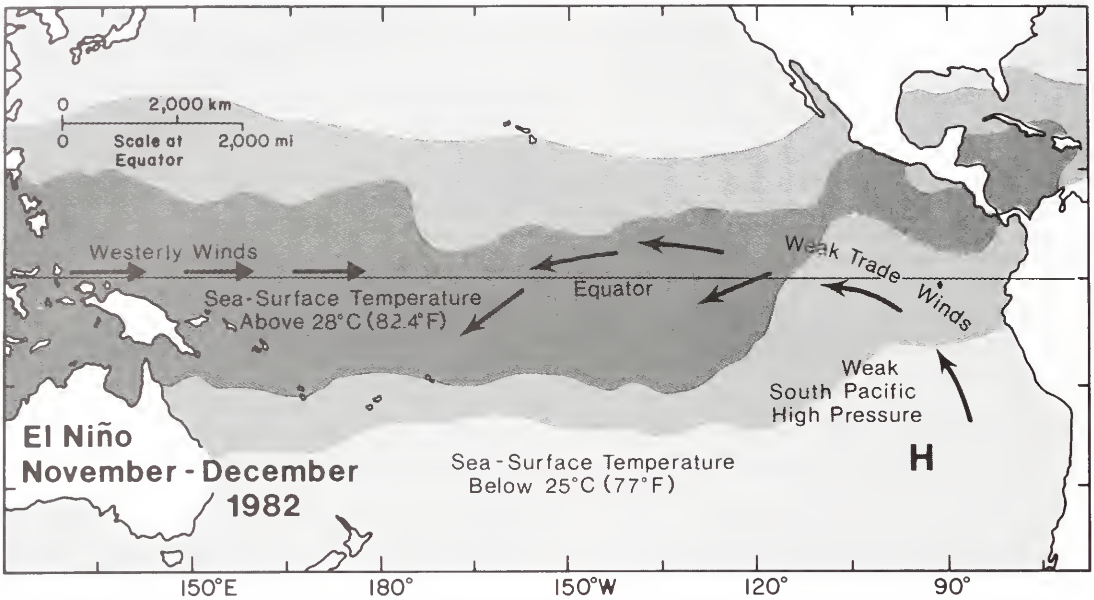

Figure 1. Low-level atmospheric conditions and oceanic surface temperature distributions during the climatic extremes of El Niño and La Niña. The former is characterized by a relaxation of trade winds and an eastward flow of warm waters, while the latter, opposite page, is marked by intensified winds and a westerly flow of cold water.

The Interplay of El Niño and La Niña

by Ants Leetmaa

North America suffered an exceptionally hot and dry summer in 1988. India occasionally experiences a disastrous failure of the monsoons. In Africa, severe droughts can persist over large areas for extended periods. These are all examples of climate variability caused by complex interactions between the atmosphere, the oceans, the ice, and the land.

Efforts to understand and simulate these interactions, especially those between the ocean and atmosphere, have thus far focused on a phenomenon known as the Southern Oscillation, an irregular interannual fluctuation between warm El Niño and cold La Niña states (Figure 1). The trade winds that prevail over the tropical Pacific are exceptionally intense during La Niña and drive warm surface waters westward while exposing cold water to the surface in the east. During El Niño, the trade winds relax and the warm waters return eastward. This is the oceanographic point of view.

To meteorologists, the reason for the intense trades during La Niña is the relatively small area of warm surface waters in the western tropical Pacific. In that region, which is also one of cloudiness and heavy rainfall, moist air rises, causing a convergence air masses near the ocean surface. This convergence results in the westward trade winds over the Pacific. When this area of warm sea-surface temperatures is large, during El Niño, then there is rising motion of the air masses, cloudiness, and heavy rainfall over much of the tropical Pacific. The east-west component of the wind becomes weak, and instead the winds blow toward the equator to maintain the rising motion.

Oceanographers explain the Southern Oscillation in terms of wind changes.

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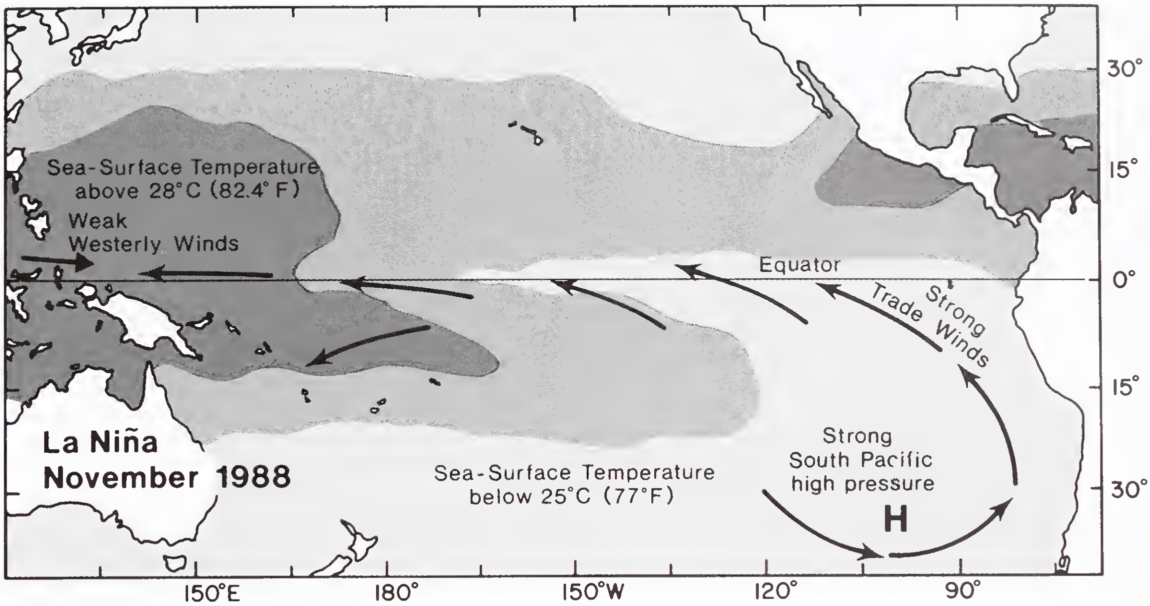

Meteorologists, on the other hand, attribute the wind variations to changes in the ocean, specifically the sea-surface temperature changes. These circular arguments indicate that interactions between the ocean and atmosphere cause the Southern Oscillation. For example, a slight relaxation of the winds during La Niña can cause an eastward expansion of the warm surface waters in the western tropical Pacific. This expansion affects the atmosphere in such a manner as to cause further relaxation of the winds. This positive feedback between the ocean and atmosphere leads to the development of El Niño. The arguments can be reversed to explain La Niña.

La Niña was much discussed during the summer of 1988 because theoretical studies implicated it in the hot, dry summer that North America experienced that year. El Niño attracted enormous public attention in 1983, when its warm phase attained an exceptionally large amplitude and was associated with devastating droughts over the western tropical Pacific, torrential floods over the eastern tropical Pacific, and damaging weather patterns over various parts of the world (*Oceanus*, Vol. 27, No. 2). Oceanographers and meteorologists were caught completely by surprise. When a group of experts met in Princeton, New Jersey in October 1982 to discuss plans for a program to study El Niño, no one realized that its most severe manifestation in a century was then occurring. Although the interactions between the ocean and atmosphere that cause the Southern Oscillation were reasonably well understood by 1982, little had been done to put that knowledge to practical use.

Matters were very different by the time of

El Niño and La Niña are virtual mirror images of each other. During La Niña trade winds over the tropical Pacific strengthen significantly, creating stormy seas, as in the photo at the left. During El Niño, the winds relax and warm waters flow gently eastward, leaving the seas calm, as in the photo at the right. (Courtesy of the Woods Hole Oceanographic Institution).

the next El Niño in 1987. By then the National Meteorological Center (NMC) in Washington, DC, an arm of the National Oceanic and Atmospheric Administration (NOAA), had started to issue a monthly bulletin that described, in detail, oceanic and atmospheric conditions related to the Southern Oscillation. It was possible to follow the erratic development of El Niño of 1987 as it was happening. A number of advances made that possible. Information about the state of the atmosphere is routinely put onto an electronic network, the Global Telecommunications System (GTS), which distributes it to major meteorological forecast centers around the world. There the information is fed into sophisticated numerical models of the atmosphere using supercomputers to provide a description of the atmospheric winds, thermal structure, and precipitation patterns several times a day. This information is routinely monitored not only for short range weather prediction but also to assess the climatic state of the atmosphere. More importantly for oceanographic studies, these analyses are providing increasingly accurate estimates of the momentum and heat flows at the air-sea interface over the globe, which are essential for numerical ocean models.

Real-time information about the ocean is also available on the GTS. Much of this is about surface conditions such as sea-surface temperature. However, in recent years the amount of information about subsurface thermal structure has increased. This information comes from expendable bathythermographs (XBTs), which are devices to measure ocean temperatures. Three- to four-thousand XBT reports per month are now routinely available. As part of ocean climate studies supported by NOAA and the National Science Foundation, long-term programs to measure upper-ocean thermal structure, currents, and sea level have been set up. The largest concentration of conventional measurements is in the tropical Pacific. Since early 1985 information about sea-level variability has been obtained from the altimeter on the Navy Geosat satellite. Maps of monthly sea-level variability in the tropics are now routinely distributed by NOAA's National Ocean Service. As a result of all these efforts, a quiet revolution is taking place in oceanography. Traditionally, it took several years to exchange oceanographic data. Now much of this information is telecommunicated daily by satellite to various centers and put on the GTS for the community at large to use in close to real time.

Except for the altimetrically derived sea-level information, the space and time sampling by conventional data is far too sparse to paint a coherent picture of the currents and density field in the tropics. Fortunately, as has been shown by numerical experiments of many investigators, much of the variability in the upper ocean in the tropics is strongly forced by the wind stress, or the momentum imparted by the wind to the sea. The stage is now set to combine the various types of information, that is, the in situ measurements, the sea-level and sea-surface temperature information, and the estimates of the wind stress and heat fluxes using a numerical model as is done for the atmosphere to routinely provide the oceanographic equivalent to weather maps.

With support from the Environmental Research Laboratories (ERL) and the National Weather Service of NOAA, a program to develop a real-time modeling capability for the tropical Pacific was initiated in 1985 at the Climate Analysis Center. The general ocean-circulation model chosen was developed at ERL's Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. At present, the wind stress fields are derived from the output from NMC's atmospheric global Medium Range Forecast model. Because of inaccuracies in measuring wind stress, real data must be fed into the model periodically to make up for its limitations, a process known as "data assimilation." To illustrate this, Figure 2 shows some comparisons between model and mooring data (readings from automated buoys) from

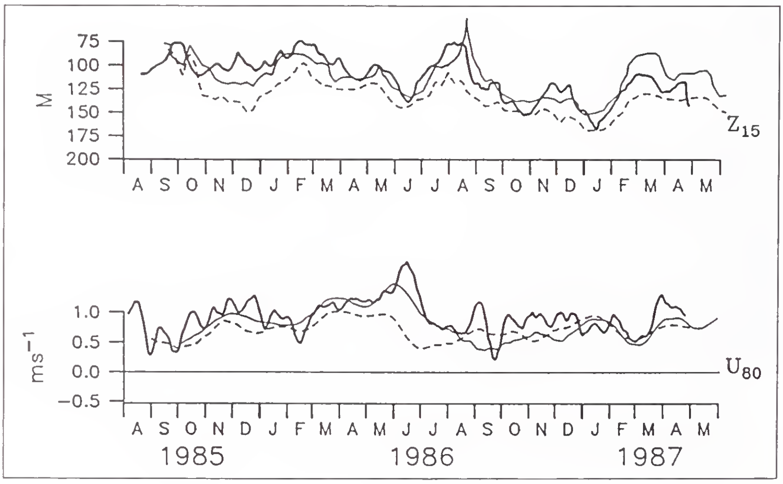

Figure 2. Comparisons between model output and mooring data on the equator at 110 degrees West longitude for the depth of the 15 degree Celsius isotherm and the zonal velocity at 80 meters. The heavy curve is the mooring data. The dashed curve is the model without assimilation; the light continuous curve is the model with assimilation.

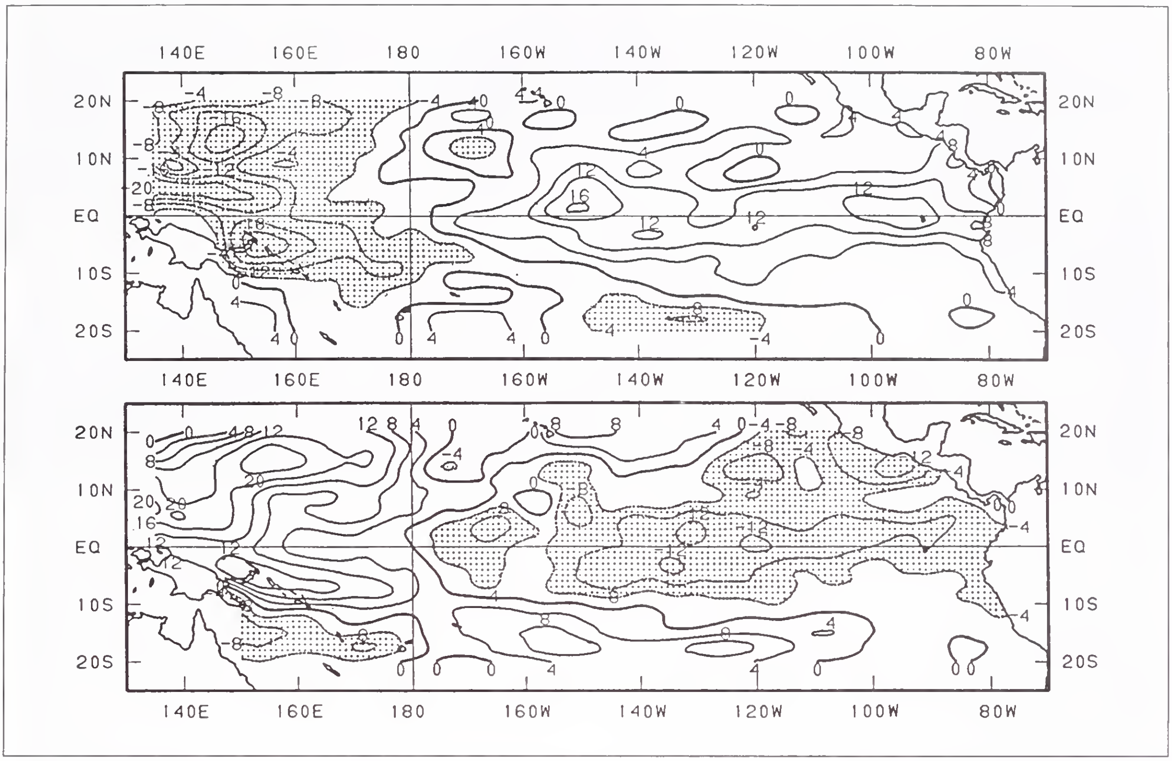

Figure 3. Interannual anomalies in sea level estimated from the model-based analyses for January 1987 (upper panel) and January 1989 (lower panel). The contour interval is 4 centimeters; anomalies less than −4 cm are shaded.

studies that compared simulations with and without data assimilation.

Corrected by Assimilation

Even without assimilation much of the month-to-month, or low-frequency, variability was simulated at the site represented in Figure 2. The model had been started with incorrect vertical thermal stratification and this resulted in the wrong mean depth for this isotherm (a line of equal temperature). The assimilation corrected the problem and, in general, improved the agreement between the observed and modeled variations. Interestingly, the assimilation of just thermal data also improved the velocity simulation. Without assimilation the model estimate of the Equatorial Undercurrent velocities at the site were weaker than those observed, and only parts of the low-frequency variability of the velocities were simulated. After assimilation the modeled velocities were greatly improved. The model at this time was forced with monthly mean wind stresses. Consequently, the higher-frequency variability is not well simulated.

Monthly model-based analyses, which use data assimilation and combine all the available thermal data with the model field, have been performed for the tropical Pacific from January 1985 to the present. Shown in Figure 3 are the sea-level fields for the extremes represented by El Niño and La Niña conditions. A mean January sea-level field has been subtracted from the total field to show this interannual variability. During the height of El Niño, sea level is anomalously low in the western Pacific and anomalously high in the eastern Pacific. During large events, the anomaly field can eliminate the normal west-to-east pressure gradient. In such a case, the Equatorial Undercurrent and the upwelling off South America disappear. These conditions result from the anomalously weak near-equatorial trade winds at this time (Figure 1). During La Niña, the trades are anomalously strong. This results in a sea-level anomaly pattern in which values are high in the western Pacific and low in the eastern Pacific.

The climatic variability associated with the El Niño-Southern Oscillation is believed to be part of a low-frequency variability of the coupled ocean-atmosphere system. However, transitions to and from the extreme states can occur relatively rapidly. This is illustrated in Figure 4, showing the time variability of the depth of the 20-degree Celsius isotherm along the equator. This isotherm is important to scientists because it lies in the middle of a zone where the water temperature decreases rapidly, the "thermocline". The normal east-west slope is a dynamical response of the ocean to the prevailing easterlies. From mid-1985 through 1986, this isotherm slowly deepened in the eastern Pacific, suggesting a gradual weakening of these

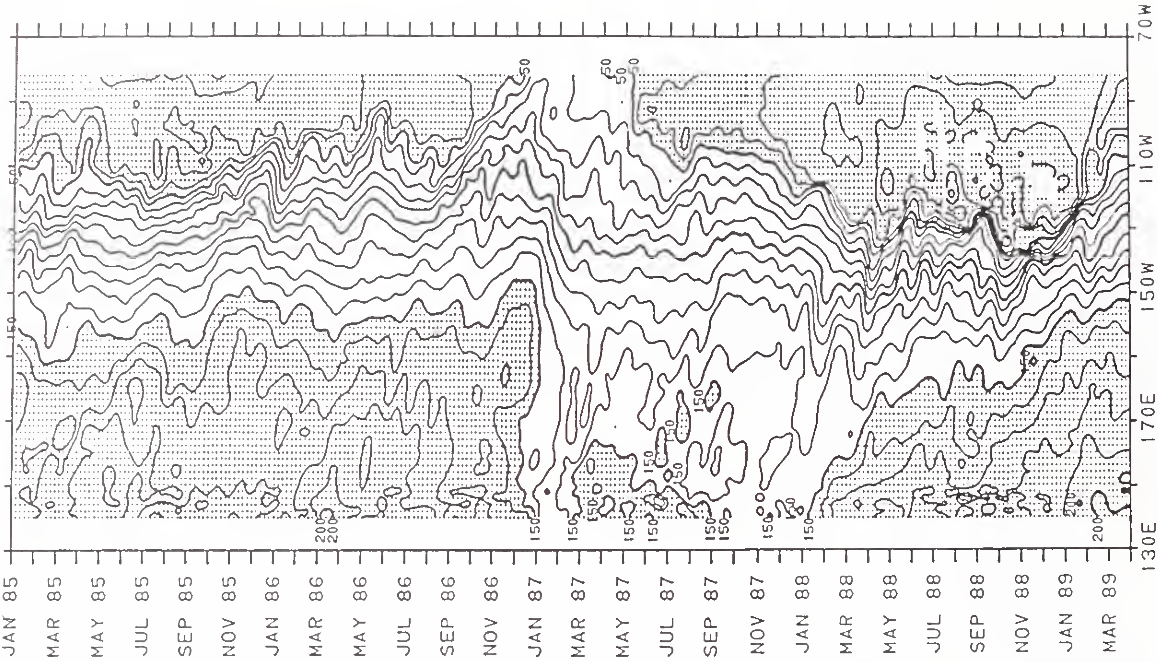

Figure 4. Time-longitude section of the depth of the 20 degree Celsius isotherm along the equator estimated from the model-based analyses from January 1985 to April 1989. Depths of greater than 150 meters and shallower than 50 meters are shaded.

easterlies. Superimposed on this gradual trend were more rapid eastward movements of the isotherm that occurred in late 1985, during early 1986, and after August 1986. These are manifestations of intraseasonal westerly wind stress anomalies. The largest of these occurred in late 1986. Shortly after this, along the equator the thermocline became much shallower in the western Pacific while moving deeper in the eastern Pacific (Figure 3). From this extreme, it took about 18 months to reach the La Niña conditions of the very shallow thermocline in the eastern Pacific and a relatively deep thermocline in the western Pacific.

The analyses in early 1989 indicate a rapid return to near normal conditions. At present, we do not know if this rapid transition will overshoot and lead to another El Niño in late 1989. In fact several of the existing forecast techniques already indicate that this might happen. As can be seen from Figure 4, the large-scale equatorial response of the ocean to wind stress changes takes place over a period of several months. However, it is commonly believed that the slower variability that determines the longer-term persistence of the El Niño-Southern Oscillation cycle lies in the planetary waves (large waves that may be as long as 1,000 kilometers from crest to crest), whose maxima lie off the equator. These waves are also excited by the same wind stress changes but propagate westward much more slowly.

Developments since 1982 have enabled us not only to follow the development of the 1987 El Niño month by month, but also to predict it months in advance. Such an oceanic model can predict developments only if the likely winds are known. Meteorologists can predict the winds with the aid of their models, provided future sea-surface temperature variations are also known. It follows that coupled ocean-atmosphere models, which simulate the interactions between these two media, are necessary for prediction. Several such models have been developed. They simulate the Southern Oscillation reasonably well, and when such a model was used for the purposes of prediction, it was able to anticipate El Niño of 1987 several months in advance. At the moment, the models are relatively crude. They can predict whether or not El Niño will occur, but cannot predict how it will evolve or what strength it will attain. Studies are under way to develop models and techniques capable of producing more accurate predictions. It is hoped that success in simulating and predicting the Southern Oscillation will lead to similar success with other aspects of predicting climate variability—for example, North American droughts such as the one that occurred in 1988. □

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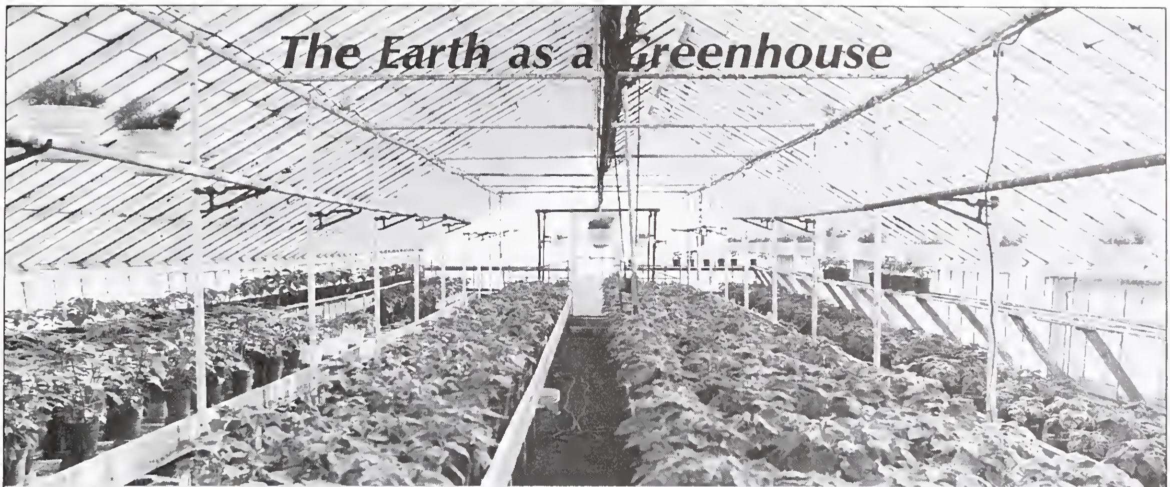
The Earth as a Greenhouse

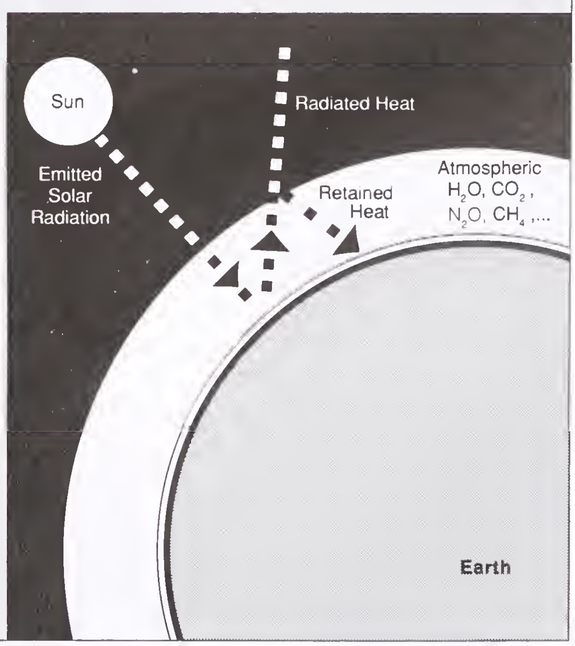


As the sunlight streams toward the Earth, it passes easily through the atmosphere, which is largely transparent to solar radiation. But when the solar heat is radiated back into space from the ground as longer (infrared) waves, it is trapped by carbon dioxide and other trace gases in the atmosphere. The atmosphere gradually warms, emulating the heating that occurs inside a greenhouse, whose glass panes also prevent the reradiated heat from escaping.

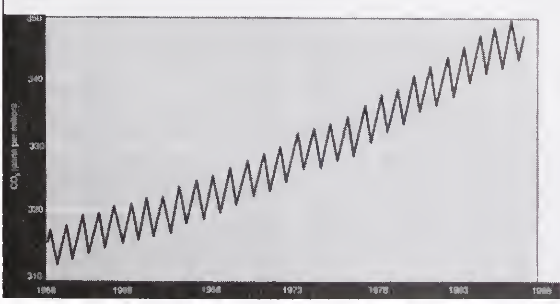
This so-called "greenhouse effect," linking atmospheric composition and climate, has been known since the last century. And the possibility that human activity could alter atmospheric composition enough to enhance the natural greenhouse effect and cause climate change has been recognized for at least 50 years.

The level of carbon dioxide in the atmosphere has increased by about 15 percent since monitoring began 30 years ago, and by about 25 percent since the beginning of the Industrial Revolution. This increase appears to be due in large part to human activities like the burning of fossil fuels (oil, coal, gasoline), which injects carbon dioxide into the atmosphere, and large-scale deforestation, which reduces the number of green plants that remove it.

In addition to carbon dioxide, a number of other trace gases, including chlorofluorocarbons and methane, have also been identified as greenhouse gases. Their levels also appear to be rising. The connection between atmospheric composition and climate, and the documented changes in atmospheric composition, have led to concern about the possibility of significant global warming and other climatic consequences, including rising sea levels and changing patterns of rainfall.



At right, how carbon dioxide and other atmospheric gases trap radiated heat, creating a global warming. Below, the increase in atmospheric CO_2 since 1958. Yearly fluctuations are due to seasonal plant growth. (Photo courtesy of H.V. Lawrence, Falmouth, Massachusetts; Diagrams, NASA)



A Really Worst Case Scenario

Rising seas from global warming may imperil coastal cities and low-lying islands.

by Jodi L. Jacobson

Don't buy land in New Orleans," warns John D. Milliman, Senior Scientist at the Woods Hole Oceanographic Institution (WHOI). The veteran researcher's comment stems from his knowledge of how sea-level rise—an expected consequence of global warming—will affect the habitability of low-lying coastal regions around the world. In the 21st century, waves now breaking on the shores of Louisiana's coast could be lapping at the doors of homes in the Big Easy. Miami is another case in point. The first settlements in that city were built on what little high ground could be found, but today most of greater Miami lies at or just above sea level on swampland reclaimed from the Everglades. Water for its three million residents is drawn from the Biscayne aquifer that flows only feet below the city streets. That the city exists and prospers is due to what engineers call a "hydrologic masterwork" of natural and artificial systems that hold back swamp and sea.

Against a three-foot rise in ocean levels, which is expected by the year 2050, the city's only defense would be a costly system of sea walls and dikes. But that might not be enough to spare the city from insidious assault. Freshwater floats atop salt water, so as sea levels rise the water table would be pushed three feet closer to the surface. The elaborate pumping and drainage system that currently maintains the integrity of the highly porous aquifer could be overwhelmed. Roads would buckle, bridge abutments sink, and land revert back to swamp.

Miami's experience would not be unique. Large cities around the world—New Orleans, New York, Venice, Bangkok, and Taipei, to name a few—would face the prospect of inundation by invading seas. For each, the choice would be fight or flight.

Protecting infrastructure and water supplies of coastal cities, not to mention saving shorelines and wetlands, will require many billions of dollars, perhaps even more than most well-off nations could afford. Sea levels have only gone up several inches over the last century, but their rise is sure to accelerate in the coming decades as global warming sets in motion an expansion of ocean volume and a melting of mountain glaciers and polar ice caps. While some universal increase in sea level is now inevitable, the rate and extent of change depends on preemptive action adopted by society today.

If sea levels rise as much as some scientists expect because of global warming, vulnerable barrier islands such as the one shown on the opposite page will be among the first to be deluged. (Courtesy of the National Geographic Society)

The Expanding Ocean

Most scientists in the climate field now agree that a global warming has begun. Its causes are by now depressingly familiar: "greenhouse" gases generated by human activity are accumulating in the atmosphere and trapping the sun's radiant heat. These gases include carbon dioxide and nitrous oxides from the combustion of wood and fossil fuels, chlorofluorocarbons (used as a refrigerant and in industrial applications), and methane (from ruminant animals, termites, and rice paddies). Meanwhile, population pressures in the Third World are forcing wholesale forest clearing for fuel, farmland, and living space. The result is fewer trees left to recapture the chief greenhouse gas, carbon dioxide.

It is now all but certain that the delicate balance between incoming sunlight and reflected heat that keeps the Earth at a relatively constant average temperature has been upset. What is not certain is just how much higher the temperature will go, and how quickly the increase will take place. Estimates based on current trends project that an average global rise of between three and eight degrees Fahrenheit can be expected within the next 40 years. [For a slightly more skeptical view of such predictions, see article, pp. 61–64.]

As temperatures rise, the waters of the Earth will expand. Glaciers and ice caps will melt. Still-higher sea levels may occur if the warming breaks loose such large frozen ice masses as the West Antarctic sheet. If correct, the predicted temperature changes would raise sea level by five to seven feet over the next century. Some climatologists now estimate that the rate of increase will accelerate after 2050, reaching about an inch per year.

The heat and dryness of the summer of 1988 drew attention to the withering effects global warming could have on agricultural productivity, but its most lasting legacy could be the displacement of peoples, the abandonment of entire delta regions, and the destruction of vital coastal ecosystems by inundation.

Building the Great Seawalls

China's 1,500-mile Great Wall is considered the largest construction project ever carried out, but it may soon be superseded in several countries by modern-day analogs: the "Great Seawalls." If nothing is done to slow global warming, then building structures to hold back the sea will become essential, but their multibillion-dollar price tags may be higher than even some well-to-do countries can afford.

Nowhere is the battle against the sea more actively engaged than in the Netherlands. The Dutch are perhaps best known for their achievements in building a nation on the deltas of the Meuse, Rhine, and Scheldt rivers. And well they should be: Without the carefully maintained stretches of dikes (250 miles) and sand dunes (120 miles) built by Holland's engineers to hold back the sea, more than half the country would be under water.

As the engineers know, the ocean doesn't relinquish land easily. In early 1953, a storm surge that hit the delta region caused an unprecedented disaster. More than 100 miles of dikes were breached, leading to the inundation of 600 square miles of land and the deaths of more than 1,800 people. In response, the Dutch government put together the Delta Plan, a massive public works project that took two decades and the equivalent of six percent of the country's gross national product each year to complete.

The Dutch continue to spend heavily to keep their extensive system of dikes and pumps in shape, and are now protected against storms up to those with a probability of occurring once in 10,000 years. But, due to sea-level rise, maintaining this level of safety may require additional investments of up to $10 billion by 2040.

Large though these expenditures are, they are trivial compared with what the United States, with more than 19,000 miles of coastline, will have to spend to protect Cape Cod, Long Island, the Maryland, Massachusetts, and New Jersey shores, North Carolina's Outer Banks, most of Florida, the bayous of Louisiana, the Texas Gulf Coast, and the San Francisco Bay Area.

Even so, industrial countries are in a far better financial position to protect their coastal regions than are developing nations. Bangladesh, for instance, can ill afford to match the Dutch mile for mile in seawalls. But its danger is no less real. The cyclones originating in the Bay of Bengal before and after the monsoon season already devastate the southern part of Bangladesh on a regular basis. Storm surges 18 feet higher than normal can reach as far as 125 miles inland and cover a third of the country.

In addition to lifting the ocean's level, global warming is likely to increase the frequency of these tropical storms. When added to the ongoing alteration of the combined delta of the Ganges, Brahmaputra, and Meghna rivers—the Bengal Delta—by natural processes and human activity, these conditions may wreak so much damage that Bangladesh as it is known today may virtually cease to exist.

This dike on the island of Walcheren in the Netherlands is one of the best of its kind, but even it could not hold back the rising sea. (Bettmann Archive)

The Danger of Subsidence

Low-lying delta regions, vulnerable even to slight increases in sea level, will be among the first land areas lost to inundation. Residents of these regions are joined in activities that amount to a lowering of defenses. By overpumping groundwater and interfering with the natural ground building that rivers achieve through sedimentation, they are causing the land to sink. In a vicious circle, the more populated these regions become, the more likely this subsidence—and the more devastating and immediate the rise in the level of the sea.

Under natural conditions, deltas are in a state of dynamic equilibrium, forming and breaking down in a continuous pattern of accretion and subsidence. Over time, these sediments accumulate to form marshes and swamps. But regional and local tectonic effects, along with compaction, cause the land to subside by as much as four inches a year if additional sediments are not laid down.

Channeling, diverting, or damming rivers can greatly reduce the amount of sediment that reaches a delta. Where humans interfere with river systems, sediment either shoots past lowlands and is borne out to sea, as with the

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Mississippi River, or it is blocked upriver, as with the Nile and the Aswan Dam. When this happens, sediment accumulation does not offset subsidence. The result is more severe shoreline erosion and a relative increase in seawater levels. Subsidence also occurs where subterranean stores of water or oil are drained. In Bangkok, Thailand, net subsidence has reached five inches per year from a drop in the water table caused by excessive withdrawals of groundwater over the last three decades.

In Louisiana, reduced sedimentation along with extensive tapping of groundwater and underground stores of oil and gas have accelerated the disintegration of the Mississippi delta. That state now loses more land to subsidence and sea-level rise on an annual basis—50 square miles per year—than any other state or country in the world.

According to WHOI's Milliman, the combined effects of sea-level rise and subsidence in Bangladesh and Egypt, whose populations are concentrated on deltas, threaten the homes and livelihoods of some 46 million people.

To arrive at that figure, Milliman's research team started with two estimates of sea-level rise: a minimum of 5 inches by 2050 and 11 inches by 2100, and a maximum of 31 inches by 2050 and 85 inches by 2100. They then calculated the effects under three scenarios.

Under the "best case" scenario, the researchers assume the minimum rise in sea level and a delta region in equilibrium. The second scenario, called the "worst case," assumes the maximum rate of sea-level rise and the complete damming or diversion of the river system draining into the delta. As mentioned, the resulting subsidence must then be added to the absolute rise in sea level. The third scenario is referred to as the "really worst case." It assumes that excessive groundwater pumping for irrigation and other uses accelerates subsidence.

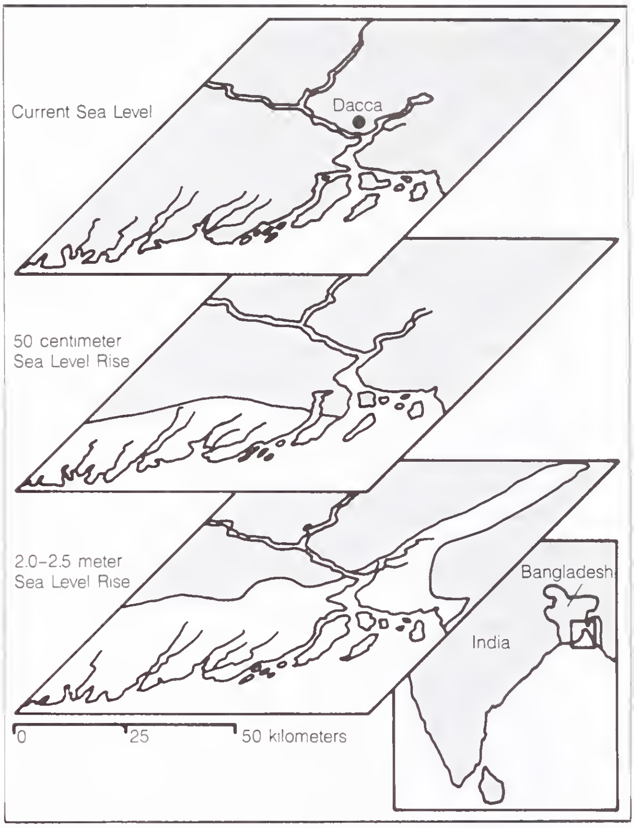
To calculate the economic implications of these three cases on both Egypt and Bangladesh, Milliman and his colleagues assumed present-day conditions, such as the estimated share of total population now living in areas that would be inundated and the share of economic activity that is derived from them. Continued settlement and population growth in these areas will only make for more environmental refugees.

Seven Feet from Disaster

Milliman's calculations bode poorly for Bangladesh, the country built on the world's largest deltaic plain. The Bengal Delta occupies about 80 percent of Bangladesh's total area. Much of the remainder is water. As a result, the nation's inhabitants are subject to annual floods from the rivers and from ocean storm surges.

Just how severely sea-level rise will affect Bangladesh depends in part on the pace at which damming and channeling proceeds on the three giant rivers and their tributaries. Although annual flooding is severe and can damage crops grown on the flood plains, large areas of the delta region suffer drought for the rest of the year. The diversion of river water to parched fields leaves Bangladesh in its present predicament: sedimentation is decreasing and subsidence is increasing.

The WHOI researchers have also concluded that the increasing withdrawal of groundwater in Bangladesh is exacerbating subsidence. Between 1978 and 1985, there was at least a sixfold increase in the number of wells



How the low-lying Asian nation of Bangladesh would be affected by various amounts of sea-level rise. (Courtesy of United Nations Environment Program)

drilled in the country. Sediment samples suggest that the withdrawal of well water may have doubled the natural rate of subsidence.

Taking these factors into account, Milliman and his colleagues estimate Bangladesh is going to experience the "really worst case" scenario. The effect of sea-level rise will be as much as 82 inches along the coast by 2050, in which event it's likely 18 percent of the habitable land will be under water. More than 17 million people would become environmental refugees. The 57-inch rise in the worst case wouldn't spare the nation: 16 percent of its land would be lost.

By the year 2100, the really worst case scenario would have progressed to the point that 38 million Bangladeshis will be forced to relocate.

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Sea Levels: Past, Present, and Future

by John D. Milliman

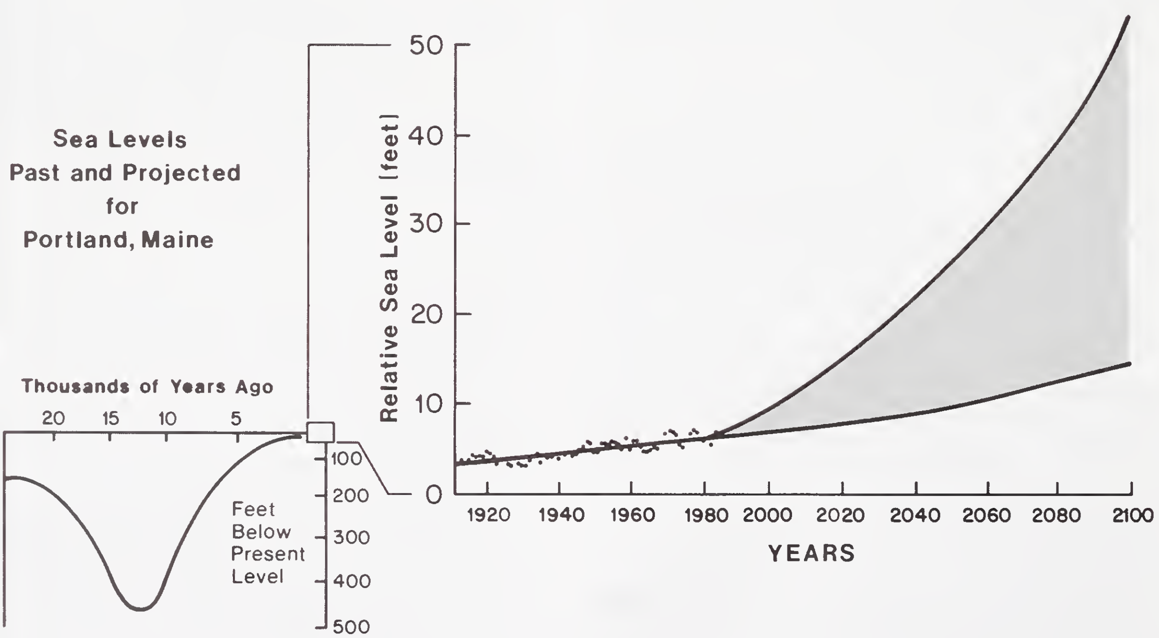
The popular accounts about rising sea levels often make it seem as if the ocean is guilty of a subversive activity. In truth, global sea level has never remained constant. It changes as ice shelves (say, on Antarctica) and glaciers freeze or melt, air temperatures warm or cool (thereby causing thermal expansion or contraction of the oceanic water masses), and ocean ridges change their rates of expansion.

To complicate the picture even more, local sea level depends not only on fluctuations in the sea, but also on the geological stability of the land itself; a site uplifted at the same rate as global sea-level rise would, for instance, experience no relative rise in sea level.

Over geological time, changes in global sea level have occurred in two ways, each having distinct magnitudes and durations. As the sea floor spreads from the midocean ridges, igneous rock, or lava, is piled on older ocean crust. With time, the crust settles under the increased rock load. If spreading rates decrease, the subsidence can exceed the production of new volcanic rock, and the surrounding basin will deepen, increasing its volume. If, on the other hand, the spreading rate increases, the production of new volcanic rock can exceed subsidence and the volume of the basin will decrease.

As the basin increases or decreases its holding capacity, water levels will fall or rise. Although the times involved in ocean-ridge spreading (and therefore basin volume) are geologically slow—many millions of years—the actual vertical change in sea level can be impressive, often hundreds of meters. Evidence of tectonically lowered sea level can be seen most easily in seismic profiles across continental margins, as well as by geological samples of older strata. These show the signs of ancient sea floors many hundreds of feet beneath the modern sea floor.

Superimposed on these long-term changes in sea level are glacially induced



Over the last 15,000 years, sea level off the northeastern United States has risen by more than 300 feet, reaching the present-day level about 1,000 years ago (lower left). Within the last 60 years, mean annual sea level has fluctuated somewhat, but generally risen by about four inches, as indicated by the mean annual average at Portland, Maine (determined by David G. Aubrey and Kenneth O. Emery). The far right part of this figure shows both the projected rise in sea level by the year 2100, if the rate of rise remains similar to that of the last 60 years (lower line). But various models proposed by the National Academy of Sciences and the Environmental Protection Agency predict a greater rise of sea level, varying between a foot and seven feet by the year 2100. The right-hand illustration has been expanded vertically to show more clearly the oscillations in annual sea level at Portland.

fluctuations. The water supplied to glacier ice ultimately comes from seawater evaporation. Thus, during glacial periods sea level falls by 150 to 450 feet, while oceanic salinities can increase by as much as several percent. In contrast to changing rates of crustal genesis, the glacial cycle is relatively fast, each complete cycle lasting only about 100,000 years. The last glacial cycle, the so-called Wisconsin Glaciation, ended only about 15,000 to 20,000 years ago, after which sea level began to rise as the ice sheets melted. From 15,000 to about 7,000 years ago, sea level off New England rose more then 300 feet—rising nearly an inch a year at times—and advancing horizontally by as much as 30 to 60 feet a year.

The method of determining the timing and extent of the last low stand of sea level is inexact at best. Basically, we date intertidal or terrestrial fossils found as much as 300 feet below present-day sea level. For instance, the occurrence of mastodon teeth on the continental shelf off the coast of the northeastern United States clearly indicates that this area was above water at some point in the past. Similarly, old oyster shells would indicate intertidal conditions. By knowing the approximate nature of their habit, the present water depth in which they are found, and their age (usually determined by carbon-14 dating), we can estimate the time at which that area was at or near sea level. Inexactitude comes from carbon contamination on the one hand and accidental shifting of the fossil on the other. At present, we have about 100 data points for the eastern United States, but even these are not enough to construct a sea-level curve in which we can have great confidence.

Recent studies show that the maximum drop of sea level off the southeastern United States during the last glaciation was perhaps no more than 200 feet, about half that off New England. At least part of this large difference between the two areas of the eastern seaboard can be explained by actual shape of the ocean surface. Geodetic measurements made from satellites show that ocean-surface topography at present varies by 100 to 200 feet. So there presumably was sea level "doming" off the Southeast, and a deepening off New England. Changes in the mass loading of the polar regions by glacial ice (for example, the northern latitudes during the last glaciation) presumably can affect the Earth's wobble, and thereby ocean-surface topography.

Over the last 5,000 years, the average world climate has varied only slightly, and sea-surface fluctuations have been correspondingly small, probably no more than three feet in terms of a global average. In fact, a close look at sea-level changes as evidenced by both archaeological ruins and tide gauges indicate that most dramatic changes in sea level have occurred in those locales exposed to substantial uplift or subsidence, rather than an actual rise of the sea. In the Mediterranean, for example, N. Flemming of the Institution of Ocean Sciences in Wormley, England, has noted the remains of old Roman ports on the coast of Israel, and submerged Roman ruins off parts of North Africa and Europe. Since sea level cannot have fallen in one part of the Mediterranean and risen in another, it's clear that what we see is relative land motion.

The most common way to measure modern changes (say, over the last 100 years) in sea level is with tide gauges, using the annual mean at a station. This number averages out most seasonal variations in freshwater discharge (where gauges are on or near rivers), atmospheric pressure, winds, and tides. But because mean river discharge and winds vary annually, the change in mean tidal elevation in successive years does not necessarily indicate an actual change in sea level. Instead, one must use many years of readings to detect a meaningful trend.

David G. Aubrey and Kenneth O. Emery at the Woods Hole Oceanographic Institution find that at least 20 years of continuous records are necessary for most tide gauges, and a 30- to 40-year period is preferred. Using statistical analyses of the data points, Emery and Aubrey have been able to calculate relative trends in sea-level change over much of the world.

Long-term gauges indicate that global sea level has risen about four to six inches in the last 100 years. Although the year-to-year resolution is admittedly poor, there appears to be no scientific evidence to indicate that sea-level rise has accelerated as the concentration of atmospheric carbon dioxide has increased. On the other hand, because of the local fluctuations in river discharge and winds, it probably would take 5 to 10 years of annual means at any tidal station to detect a meaningful rise or fall in sea level.

At present, sea level is rising by about 0.04 to 0.06 inches a year. If this rate were to continue for another 100 years, it would increase sea level by half a foot. While this change may be significant for residents of very low-lying areas, it hardly lives up to the scary headlines we've seen in the last few years. How, in fact, do scientists forecast a three- to six-foot rise in sea levels by the year 2100? More important, are these forecasts realistic?

By trying to quantify the factors that control glacially induced changes in sea

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level, scientists have created many predictive models; indeed the number of models seems to be rising at far greater rates than sea level itself (article, pp. 16–21). The assumptions used underlie the major disagreements between the different models. For example, the coefficient of thermal expansion of seawater is well known, but how quickly would ocean volume respond to a one degree rise in atmospheric temperature? Clearly, this depends on how quickly the surface layers warm and the degree of warming felt by the deeper water masses. Similarly, given a one-degree (or two- or three-degree) rise in air temperature, how quickly would alpine glaciers ice melt, and, more important, what would be the response of the Antarctic ice shelf (the single largest ice body within the ocean) to such warming? The literature abounds with best- and worst-case scenarios (article, pp. 36–39), but the simple fact is that there seems to be no more basis for saying that world sea level will rise by three feet by the year 2100 than to say it will rise by a foot. The variables in each of the predictive models are simply too unknown, although many scientists are working hard to quantify their models.

Clearly, the scientific community needs to choose several coastal areas that appear to be relatively stable (based on the worldwide tide gauge analysis by Aubrey and Emery), and monitor the relative rise of sea level at these locations with a rapid turn-around of the data. Use of satellite-based geodesy, some types of which have absolute accuracies of 0.4 inch or less at present, would be an important step, because it could detect a dramatic change in sea level almost immediately, whereas the more time-proven tide gauge measurements might take as much as 5 to 10 years to average environmental factors.

For the near term, all but those people living in low-lying coastal areas probably have little fear of being inundated by the rising sea. But in the longer term, say beyond the next 10 to 15 years, it's still anyone's guess.

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The social and economic effects will be jarring. Because nearly a third of the country's gross national product is generated within the land area that will be lost, an already poor country will have to accommodate its people on a far smaller economic base. Coastal mangrove forests, upon which 30 percent of the country's population depends to some extent for its livelihood, will be the first victims of advancing seas and extensive river diversion.

Where will the people displaced by rising seas go? Moving further inland, millions of refugees will have to compete with the local populace for scarce food, water, and land, perhaps spurring regional clashes. Moreover, existing tensions between Bangladesh and its large neighbor to the west, India, are likely to heighten as the trickle of environmental refugees from the former becomes a torrent.

Egypt's habitable area is even more densely populated than that of Bangladesh. By and large, Egypt is desert except for the thin ribbon of productive land along the Nile River and its delta. Egypt's millions crowd onto less than four percent of the country's land, leading to a population density there of 700 people per square mile.

Milliman's study points out that because the Nile has already been dammed—which means most of the sediment that would offset subsidence of the delta is trapped upstream—only the "worst" and "really worst" cases are relevant for Egypt. Consequently, local sea-level rise would range between 16 and 22 inches by 2050, rendering up to 19 percent of Egypt's good land uninhabitable.

If the increase is 22 inches, more than 8.5 million people would be forced to relinquish their homes to the sea, and Egypt would lose 16 percent of its gross national product. By 2100, local sea-level rise will range between 101 and 131 inches, submerging up to 26 percent of habitable land and affecting an equal portion—24 percent—of both population and domestic economic output.

While neither Bangladesh nor Egypt is likely to influence the global emission of greenhouse gases or sea-level rise, they do wield considerable control over local sea levels. The development policies they choose in the near future will have a significant effect on the future of their deltas and the people who live on them.

Ecosystems at Risk

Coastal swamps and marshes are areas of prodigious biological productivity. The ecological and economic benefits derived from areas such as Louisiana's wetlands are inestimable. Nearly two-thirds of the migratory birds using the Mississippi flyway make a pitstop in those wetlands, while existing marshlands and barrier islands buffer inland areas against devastating hurricane surges. Marshes not only hold back the intrusion of the Gulf of Mexico's salt water into local rivers but are a major source of freshwater for coastal communities, agriculture, and industry. Louisiana's wetlands supply 25 percent of the U.S. seafood catch and annually support a

$500 million recreational industry devoted to fishing, hunting, and birding.

What was laid down over millions of years by the slow deposit of silt washed off of land from the Rockies to the Appalachians could be jeopardized in a little over a century. Louisiana's famous bayous and marshland may be overrun by the year 2040, when the Gulf of Mexico will surge up to 33 miles inland. With the delicate coastal marsh ecology upset, fish and wildlife harvests would decline precipitously and a ripple effect would flatten the coastal economy. Communities, water supplies, and infrastructure will all be threatened.

According to Environmental Protection Agency estimates, erosion, inundation, and salt-water intrusion could reduce the area of coastal wetlands in the United States by 30 to 80 percent if today's projections of sea-level rise are realized. Vital wetlands such as the Mississippi delta and Chesapeake Bay regions would be irreparably damaged. No one has yet calculated the immense economic and ecological costs of such a loss for the United States, much less extrapolated it to the global level.

Were it not for the enormous pressure human encroachment puts on them, coastal swamps and marshes might have a chance to handle rising seas by reestablishing upland. But heavy development of beach resorts and other coastal areas throughout the United States means that few wetlands have the leeway to "migrate."

Highly productive mangrove forests throughout the world will also be lost to the rising tide. Mangroves are the predominant type of vegetation on the deltas along the Atlantic coast of South America. On the north coast of Brazil, active shoreline retreat is possible because there is little human settlement; the mangroves can possibly adapt. In the south, however, once-extensive mangroves have been depleted or hemmed in by urban growth, especially near Rio de Janeiro. No more than 40 square miles of mangroves remain where once thousands of square miles stood. As sea level rises, these remaining areas will disappear.

In 2100, cartographers will likely be redrawing the coastlines of many countries. They may also make an important deletion: by that year, if current projections are borne out, the Maldives, southwest of India, will have been washed from the Earth. The small nation, made up of a series of 1,190 islands in atolls, is nowhere higher in elevation than six feet. A mean sea-level rise of equal height would submerge the entire country.

By 2050, the Florida Keys "will no longer exist," according to Elton J. Gissendanner, past executive director of the Florida Department of Natural Resources. Loss of the Keys will displace thousands of permanent residents and wipe out a tourist industry that brings 100,000 people to the area each year. Approximately 70 percent of Florida's residents live right on the mainland coast, but no study has been done to determine how many will become environmental refugees.

Although increases in sea level will occur gradually over the next several decades—accelerating in 2030, when the greenhouse effect is expected to really kick in—the issue has already sparked a number of debates.

For one, should society continue on its current path and accept sea-level rise as inevitable, or should it change consumption patterns for fossil fuels and chemicals to mitigate a global warming? How long should local and national governments wait before investing heavily to defend their shores against a future threat, especially when other needs are pressing? When will it be too late? Conversely, should they seek to protect these areas at all? How can coastal residential and resort development be allowed to continue if the land is projected to disappear within a few decades? And who should provide insurance against catastrophe to those living in high-risk areas? Perhaps most important, who will help the Third World cope with the massive dislocations?

For some areas, it could be the end of the road. (Courtesy of the Woods Hole Oceanographic Institution)

The industrial nations, heavily reliant on the burning of fossil fuels over the last century, are primarily responsible for initiating global warming. But today, virtually every citizen of every nation engages in activities that make the problem worse. Meanwhile, development strategies currently being adopted by many poorer countries—water projects that lead to subsidence, policies that encourage deforestation, and development programs based on fossil-fuel-intensive technologies—are likely to exacerbate, the warming and its effects.

If current trends persist, global warming and the subsequent rise in sea level will accelerate. If, on the other hand, concerted action is taken now—to raise energy efficiency and curtail overall fossil fuel use, to find substitutes for chlorofluorocarbons and other industrial chemicals that aggravate the greenhouse effect, to stem the tide of deforestation—then sea-level rise can be kept to a minimum. □

The Impact on Water Supplies

by Harry E. Schwarz and Lee A. Dillard

What impact would the greenhouse effect have on our drinking water? Urban water supplies have, of course, always been subject to the uncertainties of population growth (or decline) and the variability of weather. But the climate changes anticipated under a general global warming would bring water supply changes of a different order of magnitude. How would they affect the ability of water systems to deliver good, potable water? Moreover, are urban water systems preparing for the possible changes that would accompany the higher sea levels and new patterns of temperature and rainfall?

To answer these questions, we interviewed senior managerial and technical people representing nine urban water systems. Out of these extensive discussions,*

If sea levels rise, storm sewers will back up. (Courtesy of the National Oceanic and Atmospheric Administration)

we were able to draw certain general conclusions.

Warming, especially longer and more severe hot spells, would initially trigger increased demand, especially in normally dry regions. Such increases might also exacerbate water quality problems, particularly with trihalomethanes—a family of toxic (and possibly carcinogenic) compounds formed out of certain industrial waste products. Higher temperatures would increase the rate of reactions that produce these chemicals.

Increased average precipitation, greater extremes of weather, and more frequent storms would cause problems in storm drainage. Greater runoff extremes would affect flood protection and hasten the deterioration of levees and floodwalls, making presently protected areas vulnerable.

For coastal cities, the effect of sea-level rise on system components would be twofold. First, salt water moving upstream in estuaries or bays would compromise quality. Initial increases in salinity would cause increased corrosion in pipes and pumping facilities. At higher salinity, water from urban systems with intakes in tidal rivers would not be potable. Yield of upland sources could also be affected, if water had to be released from reservoirs in order to keep the salt front below intakes. New Orleans is an example of the former, New York City of the latter.

The higher sea level is itself a second critical effect. Large areas, developed and otherwise, could be inundated. Decisions to abandon or protect these areas would have to be taken. Greater pumping heads (that is, higher pressure) on drainage and sewage pumping stations, along with higher levees and sea walls, would require expensive solutions, often with long lead times. Abandonment of existing facilities would be politically difficult and expensive in terms of lost productivity and investment. Less rainfall and lowered groundwater, along with flooding, could force salt water into coastal aquifers, contaminating water supply.

Because many cities depend on mountain water, any reduction of the annual snow pack would significantly affect supplies. Also, there is the matter of the melt's timing. If early and rapid melting were to produce runoff in excess of reservoir capacities, the water would be wasted as an uncontrolled flood.

Health effects of the projected scale of climate change appear to be relatively minimal given the present regulatory environment. If standards for potable water are maintained, health—as it relates to water—would not be affected by climate change, although costs would tend to rise. For example, unless upgrades are made,

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**The systems involved in our survey were: New Orleans, New York City, Salt Lake City, Salt Lake County, Washington D.C., Weber Basin Water Conservancy District, Worcester (Massachusetts), Indianapolis, and Tucson.*

treatment in plants overloaded with more turbid water could have some health effects. Unless combined (sanitary and storm) sewers are separated and/or effluent is treated, contaminated overflows could also have some adverse health effects. Further, expensive additional treatment might be required to maintain standards where longer warm spells increased the formation of trichloromethane, a toxic byproduct of industrial wastes that forms during chlorination.

In addition to estimates of system sensitivity, our interviews with urban water managers provided information about the attitudes and perceptions of the managers themselves. Perhaps due in part to scientific disagreement, many of the officials we interviewed aren't convinced that climate change will occur, or even if it does, that it will cause problems for urban water management.

Only one system in our survey, New York City, has studied the possible impact of climate change. New Orleans and Tucson indicated that planning studies would come after recognition of the problem by the Corps of Engineers and the Central Arizona Water Conservation District, respectively. Washington D.C. officials said they would begin to study the problem if there were "believable" predictions of changes of at least 10 percent in such things as temperature, rainfall and runoff. Unfortunately, what they meant by believable wasn't defined.

Have any building decisions been affected by the prospects of climate change? We found only one example—again in New York City. It involved raising a drainage outlet. Still, the final choice was based not so much on the likelihood of rising sea level as on the comparatively low cost of the improvement. Clearly, benefit/cost considerations will remain integral to such decisions.

This is not to say that decision makers will only respond incrementally; we believe that where anticipation of climate change is economical, there will be an appropriate response. Instead, our survey points to the difficulty that urban water managers have in thinking about planning for climate change in light of the immediacy of many other problems vying for their attention and dollars.

Our most significant finding is the lack of acceptance of the likelihood and extent of climate change among the managers and planners we spoke to. Most professionals questioned are taking a "wait-and-see" attitude.

This go-slow approach is mitigated by evidence from our survey that various components of urban systems are resilient enough to accept early manifestations of climatic change without undue damages. Most urban systems could cope—but at a price. They might have to add to existing systems, create entirely new ones, and perhaps abandon parts of old ones. In areas affected by a rising sea level, negative impacts would compound and likely be severe. Water supply systems in some locations would require major changes with long lead times. Sanitary sewers and waste water systems would be least affected because they could be adjusted in gradual stages.

Adding new ports (foreground) to the nearly century-old gatehouse of New York City's Croton Reservoir. (Photo by Marion Bernstein, New York City Department of Environmental Protection)

Ironically, the oft-maligned "overbuilding" and extreme "safety factors" now used in water management may serve some areas as a first round of protection against climate change. Furthermore, many measures that increase our ability to withstand climatic variability will increase resilience to climate change no matter how it is manifest.

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IDEAL MAP
of
NORTH AMERICA
during the
ICE AGE
T.C.Chamberlin
1894

The Historical View

Over the centuries, the debate about the whys and wherefores of climate has raged hot and cold.

by Diana Morgan

Climate, along with the stars and the tides, is one of the oldest subjects of human speculation. What accounts for heat waves and times of drought? How does climate influence the evolution of societies and the course of history?

In China, archaeologists have unearthed some of the oldest evidence of man's anxiety about climate: a set of oracle bones inscribed with a weather report for the 10 days from 20 to 29 March, 1217 B.C., along with prayers for snow and rain. Three thousand years later, climatologists have the technology to chart the outlines of the world's changing climate over a timespan going back millions of years. Even without the aid of Chinese oracle bones, they can now reconstruct a portrait of the weather in some parts of the world around the year 1217 B.C. with a reasonable degree of accuracy. Scholars have recently managed to document the periodic droughts, hot and cold spells, and other climatic fluctuations that have afflicted, and sometimes aided, human societies in various regions of the Earth over the centuries.

Yet scientists and other researchers are still far from understanding *why* climate changes and far from agreeing on *how* (or whether) climate has altered human history. They still cannot reliably predict the weather 10 days from now, or the climate 10 years from now. As Reid A. Bryson of the University of Wisconsin, Madison, observes, climatologists sum things up with the quip: "Forecasting is very difficult, especially if it deals with the future."

The Greeks may have been the first people to recognize climate as something distinct from weather, as a phenomenon that might change over time and distance. More than 2,000 years ago, Greek captains sailing north in the Black Sea to trade wine and oil found the air turning colder, just as the weather grew more inviting as they sailed farther south from their homeland toward Crete, Egypt, and Libya. *Klima*, a word originally denoting latitude, came also to mean the kind of weather specific to a locale.

The Greeks were also the authors of the oldest surviving theories about the effects of climate on human health and history. A fifth-century B.C. medical treatise, "On Airs, Waters, and Places," possibly authored by Hippocrates, attributed what the Greeks viewed as the

Opposite: This map by the American geologist T.C. Chamberlin, circa 1890, was the first attempt to depict the extent of ice in North America during the last ice age. At right, an Andean glacier showing bands representing a year's accumulation of ice. Such old ice can be used to reconstruct past climates. (Photo by Lonnie Thompson) "pusillanimity and cowardice" of the Asians to "the nature of the seasons [in Asia], which do not undergo any great changes either to heat or cold, or the like; for there is neither excitement of the understanding nor any strong change of the body whereby the temper might be ruffled.... It is changes of all kinds that arouse the understanding of mankind, and do not allow them to get into a torpid condition."

Greek notions about climate and its effects persisted for centuries. "In the North," wrote Thomas Jefferson in 1785, men are "cool; sober; laborious; independent.... In the South they are fiery; voluptuary; indolent; unsteady."

But no grand theory of climate's effects emerged until the early 20th century, after Darwin's concepts of natural selection and evolution had opened the way to a questioning of man's position in the natural world. No longer would man be universally regarded in the Christian world as a creature made in God's image, only modestly affected by his surroundings on Earth. Adherents of a new school of climatology marched in Darwin's wake. To these determinists, man was solely a creature of his environment, especially climate.


Yale's Ellsworth Huntington believed climate determined national as well as individual character. (Courtesy of Anna Deming)

The "grand old man" of climatic determinism was Ellsworth Huntington, a Yale geographer who expounded his theories in a series of semipopular books, such as *The Pulse of Asia*, between 1907 and 1945. Huntington contended that the productivity and mental ability of individuals—and, ultimately, the rise and fall of entire civilizations—were inseparable from the impact of climate.

In some of the first scientific studies of climate's physiological and psychological effects, Huntington diligently measured the impact of seasonal fluctuations of temperature and humidity on human beings: the weight gains of 1,200 tubercular patients in New York between 1893 and 1902, the efficiency of 65 young women in a North Carolina label-pasting factory, and the mathematics grades of 240 West Point cadets between 1909 and 1912.

Huntington's conclusion: A climate with an average temperature of 64 degrees Fahrenheit and relative humidity of 60 percent was most conducive to health and to physical and mental performance. Equally important were the stimulation of daily and seasonal weather fluctuations and, significantly, racial inheritance. (For example, the "Teutonic race," he wrote, enjoyed "an ineradicable" advantage in "mentality.")

Writing at a time of Anglo-Saxon hubris, when the British Empire was at its apex and the United States was a rising power, Huntington maintained that no nation "has risen to the highest grade of civilization except in regions where the climatic stimulus is great." The civilizations of Rome, Persia, and Egypt had declined, he believed, because of changing climates. He singled out northwestern Europe, the Pacific and northern Atlantic coasts of the United States, and Japan (which had recently won a startling victory over the Tsar in the Russo-Japanese war of 1904–05) as regions with the greatest natural "climatic energy" of modern times.

Huntington's ideas gained a following in academia, especially among scientists. But in the late 1920s, Arnold Toynbee, a noted English historian and admirer of Huntington, developed a new theory, arguing that climate and culture throughout history had been involved in a dialectic of challenge and response. "The stimulus toward civilization," he wrote, "grows stronger in proportion as the environment grows more difficult," citing as one example the flowering of Hellenistic Greece in the arid heat of Attica.

Although Huntington's empirical data on climate and individual behavior are still generally respected by specialists, his conclusions were soon rejected as racist, exaggerated, and overly deterministic. (Toynbee fell out of favor for other reasons.) Huntington's notions were also undermined by the work of scholars in several new specialties. By the 1930s, sociologists and other practitioners of the social sciences were

Diana Morgan is a Washington-based science writer who was formerly an editor for Science 86. *This article originally appeared in the Winter 1988 edition of* The Wilson Quarterly *(Vol. XII No. 5). Copyright © 1988 by Diana Morgan.*

advancing a more sophisticated picture of the evolution of human societies; they included such influences as religion and migration. At roughly the same time, the field of climatology was moving away from speculation about climate's influence into an era of technological inquiry and precise historical measurement of climates past.

It is difficult for modern American city-dwellers, cossetted by central heating in winter and air conditioning in summer, and virtually assured of supermarket groceries even when drought-stricken crops are withering in farmers' fields, to comprehend how important a predictably stable climate was to the people of earlier times. As late as the 15th century, historian Fernand Braudel writes, the world population "consisted of one vast peasantry where between 80 and 95 percent of people lived from the land and from nothing else. The rhythm, quality, and deficiency of harvests ordered all material life."

But prior to our own century, man's ability to measure the vagaries of weather and climate was limited—and slow to develop. The first known attempts were in ancient Egypt, from which archaeologists have unearthed fragments of a large stone stele, carved by minions of the pharaohs during the 25th century B.C., that was used to record the levels of the annual Nile River floods. The Egyptians counted on these annual floods to irrigate the fields and nourish the croplands with nutrients from upstream. The Chinese, who began systematic observations shortly after the Egyptians, were compulsive record-keepers. They can probably claim mankind's longest continuous documentation of natural events. But, aside from crude rain gauges, weather vanes, and other simple devices, these early investigators possessed few reliable measuring instruments.

The Greeks paid tribute to several gods of the winds, including Zephyrus, who ruled the western wind; medieval Catholics appealed to Saint Médard for rain. The earliest climatologists were probably priests; they studied the sky to determine the time for sowing and reaping. In ancient Sumer, they were responsible not only for predicting the onset of the seasonal rains and floods but also for inspecting the irrigation canals, which channeled precious water to the fields.

Man's sinfulness was believed to be at the root of many calamities. In medieval Europe, times of famine were often followed by purges of heretics and unbelievers. In Germany, Catholic priests exhorted their congregations to destroy witches in the wake of hailstorms and other meteorological scourges. But things began to change by the 16th century. About 1590 Galileo invented the thermometer; one of his followers, Evangelista Torricelli, created the first barometer. Comparative meteorology was born in 1654, when the Grand Duke of Tuscany, Ferdinand II of the de' Medici family, ordered dozens of identically calibrated thermometers from an Italian glass blower and established the world's first meteorological network across Italy.

After periods of unusually bad weather, the anxious monarchs of France (in 1775) and Prussia (in 1817), fearful of a permanent climatic change, also established nationwide networks to record daily temperatures, barometric pressure, and rainfall.* For the first time, Europeans had turned to scientists rather than priests or folklorists to understand the forces of climate.

Toward the end of the 19th century, scientists were able to report that, while average temperatures did indeed fluctuate from year to year, they could find no evidence of long-term changes. Classicists, poring over the scattered weather observations of the ancient Greeks, concurred. Europe's climate, they believed, had not changed for at least 2,000 years.

At the end of the Little Ice Age, European glaciers like this one in the village of Argentierre in the French Alps, were much more extensive. (Courtesy of the National Center for Atmospheric Research)

Of course, there had been inklings that the Earth's climate had once been dramatically different. In Europe's glacier-studded Alps, country folk who lived surrounded by ice-scarred rockface and rubble at the foot of the mountains took it for granted that the glaciers had once advanced and then retreated. Until the mid-19th century, however, most geologists rejected the notion as fanciful.

The so-called erratic boulders in the Alpine valleys, early 19th-century geologists said, still

*As researchers now know, the climate of 18th- and early 19th-century Europe *was* in flux. But Prussia's King Frederick William III acted after the extraordinary (and disastrous) "year without summer" of 1816, when crops in some parts of the Northern Hemisphere were killed by frosts as late as mid-June. Many climatologists now suspect that the violent eruption of Indonesia's Mount Tambora in April 1815 was the likely cause. They believe that ash and gases from the volcano, high in the atmosphere, reduced the amount of sunlight reaching the Northern Hemisphere.

adhering to Biblical chronologies of an Earth born only 5,000 or 6,000 years ago, were probably deposited by the Flood described in Genesis.

Bits of contrary evidence continued to accumulate, however. By 1832, Reinhard Bernhardi, a German professor of forestry, dared suggest that an enormous ice sheet had once blanketed northern Europe. A few years later, the Swiss-born naturalist Louis Agassiz began to popularize this view, writing dramatically of a frozen Europe that heard only "the whistling of northern winds and the rumbling of the crevasses."

The Glacial Epoch, later research would show, began almost three million years ago—in fact, we may still be living in it. At various times, the Earth was as much as 36 degrees Fahrenheit colder than it is today, and the oceans were perhaps 500 feet below current levels. Ice sheets up to two miles thick blanketed a third of the Earth's land mass, extending as far south as the Great Lakes and Cape Cod in North America, covering Scandinavia and the British Isles in Europe, and burying much of northern Asia.

Louis Agassiz popularized the view that Europe was once covered with ice. (Courtesy of the Marine Biological Laboratory Archives)

These cold periods during the Glacial Epoch were the ice ages. There have been perhaps 10 of them during the last million years; scientists still are not certain. (It was probably during the last Ice Age, 15,000 to 35,000 years ago, that humans first crossed what is now the Bering Strait from Asia to North America.) The ice ages were punctuated by warmer spells known as "interglacials." It was not until about 8000 B.C., as the Earth began to warm during one such interglacial, that *Homo sapiens* first took up farming, probably in ancient Mesopotamia and other areas. The interglacials have been rare and relatively short, lasting 9,000 to 12,000 years. "The present 'interglacial,' " observes climatologist Reid Bryson, "has been with us for about 10,800 years."*

During the 1860s, Scotland's James Croll, a self-taught physicist who was employed as a janitor at Glasgow's Andersonian College before his theories won him international acclaim, suggested that 100,000-year variations in the Earth's orbit may have drastically reduced the amount of sunlight reaching the planet during the ice ages.

Others speculated that the solar system had passed through one of the Milky Way's spiral arms, becoming blanketed in dust dense enough to filter out light from the sun. Other scientists scrutinized the influence on climate of everything from the tidal effect of neighboring planets and the slow "drift" of the Earth's continents to the spewed effluvia of volcanoes, the wandering of the magnetic poles, and sunspots. Finally, during the 1920s, a Serbian mathematician named Milutin Milankovitch reworked Croll's theory of variations in the Earth's orbit, showing with a series of complicated equations how "stretch," "tilt," and "wobble" might have produced the ice ages. Gradually, climatologists came to accept (albeit with many qualifications) the general outlines of Milankovitch's theory.

Meanwhile, geologists and climatologists searched the glaciers and other sites for physical clues to date the waxing and waning of the ice ages—though the concept of nature as self-chronicler was not new. In 1686, Robert Hooke, a brilliant, irascible English philosopher who had a famous feud over the nature of gravity with Sir Isaac Newton, toying with fossilized shells that resembled tropical species, wondered whether Britain had once lain within a "torrid zone." It is very difficult "to raise a *chronology*" by examining the shells, he observed, "and to state the intervals of the times wherein such and such catastrophes and mutations have happened; yet 'tis not impossible."

Before they could "raise a chronology," scientists needed field methods and technologies that would allow them to quantify past climatic change.

One such method was dendrochronology—counting growth rings to determine the ages of

*During the 1970s, a cluster of especially cold winters in the United States stirred widespread fears that a new Ice Age was dawning. The National Academy of Sciences warned that it could begin within 100 years; analysts at the U.S. Central Intelligence Agency prepared an assessment of American power in "a cooler and therefore hungrier world."

trees. At the turn of the century, Andrew Douglass of the University of Arizona likened the annual rings to Morse code: The sequence of dots (narrow rings indicating growth-limiting conditions) and dashes (wider rings indicating years of favorable conditions) relayed a message about the climate during the tree's lifespan. Douglass showed how the rings of a recently felled tree could be matched with those of an older stump or piece of fossilized wood, which could then be linked to an even older sample, ultimately allowing dendrochronologists to stretch the record back 8,200 years, the edge of the last ice age.*

The Earth's history is written in layers of environmental debris. If each stratum of ocean sediment, ancient soil, or Arctic ice was layered more or less chronologically, scientists reasoned, the perceptive investigator, by sifting through layered clues, would be able to discover the climate at the time each layer was formed.

In 1916, Swedish botanist Lennart von Post capitalized on this now-common notion when he reported on his study of rich deposits of pollen grains dug from lakes and bogs in his native land. Soon, scientists throughout the West were digging up soil samples, analyzing everything from beetle genitalia and fossilized leaves to microscopic creatures and chemical isotopes for clues to climate changes in the past.

By examining a millimeter of soil under a high-powered microscope, investigators such as von Post could make a connection between the relative amounts of pollens and prehistoric climate, up to 100,000 years in the past. An abundance of grass and shrub pollen suggests the existence of frigid tundra and grasslands at the edges of glaciers; birch and pine pollen hints at a somewhat warmer climate; and the presence of oaks and elms signals a temperate zone. In China, the spread of bamboo is a reliable indicator of regional warming in centuries past.

In the United States, the Dust Bowl disaster in the Great Plains during the 1930s (which was exacerbated by poor farming methods) and several abnormally hot summers jolted the public into a new awareness of climate. Actually, the warming trend had begun during the 1890s; it peaked during the 1940s, when the Northern Hemisphere endured its highest summer temperatures, and enjoyed its mildest winters, in perhaps 1,000 years. (The 1980s have been warmer still, with several of the hottest years on record; yet *average* annual temperatures have been less than one degree Fahrenheit above normal.)

In America and Europe, all of this prompted the first wide discussion among scientists (if not in the press) of the "greenhouse effect": Heat that formerly would have escaped into outer space, the argument went, was being trapped close to Earth by vast amounts of carbon dioxide pumped into the atmosphere from factory smokestacks and other manmade sources. For the first time, it seemed possible that man could inadvertently alter the global climate.

One of the most important new technological developments was radiocarbon dating, a technique developed in 1947 by Willard Libby, a University of Chicago chemist, later a Nobel laureate. It allowed scientists to determine the age of fossilized plants and animals up to 40,000 years old. At about the same time, Harold Urey, also an American Nobel laureate in chemistry, introduced another far-reaching technique: isotope analysis of ocean sediments and ice cores.* Suddenly scientists could peer into the very distant past—up to 570 million years ago—when ancient deep-sea creatures began absorbing oxygen from the oceans to form protective shells.

A 20-foot "core"—a cylinder of compacted mud and ooze from the ocean floor—can provide a sampling of sediments built up over millions of years, allowing geologists, using Urey's method,

Some 3,000 years old, gnarled bristlecone pines in California's White Mountains provide a window on past climate. (Courtesy of the Laboratory of Tree-Ring Research, University of Arizona)

*Tree rings are wonderfully specific, however, and recent techniques allow scientists to calculate yearly variations in temperature, rainfall, and even atmospheric pressure at sea level.

*On average, 99.8 percent of the oxygen in water is ordinary oxygen, ^{16}O, but 0.2 percent is composed of an isotopic form ^{18}O, with two extra neutrons. In warm weather, when ocean water evaporates quickly, the relative amount of ^{18}O increases as the lighter ^{16}O is drawn up into the clouds. Urey reasoned that past ocean temperatures could be measured by determining the ratio of the two isotopes in ancient sea fossils: the more ^{18}O in the fossil, the warmer the weather had been. Urey's method did *not* allow scientists to date samples; that had to be done by other means, chiefly by counting the layers of sediment or ice.

to chart not only the progressive deep freezes of the ice ages but also the temperature fluctuations of the interglacial warm spells. In 1950, when Urey shaved a sliver from the 150 million-year-old fossil of a squidlike creature, he was able to determine that the creature had been born in early summer and died four years later in early spring.

When the technique was later applied to the comparatively spongelike material of the Greenland and Antarctic ice sheets, scientists were able to trace the waxing and waning of the interglacial periods with remarkable precision. They were suddenly much closer to an understanding of past climatic change—and, possibly, by extension, climate present and future.

Just as scientists after World War II were mapping broad climate variations across millions of years, a new breed of "documentary" climatologist began the painstaking task of reconstructing climate over a shorter timespan.

A leader of the "documentary" school was Emmanuel Le Roy Ladurie, an unconventional French historian. Ladurie was determined to develop a new historiography of the past 1,000 years, with special emphasis on Western Europe during the 16th, 17th, and 18th centuries. His chief method was to assess written records of vineyard harvest dates in 18th-century France. The principle behind this "phenological" method, as Ladurie described it in 1971, was simple. The date at which the grapes ripened reflected the temperatures "to which the plant [was] exposed between the formation of the buds and the completion of fruiting.... These dates are thus valuable climatic indicators."

Other "documentary" climatologists, before and since, have dusted off epistolary accounts of winter storms or counted the number of prayers said for rain. They have looked for clues to climatic change in the accounts of Venetian diplomats, the ships' logs of sea captains, and in reports on the frequency of the canals freezing over in the Netherlands. They have made two periods of relatively drastic climatic change the focus of especially obsessive examination.

The Medieval Warm Epoch (circa A.D. 1000 to A.D. 1400) brought the world the highest temperatures in perhaps 5,000 years. During this brief spell, the Vikings, unconfined by sea ice, invaded Europe's Atlantic coast, traded with the Italians and Arabs, colonized now inhospitable Greenland, and possibly voyaged to North America. Plagues of locusts descended on Continental Europe. In Britain, farmers cultivated flourishing vineyards and began working lands in the north of Scotland, only to abandon them forever a few centuries later.

The Earth began to cool again around A.D. 1200, gradually dropping about two to four degrees Fahrenheit below today's levels, and the period from 1400 to 1850 has been christened, with considerable exaggeration, the Little Ice Age (*Oceanus* Vol. 29, No. 4, pp. 38–39). Those four centuries saw the modest advance of glaciers in the Alps and elsewhere, the occasional wintertime freezing of the Thames River, and periods of widespread famine, as Europe's summers became shorter, cooler, and wetter. Massive ice floes hampered ocean travel in the northern Atlantic: in 1492, Pope Alexander VI lamented that no priest had visited Greenland for 80 years.

The Europeans of that era scribbled as busily as do their chroniclers today: diaries, monastic and manorial chronicles, and tax reports have all become fodder for countless late-20th-century doctoral theses packed with the minutiae of a lost age. It is difficult to find a season in Europe during the past 1,000 years for which there is not an account of someone's impression of the weather.

Until the last decade or so, however, the "documentary" climatologists, for all their obsession with detail, were regarded with indifference by most "hard" scientists, who dismissed their attempts to stitch together definitive analyses from stacks of crumbling church records and other sources. However, since the 1960s, when Britain's Hubert H. Lamb, originally trained as a meteorologist, came to the fore of documentary climatology and began urging his colleagues to employ greater rigor, the discipline has gradually won more acceptance from scientists.

Recently, other scholars, such as historian David Hackett Fischer of Brandeis University, have criticized some of the "documentary" climatologists (and most mainstream historians) for giving short shrift to the effects of climatic change on human affairs. Ladurie came in for especially harsh criticism for his view that "the human consequences of climate seem to be slight, perhaps negligible."

Fischer, in sharp disagreement, proposed a history of the "conjunctions" of climate and culture. During the first conjunctive period, up until about 10,000 years ago, he said, "variations in climate determined the possibility for human culture to exist at all." Later, climate influenced the survival of complex civilizations. During the third epoch, from about A.D. 1000 to the present, man has been able to adjust, albeit painfully at times, to changes in climate.

These modern historians, along with a few climatologists and popular writers, have avoided the determinism of Ellsworth Huntington; but they have not shied away from large generalizations. Even Fischer, an exacting historian, has pointed out that during the climatic upheaval of the sixth and fifth centuries B.C., which seems to have brought droughts to large parts of the world, many of the "world's great ethical and religious systems were created." He suggests that the teachings of Confucius in China, Buddha in India, Zoroaster in Iran, and the Jewish prophet Deutero-Isaiah were all responses to the same problem of creating stable values in a world of

This abandoned farm near Pierce, Nebraska, in 1937 after its soil was ravaged by wind erosion during the Dust Bowl offers proof that climate can change abruptly and disastrously. (Courtesy of the National Archives)

disquieting social and climatic change.

No less single-minded, other researchers have debated the reasons for the disappearance of the advanced Indus society in northwestern India 5,000 years ago, pitting the impact of Indo-European invasions against flooding in the Indus Valley and, dubiously, to a long period of drought. Analysts have variously tied the global distribution of political stability to temperature, and correlated the size of standing armies with the degree of north or south latitude. In 1970, a popular author, Robert Claiborne, went so far as to suggest that a climate shift in A.D. 1200, which led to the failure of the German herring fishing fleets, paved the way for the rise of Adolf Hitler seven centuries later.

And just as Ellsworth Huntington advanced a theory of climate with an explicitly ideological message earlier in the 20th century, so have others in more recent times. For example, Jayantanuja Bandyopadhyaya, an Indian political scientist, argues, much as Huntington did, that climatic handicaps account for the underdevelopment of the Third World. Western scholars, he claims, have suppressed the study of warm weather's negative impact on man, emphasizing racial superiority as the cause of the West's economic preeminence. But Bandyopadhyaya argues that the "neo-imperialist" West has a moral obligation to level the climatic playing field. His proposal: The United States and Western Europe should invest in research on "global climatic engineering" to find ways to artificially cool down the tropics.

Eccentric as Bandyopadhyaya's position may be, some climatologists warn that ideology subtly influences all scholarly research on climate and culture. "Even among the modern scientific community," observe British researchers M. J. Ingram, G. Farmer, and T. M. L. Wigley, "ideas about climate are inevitably influenced to some extent by current ideologies." They see the rising worldwide alarm about threats to the environment since the 1970s as the chief impetus to the growing debate over the relationship between changing climate and man's culture.

Just as 16th-century Germans viewed hailstorms as punishment by God for individual sins, many scientists (and laymen) today see man on the verge of self-destruction as a result of sins against nature—the rapacious exploitation of natural resources, pollution, the development of harmful technologies. According to Ingram and his colleagues, the personal views of climatologists "undeniably condition differing interpretations of the often ambiguous evidence."

Even without such sentiments, serious scientists trying to penetrate the mysteries of climate past and present confront a frustrating task, for climate is the result of a vast array of thousands of interacting variables. Climatologists now often find themselves in the uncomfortable position of knowing more about climate every day, and, in some ways, seeming to understand less. □

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How Venus Lost Its Oceans

by James F. Kasting

Venus today is an extremely inhospitable place. Its closeness to the Sun and its dense carbon dioxide atmosphere combine to produce a surface temperature of some 460 degrees Celsius (800 degrees Fahrenheit)—far hotter than your kitchen oven. It is also exceedingly dry; the total water on Venus is comparable to that held in Earth's much thinner atmosphere—100,000 times less than the water in the Earth's oceans.

Was Venus always this dry? I think not. A much more plausible theory is that Venus once had abundant water, but lost it as the water vapor in its upper atmosphere was broken into its component atoms, oxygen and hydrogen, and the lighter hydrogen escaped to space. Venus may also have once been cool enough to form oceans. Indeed, the early Venus may not have been all that different from the early Earth. (For an opposing view, see following article, pp. 58–60.)

To appreciate why the young planet may have been wet, it helps first to understand the opposing view: the equilibrium condensation model for planetary formation, which has been most

This view of an oceanless Venus was created from data acquired by the U.S. Pioneer orbiter and the Soviet Venera spacecraft. (Courtesy of the U.S. Geological Survey, Flagstaff, Arizona) vigorously defended by John Lewis and his colleagues at the Massachusetts Institute of Technology and the University of Arizona.

This model begins with a gaseous nebula slowly condensing to form the Sun, planets, and assorted debris. It prescribes a temperature structure for the nebula:·hotter on the inside, cooler farther out.

Most of the Earth's water was incorporated into our planet as water-containing minerals, such as tremolite or serpentine. We would expect such minerals to form at the low temperatures beyond the orbit of the proto-Earth, but not in the warmer regions near the orbit of proto-Venus. The nebula cooled slowly and peacefully, according to the model, and materials that condensed at a given distance from the nebula's center would have a uniform composition.

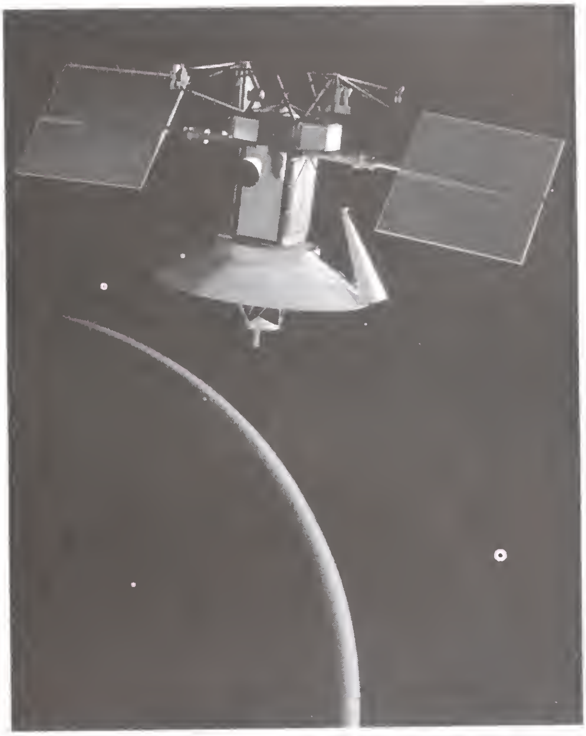
The equilibrium condensation model successfully accounts for the shift from rocky to icy materials as we move outward in the solar system. But there are at least two good reasons why its predictions might be misleading. It presumes that the planets formed only from materials that condensed in their immediate vicinity and that there was little or no mixing of distant planetesimals (small, solid bodies that may have grown into planets as they collided and accreted gravitationally). The question of how much mixing actually occurred is unresolved. Gravitational interactions among planetesimals could have jumbled up materials formed in different regions of the nebula.

The Role of Meteorites

Another way of thinking about this question is to ask whether the terrestrial planets (Mercury, Venus, Earth, and Mars) can be built from known types of rocky fragments from the original nebula. This, of course, presumes a certain amount of nebular mixing so that different materials can be incorporated into each planet. Various researchers have suggested that the Earth received its volatiles (substances easily evaporated at low temperatures, such as water) from carbonaceous chondrites, a type of organic-rich meteorite. These meteorites are roughly 10 percent water by weight in the form of hydrated minerals, along with large amounts of carbon with hydrogen atoms attached. Oxidation of this organic carbon by ferric oxides (minerals containing iron and oxygen) would have released carbon dioxide and water to the Earth.

Other researchers have suggested that the Earth's volatiles were brought in by ordinary chondrites—less highly oxidized meteorites with much fewer volatiles than their carbonaceous cousins. Oxidation of their carbon would have yielded carbon dioxide but no water. Ordinary chondrites do, however, contain some water (about 0.2 percent by weight) in hydrated materials. Thus, such materials must have been completely absent from the neighborhood of proto-Venus for the planet to have been born dry.

The second problem with the equilibrium condensation model is that it ignores comets—surprising, in a way, because David Grinspoon and Lewis have since invoked comets to explain the excess amounts of the hydrogen isotope deuterium in Venus' clouds (see box, pp. 58–60). The comets that now make up the Oort Cloud, which circles the Sun far beyond the orbits of the nine known planets, are thought to have formed originally in the vicinity of Uranus and Neptune. Orbital perturbations from these giant planets would have sent most of these comets away from the Sun and out of the ecliptic (the plane defined



The Magellan spacecraft as it will look when it reaches Venus in the summer of 1990 and begins orbiting the planet. (Courtesy of the Jet Propulsion Laboratory)

by the Earth's orbit about the Sun). Many, however, would have been scattered into the inner solar system, where they could have collided with the newly formed terrestrial planets, including Venus. Indeed, the flow of comets through the solar system during its first several hundred million years may have been 1,000 to 10,000 times greater than it is today.

Christopher Chyba of Cornell University has recently estimated that the water in the

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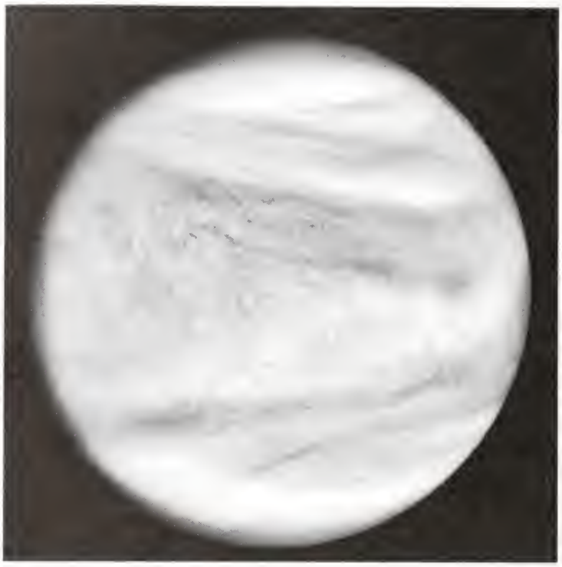
Earth's oceans could have been entirely derived from comets even if they comprised only 10 percent of the impacts recorded on the moon. (Since the Earth's constantly changing crust eventually erases evidence of impacts, the moon's mostly inert surface is a good record of past bombardments.) Venus would presumably have received a comparable amount.

Yet in about a hundred million years or less, depending on the energy output of the young Sun and the efficiency with which it helped hydrogen to escape from the planet's atmosphere, Venus would have lost its water. A late veneer of cometary water would not have been enough to form oceans. However, compared to today, Venus' primitive atmosphere would still have been very wet.

Another argument favoring an ocean-free Venus is that it would have been impossible to get rid of large amounts of water through photodissociation (when light energy breaks apart a chemical compound) and the escape of hydrogen to space.



Despite its similarity to Earth, Venus is shrouded in a dense layer of sulfur-laden clouds, which trap heat and keep the planet's surface hotter than a kitchen oven. (Courtesy of NASA/Ames Research Center)

Blowing off Hydrogen

The specific mechanism for losing hydrogen involves hydrodynamic outflow—a process analogous to the way material is blown off from the Sun as a stream of charged particles called the solar wind. Theoretical studies have shown that hydrodynamic escape would have efficiently removed the hydrogen if the upper atmosphere was rich in that element. But water vapor (and thus hydrogen) could have been confined to the lower atmosphere by a cold trap, an atmospheric region where water vapor condenses to droplets and falls back toward the surface.

Climatic models predict that an atmospheric cold trap does not work well if the lower atmosphere contains more than about 10 percent water vapor (by mass). A wet young Venus would have had at least this much water vapor in its atmosphere, so the cold trap would have been forced up to very high altitudes. There the pressure is so low that water vapor has little urge to condense and fall back to the planet. It would therefore have made its way into the upper atmosphere, where it could have been photodissociated. The hydrogen could then be lost to space.

Lewis and his colleagues have not challenged the idea that early Venus could have lost lots of hydrogen in this way. Rather, they point out what they perceive to be grave difficulties in disposing of the oxygen left behind.

Whether or not this oxygen poses a problem for the wet young Venus model depends in part on when the water was acquired. If much of the water came in as the planet was accreting, then its surface should have been molten and the entire mantle (the planet's interior region between its crust and core) should have been turning over vigorously. A virtually unlimited amount of oxygen could then have entered the mantle. Water would probably have reacted with melted elemental iron and released its hydrogen, forming our old friends, the ferric oxides.

Once released, this hydrogen would have made its way to the top of the atmosphere and escaped if enough solar energy was available. If, on the other hand, the inner solar system was still filled with dust blocking the sunlight, then the hydrogen would have remained in Venus' atmosphere until the nebula cleared and it could escape. In either case, lots of water could have been lost without creating much free oxygen.

If Venus got its water from cometary bombardment after it had accreted, that presents a bigger problem. The amount of water that could have been lost might then have been something less than a full terrestrial ocean. If fresh crustal material was produced at the same rate as it is on Earth, it could have taken up oxygen equal to about one-thirtieth of the Earth's ocean (or an average depth of 100 meters).

Lewis and his coworkers have ignored other possible oxygen sinks—processes and places that could take up the element. For example, Venus may have originally outgassed its carbon dioxide (CO_2) as carbon monoxide (CO). One-tenth of a terrestrial ocean could have been consumed in oxidizing CO to CO_2. Or oxygen could have escaped to space if the solar energy was strong enough. Indeed, from an energy standpoint, Venus could have lost several oceans, including the oxygen, during its first hundred million years.

The real Achilles heel of the "runaway greenhouse hypothesis," as the original wet young Venus model was called, lies in getting rid of the last part of the original water. Climatic

Under Venus' dense cloud cover, radar probes from Earth and spacecraft have discovered continental-like land masses that may once have been surrounded by oceans. (Courtesy of NASA/Ames Research Center)

theory predicts that a cold trap would have developed as the water vapor content of Venus' lower atmosphere fell below a tenth of a percent. If Venus already had its massive 90-bar carbon dioxide atmosphere, then roughly 10 Earth atmospheres of water would have remained in its lower atmosphere when the cold trap began to become effective. The rate of this water's escape depends on the temperature and height of the cold trap, and so is hard to estimate. But crude calculations suggest that it would have been hard to lose this much water even over several billion years.

Furthermore, at some stage sulfuric acid clouds like those enshrouding Venus today would have started to form. These water-loving clouds would have taken up the errant water and dried out the upper atmosphere even more, further reducing the rate of hydrogen escape.

Some Very Hot Seas

Why, then, does so little of Venus' original water remain? If we start with an Earth-like planet covered with an ocean and then calculate how much solar heat is needed to vaporize the ocean, climatic models (mine, at least) predict that the Sun's energy today falling on Venus is more than enough to do the job. However, shortly after it formed, the Sun was about 30 percent dimmer than it is now, so the energy falling on primitive Venus could well have been cool enough for liquid water to form. Thus, if Venus did start out with an Earth-like water endowment, much of that water should have condensed to form a hot ocean. That ocean's temperature would have depended on the effects of clouds and the amount of carbon dioxide in the atmosphere, but it was probably between 100 and 200 degrees Celsius (212 and 392 degrees Fahrenheit). Since the overlying vapor would have kept the water from boiling, liquid water should have been stable on early Venus even if the planet had only a fraction of the Earth's water.

An ocean on early Venus should have caused great changes in its atmosphere. On Earth, water weathers silicate rocks, converting them to carbonates and taking up atmospheric carbon dioxide in the process. Similar weathering reactions, which occur in the presence of liquid water, would have reduced Venus' atmospheric pressure by sequestering carbon dioxide in the planet's crust. This reduction of atmospheric carbon dioxide would have facilitated water's escape because much less water would have been present when the cold trap started to form.

The presence of liquid water would also have helped solve the problem of the water-trapping sulfuric acid clouds. All common sulfur gases are soluble in water, so if an ocean was present, they would have eventually dissolved to form various sulfur-containing minerals. The sulfuric acid clouds that today hide the planet's surface could not have formed until the ocean had disappeared and sulfur was recycled into the atmosphere by volcanic activity. Carbon dioxide could have been regenerated similarly. Over billions of years, volcanic outgassing would have produced the present atmosphere.

A reasonable history of water on Venus, then, might go like this: Venus started off wet because it could not avoid receiving some of the same volatile-rich material that formed the Earth. Once the initial accretion period was over, the combination of a dimmer Sun and protecting clouds would have given Venus a relatively cool surface. If it had anything approaching the Earth's water inventory, much of it would have condensed to form oceans. Carbon dioxide would have been slowly converted to carbonate rocks, and the atmosphere would have thinned.

Water would have remained a major component of the atmosphere, its abundance gradually decreasing through photodissociation and hydrogen escape. Some of the oxygen may have been dragged off to space with the hydrogen; the rest was consumed in oxidizing carbon monoxide and in reacting with minerals in the planet's crust. Because the atmosphere was thinner then than it is today, most of Venus' original water would have escaped by rapid, hydrodynamic outflow. The rest was lost over billions of years by slower, nonthermal escape processes. The disappearance of water allowed the carbon dioxide and sulfur dioxide released by volcanos to accumulate, and the atmosphere gradually approached its present state. □

The Venus Question Is Still Up in the Air

by David Grinspoon

In planetary science, "proof" is often hard to come by since we are starved for data and the problems are so grand. Yet I believe that on the question of ancient oceans on Venus, flimsy or circumstantial evidence has been given more weight than is justified, and that, whether we like it or not, the question still rings truer than any answers we have found.

Restricted at present to our own solar system, we must be content with data from but a few distant laboratories, inventing theories after the fact for ancient experiments beyond our design. Could Gregor Mendel have discovered the laws of genetics if he had had only one pea plant to work with and one hour to observe it, rather than gardens and generations? The limitation of this small array of planets increases the temptation to regard Venus—with its strikingly similar size and closeness to Earth—as a dry, lifeless control for the terrestrial experiment. Thus a persistent approach to the study of Venus has been to assume that initial conditions were essentially identical to those on the primordial Earth and ask, in effect, "What went wrong?"

The realization that Venus' pearly brilliance in our morning and evening skies is due to a permanent planet-wide cloud cover supported scientists' expectations, widespread in the 19th and early 20th centuries, that the surface would be found to be a tropical swamp resembling the carboniferous Earth. However, the discovery in the late 1950s of an unusual source of microwave radiation coming from Venus, found to be the thermal glow of an extremely hot surface (not quite red-hot, but almost) eventually dispelled the notion of oceans on present-day Venus. The very small amount of water—measured above the clouds by Earth-based spectroscopy, and in the lower atmosphere by Soviet and American spacecraft—coupled with the finding that the clouds are composed of concentrated sulfuric acid, confirmed that "Earth's twin" is a hellish place.

When it was established that Venus has 100,000 times less water than Earth, some scientists tried to account for the "missing" water. Several groups of researchers have applied themselves to this problem, most recently James Kasting and his colleagues. They've built an internally consistent and credible scenario, supported by detailed modeling, of a once-Earthlike Venus that has lost its oceans due to a "runaway greenhouse" that boiled the oceans, sending much of the water to the upper atmosphere where sunlight tore hydrogen atoms from the water molecules.

In this scenario Venus and Earth are identical twins separated at birth, with only environment to blame for their vastly different fates. Venus grew up too close to the Sun and went dry. Earth was brought up farther out in the suburbs of the solar system where it's possible for a decent planet to maintain a stable ocean. But could nature as well as nurture play a role in the unfolding of these lives? Could Venus have been born dry? If so, then the two planets may have followed very different paths throughout their histories.

Sorted into Zones

According to the equilibrium condensation theory, first proposed by John Lewis in 1972, the temperature gradient of the solar nebula (the flattened disk of dust and gas out of which the planets formed) sorted the condensing materials by composition into zones.

The compositions of the planets that formed from these materials preserved this trend, varying systematically with distance from the Sun. Venus, orbiting farther in than the Earth, would have had much less initial water than our planet.

One crucial question is whether the process of planet building was orderly enough to maintain these chemical zones. After solid grains condensed and began to collide and grow into larger bodies, did these planetesimals stay in nearly circular orbits, like runners confined to specific lanes at a track? This would preserve the planets' chemical differences as they grew. Or did gravitational interactions lead to wild elliptical orbits, allowing planetesimals from inside and outside lanes to mingle, smearing out any initial compositional trends?

Proponents of a wet young Venus argue that there should have been enough mixing among the planetesimals to form the terrestrial planets and provide them with

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nearly identical amounts of volatile materials, including water. This argument has been supported by recent models by dynamicist George Wetherill, who suggests that elliptical orbits and extensive mixing dominated the growth of the terrestrial planets. Yet density differences among the terrestrial planets clearly show that they are not all made of the same stuff, so mixing was not complete.

No one would expect Venus to be born completely dry, but whether she was endowed with 1, 10, or 100 percent of a terrestrial ocean is a question related to the process by which the planets assembled themselves. Until we better understand planet formation, we should not assume that Venus was originally endowed with an Earth's worth of water.

Breaking Even

If, on the other hand, the Earth's oceans come from an early, massive comet bombardment, then Venus would have received a comparable amount of water regardless of how the planets accumulated. Thus, early oceans on Venus are not incompatible with an equilibrium condensation model of planet formation.

Recently, John Lewis and I have been studying the question of water on Venus without assuming that Venus was once wet. We've concluded that, contrary to prevailing opinion, Venus is probably not losing water, but breaking even in the long run. If you let the hydrogen contained in all the water now on Venus escape at its current rate (about 20 million hydrogen atoms per square centimeter every second), you would run out of water in a fairly short time—87 million to 870 million years depending on whose number you believe for water abundance. Even the high end of this range for water's lifetime is considerably shorter than Venus' age. This suggests to us that rather than simply being in decline, water on Venus is in a steady state, meaning that there is a continuous source of water to balance the sink of nonthermal escape.

What might this source be? One possibility is volcanic outgassing. The gas that hisses and burps from volcanos on Earth is mostly water vapor. Some researchers believe that volcanic activity is occurring on Venus today, but the amount of outgassing, if any, is totally unknown.

We also know that comets and water-rich asteroids occasionally hit Venus, adding water to the planet's atmosphere. When these objects strike Venus they should vaporize and add their water to the planet's inventory.

Using information from the number of craters on the moon, telescopic observations of comets, and orbital calculations, we can place reasonable bounds on the infalling water. Interestingly, the rate of water escape from Venus falls right in the middle of the infall range. We are not talking about the hypothetical massive early comet bombardment that may have contributed to the Earth's oceans. We are saying that a constant infall consistent with the observed number of comets in the solar system today can explain the water now on Venus.

What a bizarre life these hydrogen atoms lead! Sequestered in cold storage for billions of years in cometary ice, liberated in a violent impact on Venus with an energy of hundreds of millions of megatons, drifting for millions of years in Venus' torrid atmosphere in a variety of chemical combinations, diffusing into the upper atmosphere (perhaps doing some time in the sulfuric acid clouds on the way up), only to be flung back out into interplanetary space.

Large comet impacts should also produce dramatic fluctuations in water abundance, which could, in turn, cause strange climatic episodes and affect the surface and atmosphere. Comets strike the

If Venus was born dry, Botticelli's famous painting of her emergence from the sea may have been all wet. (Painting by Michael Carroll, Courtesy of The Planetary Society)

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Earth but don't noticeably affect the water abundance because our planet is so wet. (Who notices a drizzle when swimming?) They may, however, occasionally cause mass biological extinctions here, such as the disappearance of the dinosaurs 65 million years ago.

This steady-state model, in which a cometary source (perhaps with some outgassing thrown in) balances hydrogen escape to space, seems to do a good job of describing Venus today. But was it always like this? Is there a shred of hard evidence that oceans once existed? Some researchers would say that yes, there is a shred: the deuterium-to-hydrogen ratio.

Deuterium is heavy hydrogen. Ordinary hydrogen is the simplest atom conceivable: one proton and one electron. However, the Big Bang blessed some hydrogen atoms with an extra neutron, and these atoms are what we call deuterium. Since their electronic structures are identical, these two isotopes behave almost identically in chemical reactions, where electrons rule. But since deuterium is twice as heavy as hydrogen, any mass-dependent process, including the most important nonthermal escape process on Venus, discriminates between them.

In 1982, the American spacecraft, Pioneer Venus, measured the deuterium-to-hydrogen (D/H) ratio of Venus' atmosphere. The value was quite high, about 100 times higher than the deuterium-to-hydrogen ratio on Earth (160 deuterium atoms for every million hydrogen atoms.) At the time, this observation was seen as the "smoking gun" revealing direct evidence of Venus' wet past. The reasoning went as follows:

Hydrogen is half as heavy and is thus much easier to accelerate to escape velocity. So as the hydrogen from Venus' vanishing water supply has escaped over the eons, it has left behind a residue of deuterium, resulting in an ever-increasing D/H ratio. Since Venus probably started with the same ratio as Earth, its modern value of 100 times Earth's ratio implies an initial water abundance at least 100 times greater than the water left there today, perhaps much greater since some deuterium escapes along with the hydrogen.

No Definitive Conclusions

This interpretation of the D/H ratio has two flaws. First, it involves an assumption about the original D/H on Venus. There is a wide range of D/H values throughout the solar system, and the origin of the Earth's value is not well understood. So the assumption that the initial D/H on Venus was identical to the current terrestrial value, while a reasonable possibility, should not be used to draw definitive conclusions about the history of water on the planet.

The other problem is that it assumes that the water abundance has simply been declining over Venus' lifetime. It does not allow for the possibility of hydrogen sources. Yet the short lifetime of water against nonthermal escape strongly suggests, if it does not demand, a hydrogen source. How does this steady-state model affect the interpretation of the D/H ratio? If you bring in enough water and let a lot of hydrogen but very little deuterium escape, then over the ages the D/H will increase, with no change in the total hydrogen abundance.

New mathematical solutions allowing for hydrogen sources show that billions of years of steady-state evolution can lead to a hundredfold increase in the D/H ratio. Thus, the observed D/H ratio does not necessarily imply a past excess of water. Unfortunately, the time required to build up a respectable deuterium excess in this way depends on the average water abundance over time, which is poorly known for Venus.

Given these uncertainties, it is hard to tell whether or not the observed D/H really requires an early Venus with 100 times the water it now holds. But either way, 100 times almost nothing is still not very much: A body of water 100 times the present amount on Venus is equal to a layer only a few meters thick over the entire planet. Is this an ocean? Perhaps a small one. But there is really no evidence for the earlier massive hydrodynamic escape that is supposed to have removed most of the ocean.

The question of whether or not there were ancient oceans on Venus is intimately related to some "big picture" questions: How did the planets form? Where did Earth's water come from? Was the origin of life on Earth an inevitable consequence of cosmic evolution or freak accident? Were there unique conditions that led to this event?

In our lust for the answers, let's resist jumping on bandwagons that may or may not be heading in the right direction. Perhaps the Magellan radar mapper will reveal the telltale signs of ancient shorelines. Wouldn't that be wonderful? Or perhaps future chemical investigations will demonstrate the presence or absence of all the oxygen that would be left behind in the rocks by an escaping ocean. But for now, while we brandish our opinions and push our theories to the limit, let's also admit, without shame, all the gaping holes in our knowledge of solar system history that make this young science such a challenge and a joy to pursue.

Climatic Catastrophe: On the Horizon or Not?

by Andrew R. Solow and James M. Broadus

What's the appropriate response to the possibility of global climate change? The answer depends on many factors, including the timing, nature, and magnitude of the predicted change, as well as the benefits and costs of the response itself. Certainly, any response designed to cope with a rapid change of large magnitude could be a costly mistake if the world's climate changed much more slowly and modestly.

Our dilemma is compounded by our ignorance. For all the concern over an impending climate catastrophe, the fact remains that a great cloud of uncertainty hangs over all predictions about future climate, to say nothing of such related issues as the depletion of the ozone layer and acid rain.

Most of our information about the possibility of climate change comes from experiments with large-scale numerical climate models run on computers (article, pp. 16–21). And therein lies much of the problem. All too often the results of these experiments are treated as if they represent a picture of future climate as accurate as the forecast for tomorrow's weather. In our view, such interpretations are an example of gullibility, if not worse.

Are we being unnecessarily harsh? We don't think so. Remember these long-term forecasts depend on models that are themselves severely limited. They attempt to represent mathematically complex physical processes shaping the Earth's climate that are only incompletely understood. Among them: the solar cycle and the Earth's orbital movements; the circulation of the atmosphere along with its composition and radiative properties; the chemical, physical, and thermodynamical properties of the oceans; precipitation, streamflow, soil moisture content, evaporation, and cloudiness; the spatial distribution of ice, snow cover, and other factors influencing the reflective properties of the Earth; and the behavior of forests, plankton, and other biological populations.

Operating at varying scales of time and space, these processes are extremely complicated even functioning by themselves. When they act together, or are coupled, the complications multiply greatly. To say that we have only an imperfect understanding of their interactions, and the ways in which they influence and are influenced by climate, is probably an understatement. So, any climate models built on this limited knowledge must be considered far from perfect as well.

We are limited also by the inadequacies of the computers on which the models depend. Even the fastest and largest computers are still unequal to the "number-crunching" needed to couple the oceans and the atmosphere, and to represent important, intricate climate processes like the behavior of clouds and ocean eddies.

But let's grant for a moment the ability of a model to forecast climate accurately. One would surely expect that it could prove its skills by replicating past climate—in effect, by making a retroactive prediction. Since we're interested in what climate holds in store for us several decades hence, we might logically ask, how well does the model "forecast" climate for the last few decades?

The answer usually is: not very well. Most climate models put through such an exercise "predict" a global warming of at least one degree Celsius (1.8 degrees Fahrenheit) over the last century from the much-discussed "greenhouse effect." In fact, while there has apparently been some warming during this period, it has been no more than half a degree Celsius—and possibly much less. The difference may not seem very large, but it is an error of a factor of at least two.

As it happens, there is no clear evidence of a human-induced greenhouse warming. That means that the models err not only in predicting a past greenhouse warming that failed to occur, but also in *not* predicting past warming that *did* occur because of other causes. Yet even if the models had faithfully reproduced past climate, that wouldn't necessarily guarantee the accuracy of their forecasts for the future. This is particularly true if the climate model is "tuned,"

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directly or indirectly, by forcing it to reproduce known past climate.

That hasn't been the case, however. The models disagree substantially about future climate. They predict a global warming stemming from a doubling of the level of atmospheric carbon dioxide (the timing of which is also uncertain) ranging from one-and-a-half degrees to five degrees. Clearly, the consequences of a rise of one-and-a-half degrees would be much different than those of five degrees. The spread is even greater for forecasts of regional climate.

Climate models, to be sure, were never intended to be used to generate forecasts for many decades into the future. They were created as tools for learning more about climate processes. So in a strict sense, any scenarios generated by them are not really forecasts at all—and to treat them as such contradicts their original purpose.

Little Disagreement from Climatologists

As skeptical as these comments may sound, there is in fact little disagreement within the climatological community over their substance, only perhaps over their emphasis. Many climate modelers would choose to stress the success of climate models at reproducing certain aspects of recent climate and the extent to which model forecasts agree. But it isn't minimizing the successes of climate modelers, or their expertise and dedication, to point out that except perhaps in the crudest sense, we're still very far from that elusive goal: the creation of climate models capable of forecasting climate decades into the future with the kind of precision needed to guide policy formulation.

The availability of reasonably accurate temperature data for a large number of locations goes back a century or so. From these readings, series of mean global temperatures have been constructed. Generally, they show an intermittent warming of about half a degree from the beginning of the record in 1880 (Figure 1). During some periods, the warming has been relatively rapid. The 1980s were one such period; so were the 1890s and the 1920s. Other periods—the 1940s and 1950s, for example—have been marked by a cooling.

These data are not without problems, however. The readings are limited in their coverage of many areas, and over the years there were changes in how the measurements were made. Especially significant, many of the records contain a highly localized warming component, the so-called urban heat-island effect, which results from population growth and the buildup of heat-retaining structures like buildings and roadways. Apparently present in communities with a population as small as only a few thousand people, it may account for as much as a third of the apparent warming since 1880.

Perhaps the most careful regional study of long-term temperature data was that performed by Kirby Hanson, George Maul, and Thomas Karl for the United States. It showed that there has been no net warming in the lower 48 states over the last 100 years. Since the United States covers only a small fraction of the Earth's surface, we can't draw too general a conclusion from these results. Still, it's remarkable that in the only relatively large land area for which enough reliable data exists, there is no unequivocal evidence of long-term warming.

Despite the paucity of evidence, most climatologists believe that there has been some global warming since 1880. The question naturally arises as to whether this warming, if in fact it exists, is related to human activities and the greenhouse effect. For a number of reasons, the answer is probably no.

First, the warming began before the greenhouse effect could reasonably be expected to have begun. If it had started or intensified during the course of the data series, then there should have been a systematic acceleration of the warming rate. However, no such acceleration has been detected.

Second, as we pointed out earlier, the warming rate is less than half than that which

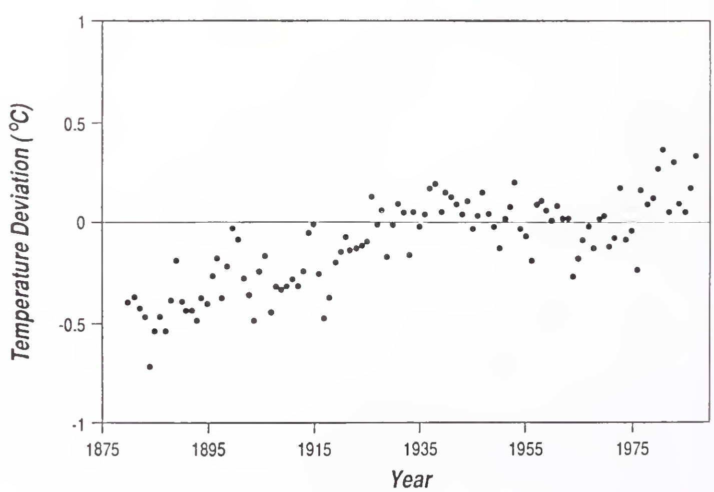

Figure 1. Long-term temperature records indicate an apparent global warming of about 0.5 degrees Celsius since 1880. This chart shows the annual deviation from the mean. (After J. Hansen and S. Lebedeff, 1988)

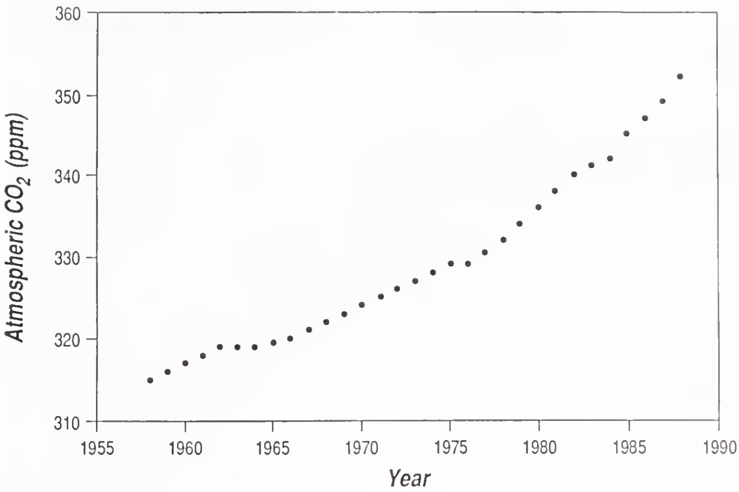

Figure 2. The level of atmospheric carbon dioxide has increased by almost 15 percent, presumably from the burning of fossil fuels but also possibly from the reduction of forests, since monitoring began in 1958.

might be expected, even in its early stages, from a human-induced greenhouse effect.

Third, the spatial distribution of the warming is also inconsistent with expectations. The United States, for example, would have experienced significant warming, yet the study by Hanson, Maul, and Karl shows none.

Fourth, there is an alternative explanation for the slow apparent warming over the past century. From about A.D. 1400 to the middle of the 19th century, the Earth experienced a cooling, clearly evident in many long-term climatological records, known as the Little Ice Age (*Oceanus*, Vol. 29, No. 4, pp. 38–39). The slow warming in the last century may simply represent a recovery from such a cooling.

Climate is constantly changing, and we know that this occurs without any human meddling. Even assuming that the apparent slow, irregular warming since 1880 is real, there is no evidence that any of it is due to the greenhouse effect. Indeed, the warming during the 1980s is not strikingly different from warming that occurred earlier in the record. So from an objective point of view, there's no compelling evidence of a greenhouse effect.

Policy Making as a Subjective Exercise

In face of such uncertainty, we must obviously exercise caution in making policy for climate change. Certain scientists, however, are convinced that the introduction of uncertainty changes the problem of policy making into a purely subjective exercise. As they see it, there is no need to justify their policy recommendations on any other basis than their personal feelings. Although there is an element of subjectivity in all policy making (just as there is also an element of uncertainty), a well-developed methodology exists for incorporating uncertainty in a rational and systematic way in the policy-making process. The object is to strike a balance among potential benefits, potential costs, and the probabilities of different outcomes.

As with experiments run on climate models, the information needed for a complete application of this methodology may be unavailable. Nevertheless, as with climate modeling, there is something to be gained by experimenting on paper with the policy process (for example, as a way to eliminate clearly inappropriate policies, or to identify the information needed to choose between various viable policies).

It is certainly possible, and probably desirable, to incorporate caution into the policy process. This isn't the same as assuming that the worst possible situation is sure to occur, even it if has a very small probability of occurring. Rather, it means keeping in mind that we face any number of potential global problems with possible consequences at least as great as those of climate change. In pondering these problems, we don't assume that the worst is sure to occur. We should act no differently in confronting the prospect of climate change.

How, then, should we act? Any large-scale policies aimed at a sharp and rapid reduction of carbon dioxide to the atmosphere are certain to be expensive. After all, the fossil-fuel burning that produces carbon dioxide is pursued, not out of any petulant urge to change the atmosphere, but to meet essential human needs. Given the current uncertainties about climate change, and the unquestioned rise in atmospheric carbon dioxide in recent years (Figure 2), it would surely be folly to expand these activities recklessly. On the other hand, some caution may be appropriate, especially if there are also other reasons for it, such as conservation of resources and the reduction of atmospheric emissions linked with acid rain.

Because the antidote to uncertainty is information, and because information takes time to gather, the proper course of action in some situations is to postpone an active policy response while more information is collected. This option becomes especially appealing under two circumstances: if information gathering is *more* likely to reduce uncertainty, and if postponing an active response is *less* likely to cause serious harm. In the case of climate change, we believe that the value of information is very great, and that postponing an active response even by several years is very unlikely to have a serious impact on the ultimate outcome of the debate over climate change. Of course, some of this research should focus on the design of policies that could be put into place fairly quickly should further information point to the likelihood of rapid, costly climate change.

An Instructive Example

One example of the value of new information seems instructive. In 1980, Stephen Schneider and Stephen Chen raised the possibility of a 7.6-meter (25-foot) rise in sea level over the next 150 years. They estimated a property loss of $1 trillion (in 1980 dollars) from this inundation. By 1989, however, Schneider was writing that a 7.6-meter rise in sea level over the next 150 years "now seems a low probability" and that most workers project an increase of one-half to one-and-a-half meters in the next 50 to 100 years. In this case, the passage of time (and further research) may have saved us from a potentially costly policy error.

There are legitimate reasons for concern over the possibility of significant and costly climate change. But if we're to respond effectively, we need to know more than simply that the possibility exists. At present, we are left with substantial uncertainties about the timing, nature, and magnitude of the prospective climate change. Our models provide only a crude representation of climate. They don't perform well reproducing the recent behavior of climate, nor do they agree in their forecasts of future climate. What's more, there is no compelling evidence in the data that indicates the onset of a greenhouse effect.

While some see a danger in expressing even legitimate doubts about the possibility of catastrophic climate change, there is also a danger in the way in which the recent discussion has evolved. By acting as if catastrophic climate change is lurking around the corner, and by associating in the public's mind certain short-term meteorological events like last summer's heat wave with long-term climate change, we run the risk of losing the public's attention and confidence should dramatic climate change not begin very soon or should there be other kinds of meteorological events, like a cool, rainy summer. □

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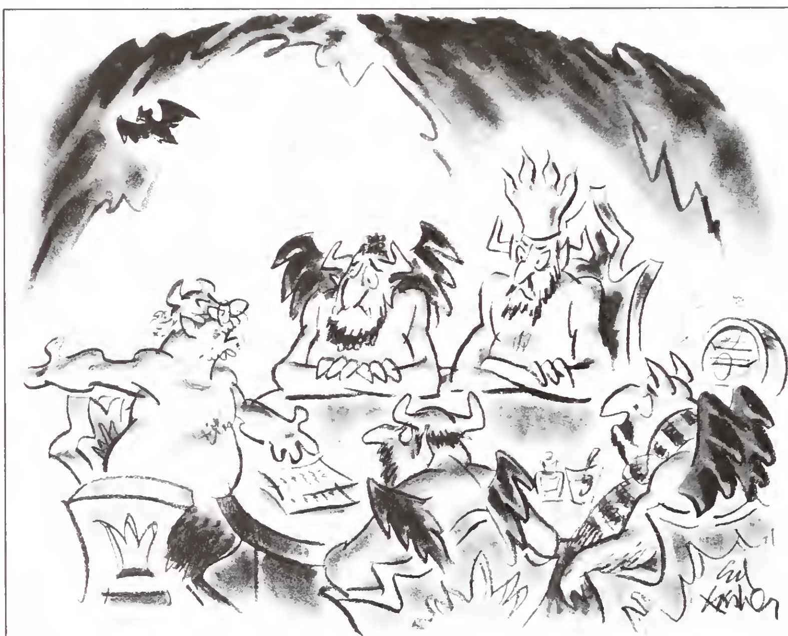

"We delayed and did nothing, in spite of one environmental warning after another—and now we're freezing over!"

The Greenhouse Effect as a Symptom of Our Collective Angst

by Jerome Namias

It wasn't too many years ago that everyone was worrying about another Ice Age. For meteorologists like myself, the inevitable, if slightly jesting, question from friends and acquaintances seemed to be: Should I sell out and move to a more southerly clime beyond the reach of the advancing deep freeze?

Now having satisfactorily allayed those fears, I find myself forced to answer questions about a new climatological threat. It's not another Ice Age but rather a phenomenon called the "greenhouse effect." As even kiddies seem to know these days, the effect is a result of the burning of fossil fuels and the increase of certain gases in the atmosphere, which serve to heat up the Earth and cause a general rise in sea levels from melting of the ice caps, as well as other climatic unpleasantness.

So the questions I'm now being asked are along these lines: Should I sell my shorefront property? Should I head inland?

Even Hurricane Gilbert, which battered the Mexican resort of Cancún (above) last September, was blamed on the greenhouse effect. (Reuters/Bettmann Newsphotos)

Doomsday Scenarios

These concerns of lay people aren't unreasonable. In less personal form, they are also the subject of scientific meetings and of journal articles, to say nothing of a blizzard of commentary in the media. The reasons for the anxiety are plain enough. As doomsday scenarios go, the greenhouse effect is more scientifically based than other more bizarre possibilities for climate change that I've encountered over the years, such as the impact of atomic testing, the influence of satellites, and reverberations from weapons of war. Moreover, it is backed by highly sophisticated numerical models requiring high-speed state-of-the-art computers. These scientific underpinnings lend a high degree of credibility to the warnings

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about global heating.

And so when last summer's devastating drought came to the Great Plains and elsewhere, it almost seemed a harbinger of worse things to come, and for many scientists who have been warning of the greenhouse effect for years, it served as a timely example to put before a believing public of what nature might do.

As a result, the greenhouse effect is now firmly part of our collective angst, along with nuclear winter, asteroid collisions, and other widely bruited global nightmares. During the long hot summer, almost every example of terrible weather—from the exceptional dry spell to Hurricane Gilbert—was laid at the door of the greenhouse effect. At the height of the drought, a poll taken by Cable News Network showed that 78 percent of the people interviewed believed that it was a sign that the greenhouse effect was already upon us—though no reputable scientist made such a claim outright. What many researchers said was that more droughts and more intense hurricanes might occur in the decades ahead—a subtly different but still disturbing claim than that we are already suffering the consequences of the greenhouse effect.

From a meteorological perspective—the only one for which one I can vouchsafe real expertise after more than 50 years in the field—what can we say for sure about such a scenario?

In the first place, we must be prepared to accept the idea that weather and climate records, like those in sports, are always being broken—everywhere, in any season, and for any single element, such as temperature and precipitation, or for a combination of elements, such as big storms or prolonged spells of abnormal weather. This is the way the ball bounces, climatologically: I would be more concerned if records stopped falling by the wayside.

It's true, of course, that global temperature averages have risen more than one degree Fahrenheit in the 1980s relative to decades about a century ago. But this rise shouldn't surprise anyone, expecially if we consider that the first part of the global temperature record is riddled with uncertainties and scarcity of observations for many areas of the world. What's more, part of the indicated warming may be due to urban heating—that is, the heat produced and retained by large metropolitan areas, filled as they are with concrete and other heat-retaining material.

The half-dozen numerical model simulations aren't unanimous in targeting the central United States for more frequent drought in coming decades, even though there is some tendency in this direction. If we assume that the increase in carbon dioxide will result in general Earth warming—a very reasonable conclusion backed up by all model results—there still remain questions of when and where the warming will occur.

Dust Bowl Memories

Some of us are old enough to remember the Dust Bowl of the 1930s, especially the devastating years 1934 and 1936, when an equally if not more severe drought than that of the 1980s devastated the American heartland, and when the rise in carbon dioxide surely was not the culprit. The same thing can be said for the droughts of 1952 to 1956 on the Southern Plains, and for those of 1962 to 1966 in New England.

Many of us have been warning for years that droughts like the great Dust Bowl of the 1930s are likely to happen again. But our concern is based not on the greenhouse threat but on the synergism between atmospheric wind and weather systems, the oceans, and the character of the land itself.

A Dust Bowl farmer in Cimarron County, Oklahoma, trying to clear drifting sands from a fence in April 1936. (Courtesy of the National Center for Atmospheric Research)

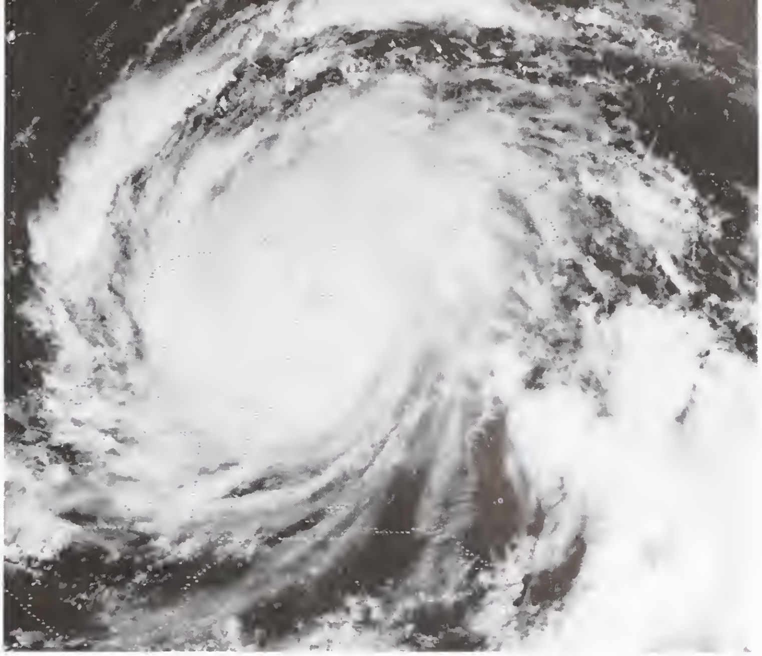
Starting with the fall of 1987, the Great Plains received little precipitation, and this deficiency continued into spring over most of the Plains states. Also, wind systems over the North Atlantic and the North Pacific, together with the associated sea surface temperature patterns, were developing so as to favor stronger than normal high pressure areas aloft, with the accompanying poleward displacement of the jet stream. Were these events merely coincidental, or could they be linked with the greenhouse effect? If so, how?

The wind systems over the North Pacific and the North Atlantic, along with associated sea surface temperature anomalies, encouraged the formation of another cell of high pressure over the Plains. Under this high pressure, which prevailed from spring to summer, the sun's increased radiative heating, augmented by cloudless skies, warmed the land directly rather than evaporating moisture from the soil.

In complex ways, this heating aggravated the drought. The increase in the upper-level pressure over the United States caused a corresponding sinking of air masses. This resulted in a compressional heating, as the air was forced to lower altitudes, and a reduction in relative humidity. The net result was a vicious circle of drought over vast areas, accompanied by the diversions of badly needed rain-bearing storms from the core of the drought area, and moist air masses from the Gulf of Mexico.

As for Hurricane Gilbert, it isn't possible to prove that it was partly influenced by some of this summer activity. The nucleus of Hurricane Gilbert came from a big cluster of thunderstorms that moved off Africa to help generate the tropical storm, which proceeded to move westward and intensify over warm surface water in southern portions of the North Atlantic.

Probably this path was determined by the strong Atlantic high-pressure area described above. It is now well established that hurricanes develop and are sustained over warm water, and if they don't encounter large land masses, they won't be destroyed by the complex frictional effects that reduce the winds and counteract the low pressure of the storm.



A satellite view of Hurricane Gilbert. The eye of the storm is directly over the Cancún area. (Courtesy of the National Oceanic and Atmospheric Administration)

Ideal Trajectory

Gilbert traversed an ideal trajectory over warm water, increasing the storm's intensity by providing it with more energy in the form of heat. Also, in the absence of any large land masses, there was nothing in the storm's path to sap its strength. Short-range forecasts out to a couple of days were good; the storm behaved as predicted, except for a failure to recurve northward in the western Gulf of Mexico. That was probably a computer failure due to improper consideration of the influence of a diverting high pressure area over the southern United States. Nothing in these two events, the great summer drought or Hurricane Gilbert, suggests that the greenhouse effect was operating. If global warming by carbon dioxide in coming decades becomes strong and regionalized to produce sustained oceanic warming in hurricane-prone areas, and targets maximum heating to the Great Plains, the events I described may be signals of what is to become the norm in future years.

Still, weaknesses exist in each link in the greenhouse theory chain:

- There is a lack of quantitative determination of the net impact of many other trace atmospheric gases besides carbon dioxide.
- Uncertainty exists that the global warming in the last century is real and not transitory.
- There are doubts that the indicated warming may be definitely ascribed to the greenhouse effect.
- Disagreements exist among numerical models as to the magnitude of warming or to regional aspects of meteorological elements.
- The all-important question of when it will take place remains unanswered.

All these uncertainties argue against a panicky initiation of fast counteractive measures. Why not wait for more certainty and adapt gradually when and if some firmer evidence appears showing that warming has really begun? Meanwhile, because of many other urgent environmental problems—pollution of the atmosphere and oceans, spread of acid rain and toxic wastes—we should proceed with all deliberate speed on conservation measures. □

Seeking the mechanism of global apocalypse: A nuclear test at Bikini in 1949. (UPI/Bettmann Newsphotos) essay

Tales of the Future

by Thomas Levenson

Galileo, holding that corrosively novel tool, the telescope; Galileo, facing his inquisitors, becomes one of the great symbols of the modern age, of modern thought. Galileo took his new tool and looked outward; in every part of the sky at which he aimed it he saw wonders, miracles to him and to his fellows. But Galileo's telescope could not remain fixed only on the night sky; it twisted in his hand, in the hands of his age, and pointed inward, toward an unscientific destination, his soul, toward the core of his time. The myth has it that when Galileo confessed his errors and assented to the orthodox claim that the Earth stood stationary while the sun revolved around it, he turned away from his inquisitors and mumbled, not quite under his breath, "But still it moves." Within that myth, this truth: the Earth moves.

The fact of motion and the knowledge of movement transformed Galileo's world, in time. What endures in legend as a symbol, though, is not the specific discoveries; they have become commonplaces, so unremarkable that today it is almost impossible to imagine how the world would appear through 16th-century eyes, or how to believe, as the Church instructed, that the Earth rested at the center of creation. What endures is that impossibility and the restless knowledge that every increment of discovery can change the world, remake what we see beyond us, and how we see ourselves within a world of constant change.

A story from the recent history of climate science captures the essence of how science performs this twin act, simultaneously transforming our relationship to the world and recasting it again within the context of the new perspective. It involves a feat of pure imagination, an apocalyptic vision played out on a world that does not exist; it is the story, thus, of the conscious effort to produce a myth that could command belief, and with belief, action.

The story begins with almost a stray thought, a question that nibbled at the edge of the questioner's mind until it became impossible to ignore. In 1981 and 1982 the Swedish journal *Ambio* sponsored a multidisciplinary study of the long-term consequences of nuclear war. The editors asked Paul Crutzen, a Dutch scientist working in Germany, to repeat and extend research documented in a 1975 National Academy of Sciences report that suggested a novel mechanism of global apocalypse—the idea that a major nuclear war could sufficiently disrupt the atmosphere of the Earth to threaten the survival of all life on the planet. In the scenario, fireballs from nuclear explosions would inject large quantities of nitrogen oxides into the stratosphere where those compounds could destroy ozone. Crutzen was asked to update the atmospheric chemistry in the earlier study and to produce a scientifically credible scenario of the effects on the stratosphere of a nuclear holocaust.

One of the central assumptions of the 1975 study was that a nuclear war would involve a large number of very big explosions, with both sides using warheads of one megaton or more. (A megaton explosion is equivalent to detonating one million tons of TNT.) However, by 1981, most of the warheads in both superpower arsenals had a much smaller yield—America's Minuteman missile, for example, carries three warheads each with a yield of about one-third of a megaton. When Crutzen and John Birks, a colleague from the University of Colorado, examined a nuclear war scenario that consumed larger numbers of smaller warheads, they found that much of the nitrogen oxides did not reach the stratosphere, which meant that the ozone layer appeared to be significantly less threatened than previously thought.

The last thing that Crutzen wished to do was to suggest that nuclear war might not be so bad after all. So the two scientists went back to look for other damaging atmospheric effects. They suggested, for example, that the smaller

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Every increment of discovery can change the world: The Byrd Glacier in Antarctica as seen from space. (Courtesy of NASA) warheads would produce a Los Angeles type photochemical smog wherever the bombs fell. Then, Crutzen was struck by a sudden realization: where there is fire, there is smoke; where there is smoke, there is a shadow; and in the shade, photochemistry ceases and plants die. Crutzen and Birks swiftly did a set of simple calculations on the assumption that a million square kilometers of woodlands would burn in the nuclear conflagrations, releasing 400 million tons of soot into the atmosphere. They concluded that the cloud of smoke could block 99 percent of the Sun's light from reaching the surface of the Earth for as long as several weeks.

If they were even close to right, then nuclear war had become vastly more horrible than the horror it already was; it threatened, with its prolonged darkness, the life of every plant on land and on the surface of the sea. It was not, this result suggested, just the combatant nations who were at risk—everybody was.

In itself, the idea of universal annihilation isn't new. In 1945, the fear was that a single nuclear weapon could ignite the entire atmosphere; in the 1950s, people believed that nuclear war might produce enough radioactive fallout to kill all life; in the 1970s, as the 1975 study suggested, the foreseen threat involved the ozone layer. Each of these apocalyptic visions was discredited in time, however. They all posed the prospect of some chain of destruction triggered directly by the initial explosions. But by the 1980s, it appeared as though the direct effects of the bomb—blast, heat, and prompt radioactivity—lethal as they may be, were essentially local and regional phenomena. Lots of bombs could kill lots of people; it has been estimated that a full-scale nuclear war involving a large portion of the global arsenal would kill a billion people outright, with another billion likely to die more slowly from the effects of radiation, disease, and starvation triggered by the social disruption attendant on such a war. Even in the worst case, however, it appeared as if it were impossible to destroy the entire human world.

Crutzen and Birks had proposed a plausible mechanism by which the bomb could cause greater damage through long-term, indirect effects than through the immediate consequences of the original blast. Their study also reaffirmed that the global climate machine was vulnerable to human action, whether leisurely changes like the "greenhouse effect," or a single, swift, catastrophic blow.

Within climate science, Crutzen and Birks's result crystallized a view that had slowly been forming from results in apparently unconnected lines of inquiry. There are enormous dust storms on Mars, and when one occurred at the time of the Mariner 9 mission in 1971, instruments on board the lander observed that beneath the shadow of the storm the planet cooled. At NASA's Ames Research Center, James Pollack and Brian Toon, along with Carl Sagan of Cornell, formed one of the groups that tried to calculate in simple models the effect of dust on planetary atmospheres and temperatures generally, including those of the earth. Then in 1979, Luis and Walter Alvarez came up with their theory that a collision with some extraterrestrial object produced debris that could have cooled the Earth long enough to cause the great extinction of 65 million years ago (*Oceanus*, Vol. 30, No. 3, pp. 40–48). Richard Turco, a researcher at a California defense think tank, joined with the NASA researchers to model that event.

So by early 1982, it was known that immense clouds of dust circulating in the stratosphere could, in theory at least, affect global temperatures. Turco used his own model to try to estimate how much smoke the fires from burning cities would produce in a variety of nuclear-war scenarios. Then he calculated the impact that this much dark, heat-absorbing material in the atmosphere would have on temperatures on Earth. In collaboration now with four other scientists—Toon, Pollack, and Sagan, joined by another NASA researcher, Thomas Ackerman—Turco found that for a reference simulation of the aftermath of a major nuclear war, mean annual temperatures across the Northern Hemisphere would drop by as much as 35 degrees Celsius (63 degrees Fahrenheit), and abnormally cold temperatures might persist for more than a year. Any survivors of a nuclear war could, according to this first attempt at simulation (known as the TTAPS model, after the initials of the five scientists), simply die more slowly, shivering in the dark.

This, at least, was the picture painted by Carl Sagan at a public conference on the phenomenon, now dubbed "nuclear winter." The meeting was held on Halloween in 1983, and the climate modelers were joined by biologists who had attempted to assess the threat to life on Earth posed by the climatic effects envisioned by the TTAPS model. The combination of cold and dark would be sufficient, particularly for a spring or summertime war, to disrupt the metabolism of virtually every plant; the sudden shock would cause significant dieback and possibly extinctions that would ripple through the food chain, thus threatening, perhaps every species of animal trapped beneath the pall. In the worst case, according to Paul Ehrlich, rapporteur for the biological study group, "We could not exclude the possibility of a full-scale nuclear war entraining the extinction of *Homo sapiens*."

There was, in the genesis of the idea of nuclear winter, a kind of epiphany in the field of climate science, a coming together of the disparate strands of research that have together altered the view we are able to take of how this planet works. Ideas do not burst forth whole, like Athena from Zeus's forehead; this one, at least, grew out of ground that had been well prepared. The dinosaur extinction problem is a study in holocaust, and the proposed solution—the catastrophic collision with an asteroid or a comet and the cascade of disaster

The global climate machine is vulnerable to human action: Brazilians of Mato Grosso region in front of a jungle patch they have cleared by burning to plant coffee. (Courtesy of the National Center for Atmospheric Research) that followed in its wake—gave rise to essentially the same concept that underlies nuclear winter.

Crutzen himself began to study smoke after George Woodwell had suggested that the burning of tropical rain forests was a major source of carbon dioxide in the atmosphere. To test the idea, Crutzen went down to Brazil in the late 1970s to collect smoke samples to actually measure the carbon dioxide content of the plume. In so doing, he found that Woodwell had probably overestimated the amount of carbon that deforestation would release. More important though, Crutzen began to gain a kind of "feel" for smoke, a sense of its importance. Martian dust storms; volcanic eruptions here on Earth (great eruptions, like Tambora in 1815 or El Chichon in 1983, which spew out enough dust to cool the Earth a little); El Ninõs, which provide direct experience of the dynamics of heat exchange between the atmosphere and the oceans; acid rain and the fallout from above-ground nuclear tests, which provide models of global transport of pollutants; the list goes on, but all of these events are relevant to the question of what will happen to global climate after a major nuclear war. Without all these lines of research—without the direct experience of climate change (like living through a major El Niño, for example) and the slowly gathered knowledge that has uncovered the links between place and place, system and system, ocean and atmosphere and plants and ultimately human beings—without such discoveries it would be impossible to imagine the mechanism that could disrupt the climate system on a global scale.

And so, in one sense, nuclear winter is nothing much new. It is simply, like other exercises in science, an extension of research that has gone before. It was taken as both authoritative and credible because it so clearly echoed research that the scientific community had already accepted. What on its face is an amazing claim—that the actions taken on a single day could transform climate globally (or at least hemispherically) for months or more—seems less outlandish when proposed in a context of dying dinosaurs and a world in which a change in atmospheric pressure over the southern Pacific can trigger record rainfall in Louisiana half a year later.

In another sense, of course, nuclear winter is absolutely revolutionary. It is incontrovertibly an exercise in scientifically generated fiction; the nuclear-winter world is a made-up world, a make-believe world. It exists entirely within a handful of computer models, and all the model experiments include some leaven of "what ifs." But the nuclear-winter simulation is qualitatively different from more conventional exercises, such as those involved in tests of the greenhouse effect. There is no analogy to a full-scale nuclear war; there is only the war. Simulations of it are necessarily explorations of the possible, first, not necessarily of the plausible. Every such simulation is based on arbitrary choices—the size and number of warheads, which targets are hit, how completely they burn, and so on and on and on. It follows that claims for given outcomes of these wars, beyond the the obvious one that the lives of enormous numbers of people will come to an end, are equally fictions.

What was predicted and announced on Halloween is only a possible future for our world. It hasn't happened, obviously and thankfully, nor is it happening now: this isn't an experiment-in-progress in the manner that research on the buildup of carbon dioxide serves as a kind of global experiment in atmospheric physics and chemistry. While it uses the methods of climate science, analogies to historical climatology, and repeated model experiments, nuclear-winter research differs from conventional research in that it is unverifiable, until and unless we blow ourselves up.

Hence the myth. Nuclear winter is a story told to frighten us into finding some way to keep us from finding out—ever—if the prediction is right or wrong. Visions of the ends of days are as old as human memory (come Gabriel and blow your horn), as is hubris, the pride that leads directly to a fall. Such fears animate the picture of nuclear winter, the destruction of the Earth triggered directly by human folly. And we believe—we believed in 1983 on Halloween—because those old familiar fears were recast within the context of a major research tradition, a rich vein of scientific discovery, all the novel findings of the science of climate that had emerged in the last decade.

To recognize the connection between ancient myth and modern science is not to criticize nuclear-winter research. Science ought to generate myths and cannot, in fact, ever keep from doing so. The existence of nuclear weapons begs interpretations, some effort to provide coherence and meaning. Nuclear winter is one of the results, an attempt to describe what the experience of a nuclear war would involve. Similarly, we speak of the greenhouse effect and illustrate it with a prediction of three months of 90-degree-Fahrenheit heat in Washington, instead of its usual 35 scorching days each year. We tell ourselves stories to understand, to persuade, to force action, to alter or adapt to one part of our material world or another.

One of the findings in the first study was of a threshold of safety, of about 100 megatons or so. If at least that much explosive power were detonated in an exchange, or even by just one side, then the smoke produced could still be enough to generate a cooling large and long enough to incur most of the disasters predicted for a much larger war. The only way out, Sagan suggested at the time and has argued since, is to reduce global nuclear armaments to a stockpile of some number of weapons of less than 100 megatons. As of this writing the United States and the Soviet Union possess jointly somewhere between 15,000 and 20,000 megatons' worth of warheads.

For obvious reasons, we could share Sagan's wish to see as many nuclear weapons eliminated as possible. But Sagan has fallen into a trap. The myths generated by science are touched with a special quality that distinguishes them from the tales of another day. The glory of the older myths was in their certainty: If Odysseus's fleet scattered, it was because Poseidon willed it, and the message was do not anger the god if you can help it. When the God of the Jews spared Nineveh after Jonah's mission of prophecy, the message was behave well and God will—not might—spare you. But in science, climate science, the models do not afford so easy an equation. In the four years since the Halloween conference, additional research into nuclear winter has robbed us of the initial simplicity of the conclusion, and with it the meaning of the myth that the science still engenders.

The most recent research has focused on areas where it is possible with the existing data and models to reduce at least some of the uncertainty inherent in forecasts about the world after the war. The TTAPS modelers used a one-dimensional simulation in which a certain amount of smoke was injected into the model atmosphere and spread evenly over a planet that was all land or all ocean. After an arbitrary portion of the smoke (based on their best guess) was washed away by rain, they then calculated the temperatures that would result.

In subsequent attempts, several climate-modeling groups used three-dimensional models in order to begin with a simulation that could reproduce many more of the features of real-world weather. They also began to modify other specialized models to generate the thunderstorms that would wash smoke out of the sky, and they tried, by making surveys of the burnable material available in cities, to gain a more accurate account than was available to the TTAPS team of how much smoke would actually be generated.

The results of these experiments, taken together, have led to a reduction in the claims for the severity of nuclear winter. In the most comprehensive recent study, Stephen Schneider and Starley Thompson used their variant of the National Center for Atmospheric Research (NCAR) model to refine the original TTAPS picture. Their version included a mechanism to rain smoke out, and it produced patchy clouds of smoke that spread irregularly with the winds and that dissipated more quickly than the TTAPS equivalent. The patches meant that some areas were densely shadowed, which produced a new climate problem that they called "quick freezes"—areas that chilled rapidly to below zero degrees Celsius beneath thick, local masses of smoke. They also found that their temperatures varied on large scales, with areas nearer the oceans cooling less than the middle of continents. For an average, the NCAR model indicated that, in a midsummer war, the temperature drop over the middle latitudes of the Northern Hemisphere would be about 12 degrees Celsius, which, when various adjustments have been applied to make the two model results more directly comparable, turns out to be about one-third as cold as the original findings suggested. Most important, while the larger the war the greater and more varied the meteorological consequences, the NCAR scientists could find no threshold, no magic number of megatons and fires, that would or would not trigger catastrophic climate effects.

The first thing to notice about this work is that while the Schneider-Thompson postnuclear world is not quite as horrible as the TTAPS world (they, half jokingly, call it "nuclear autumn"), the climate effects they predict still generate unprecedented harm. A drop of 12 degrees during the growing season could destroy much of a year's crop across the middle latitudes of the Northern Hemisphere; the quick freezes could kill plants, as well as any animals and people weakened for any other reason, even if the cloud thinned and the frozen areas warmed within a week or so. The long-term effects of a cloud that slowly thins out could include late spring and premature fall frosts, which would impose chronic stresses on agriculture that could hamper any efforts of survivors to recover from calamity. Yet, encouragingly (sort of), the two scientists also concluded that the chances that nuclear winter could cause the extinction of humankind are vanishingly unlikely.

No god out of the machine; nuclear winter does not deliver us from evil. We know now more than we knew five years ago. We know that a nuclear war will have long-term climate effects; we know that there are, almost certainly, long-term threats about which we remain absolutely ignorant. These may, should the worst occur, cause enormous damage in their own right. We are reminded once again that nuclear war is a terrible idea, one to be avoided at any cost—but that is all.

"I can call spirits from the vasty deep," says Glendower to Hotspur. "Why, so can I, or so can any man; but will they come when you do call for them?" responds Hotspur. Spirits still do not answer on demand. The story of nuclear winter, its rise and fall as a version of global apocalypse (and hence as global deliverance), captures the essence of the problems of scientific myths. Each increment of knowledge tells us more of our world, of the hazard in which we live. We know about the slow danger of the greenhouse effect; we know about the swift deaths that nuclear war may bring. But such knowledge only leaves us with a dampeningly mild admonition; "And now you know a little more, so act as best you can." The challenge we face is to reduce the danger of nuclear war, but this is a task for which science gives no prescription. Science can offer no certainty, no one answer, no compellingly obvious way out of a world in which nuclear war is a daily possibility. Sagan wishes it would, so does Schneider, so do

I, so would anyone, but it does not. We seek from science what we cannot get—a way out of our troubles, an easy solution, a gimmick.

What we are given instead is a kind of mirror, or a telescope that twists and points inward. The nuclear-winter story provides one of the triumphs of climate science, this young science. It is a triumph to have come up with the pan-subject, the world view, that enabled the scientists involved to pose the question that would illuminate the central issue of our day, of what we are actually capable of doing to ourselves and our world. It is equally a triumph to have begun to answer it, with the full armory of technology and models and historical analogy and planetary observations and all the details that cumulatively make up, not the science, but the grist for the scientist who can assemble the picture whole.

For nuclear winter, read acid rain, or the greenhouse effect, or global rainfall patterns, or the likelihood of excessive storminess this season or next. The success of the science has been to recognize the connections between place and place, time and time, people and all the natural world. But we do not gain along with that recognition any obvious methods of remaking connections lost or broken. Even with increased knowledge—especially with greater knowledge—the science leaves us at best with the realization that there is no simple device out there with which we can tinker to change the consequences of any particular human action. It is still up to us, not to any combination of machines and inventive systems of thought, to find ways to escape nuclear war, to find ways to accommodate ourselves to those changes in climate we cannot avoid. Nuclear winter is the extreme case—science has made it clear that nuclear war is even less desirable than it might have seemed a few years back—but it still establishes the paradigm: Science can alert us to an issue, but the issue itself remains for us to resolve.

So, in the end, what is the value of this change in science, this revolution in our picture of the world? Ultimately, what we get from science now (in another legacy of Galileo) is the chance to bring order—not an answer—out of the chaos of a world transformed at every turn. That order is the product of imagination, of the ability both to see into the detail (like Galileo recognizing that Venus had phases, like the moon) and to recognize the larger whole ("it moves"). We look to science with our mixture of fear (that we will all freeze, that we are not the center of the universe) and hunger (What can keep us warm? Where are we?) because it simultaneously unsettles us and provides the tales that organize our experience, make it intelligible.

Galileo said, or we believe him to have said, "But still it moves." We cannot imagine our world fixed in place, to this day. Within the computer, we ask what will happen on the sixth day and on the seventh after a war; we ask what will happen with another fifty years' worth of carbon dioxide rising into the sky; we ask where are the ties that bind us to an entire world. We cannot now imagine ourselves unscarred by the consequences of what we do. Our telescope has turned and focuses today on a world made whole. We live now within our world, not astride it. □

Science can alert us to an issue, but the issue itself remains for us to resolve: Mount St. Helens erupting in 1980. (Courtesy of U.S. Geological Survey)

voyages

A Summer at Sea with the Soviets

How an American scientist survived—indeed, thrived—aboard a Russian research ship.

by Ronald K. Sorem

As glasnost opens more doors, the number of American researchers taking part in Soviet scientific projects will certainly increase. Some marine scientists will surely be among them, for oceanography has long ranked high as a research science in the Soviet Union. What can American scientists expect if they go to sea for weeks or months on a Soviet ship? What is it like to work and live in close quarters with the Russians?

In 1986 I had the opportunity to get some answers to these questions when I spent nine weeks as a guest of the Soviet Academy of Sciences aboard the *R/V Akademik Aleksandr Vinogradov*, one of the USSR's newest oceanographic vessels, exploring deep seabed mineral deposits in the Pacific Ocean. For six of those weeks, I was the only foreigner among

Above, Soviet oceanographic ship R/V Akademik Aleksandr Vinogradov *during a 1986 cruise. (All photographs in this article courtesy of author)* more than a hundred Soviets.

Vinogradov, 140 meters long and displacing 4,842 gross tons, was built in Poland in 1983 and sails out of the far eastern Port of Nakhodka, at Vladivostok. The ship had completed seven previous cruises. The purpose of our mission, as stated by expedition head Mikhail Fedorovich Stashchuk in his proposal to the Academy of Sciences, was to understand "the regularities of contemporary authigenic mineral formation on the ocean floor." These are sedimentary deposits formed in the place where they are found. An important practical objective was to look for local chemical anomalies in the water column that might be related to useful mineral deposits on the seabed below.

Stashchuk, a professor at the Pacific Oceanological Institute of the Far Eastern Research Center in Vladivostok, began planning the cruise as an international project nearly a decade ago, long before the Gorbachev regime and the new policy of openness. In 1985, he sent formal invitations to Hokkaido University in Japan and to several American scientists and U.S. government agencies in hopes of enlisting as many as 20 foreign participants for his cruise. He was greatly disappointed when his overtures to the Americans were virtually ignored and when, at the last minute, the Japanese scientists who had agreed to take part in the expedition were prevented from joining the ship because it couldn't get a permit to dock in Japan. The embargo affected my plans as well: I had flown to Japan in mid-June and found no way to get on the ship.

No Docking in Honolulu

Once back in the United States, I received several radiograms from Stashchuk, urging me to meet the ship when it docked in Honolulu on 22 July. I arrived there on schedule, only to find that *Vinogradov* was still at sea. Coast Guard officials insisted that the United States *never* allows Soviet ships to make port in Honolulu, a fact well-known to Soviet diplomats. A permit for Hilo was approved instead.

I arrived at Hilo the day *Vinogradov* tied up and was given a hearty welcome. The ship took on 750 tons of water and several tons of food. The Russians enjoyed a two-day shopping spree in the city, and were very cordially received. At noon, 25 July, we cast off.

As we pulled away, Russians in new Levis and Hawaiian shirts crowded the upper weatherdecks, taking photos of each other and the landscape. We looked more like a cruise liner than a serious research vessel!

I heard a few words of English and tried some of the polite Russian phrases I had picked up during two short trips to the Soviet Union in 1982 and 1984. But I soon realized that I would need the help of the interpreter, Lena Koltunova. I was glad to learn that Lena, a congenial young mother from Vladivostok whose husband was an engineer on another Soviet ship, would be sitting regularly across from me at the "geology" table in the dining room with five or six Soviet geologists and geochemists.

Lena explained the daily shipboard routine to me: breakfast at 0730 hours, dinner at 1130, tea at 1530, and supper at 1930. To work off the calories, there were such sports as jogging, volleyball, and weight lifting. Other popular activities included sunbathing, dominoes, chess, and the nightly Russian movie at 2040.

The day began with a call over the cabin squawk box, "*Dobriya otra, tovarischi*..." (Good morning, comrades). This was followed by "Goot mornink. Seven o'clock. Time to get up." The English was obviously for me and, I learned later, was read from a written script. I asked Lena if I was a *tovarisch*—I had read that "comrade" is used only for party members. "Of course, you are included," she said. "You are our comrade!"

The author (in cap) on deck with some of his hosts, including expedition head M. Stashchuk (third from left).

Sampling the Polygons

The plan of expedition was to sample the seabed sediments and the water column in five areas, or *polygons*, as the groups of stations occupied in each area are called by the Russians. Most analyses of the samples were to be run at sea. Water chemistry is Stashchuk's specialty and excellent facilities were available for it. There were several wet chemistry labs on board, as well as labs for gas chromatography and atomic absorption analysis, all fully manned.

Many of the scientists and technicians came from Stashchuk's institute in Vladivostok,

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Ronald K. Sorem, a consulting geologist in Pullman, Washington, was for many years a professor of geology at Washington State University, specializing in the study of manganese deposits. His large, well-documented collection of Pacific nodules was recently acquired by the Museum of Natural History of the Smithsonian Institution in Washington, DC.

but there were also others from Moscow, Leningrad, Magadan and Novosibirsk in Siberia, and Lvov in the Ukraine.

Water samples were collected at various depths with Niskin-type bottles of several sizes. Benthic (seabed) samples were obtained by a pipe dredge and a clamshell-type grab sampler. A prototype box corer and an impact sampler for hard rock were tested, but neither saw much use. Sediment was sampled to a depth of several meters with a gravity corer, a heavy steel tube that is sunk into the bottom by its own weight and then raised to the deck of the ship. The orientation of all gravity cores was marked to permit determination of the age of the sediment by paleomagnetic dating techniques (using the ancient, or remanent, magnetism of a sample to tell when it was formed).

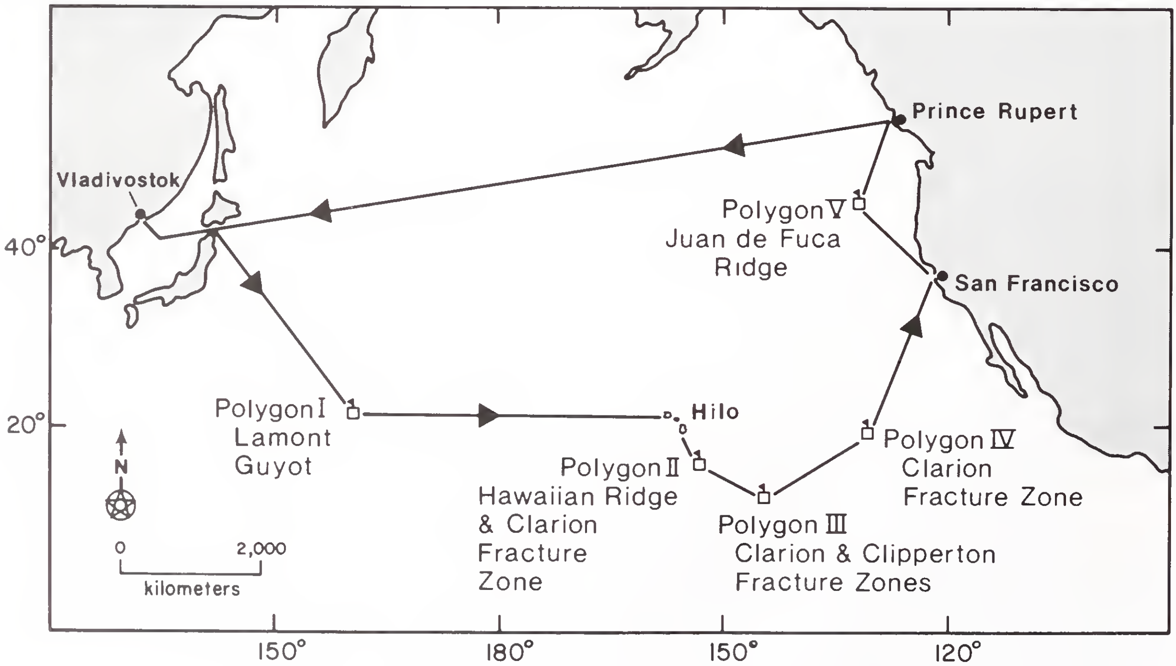
Some other technical details of the shipboard work, all of which were conducted at a high level: The mineral and microfossil content and textures of the sediment samples were determined by microscope study of smear slides and thin sections. Thin sections of rock samples were studied by polarizing microscope, and polished sections of manganese nodules by ore microscope. Some rock samples containing opaque materials were also polished for study. Mineral identification by microscope was supplemented by x-ray diffraction, and chemical composition of samples was determined by computerized x-ray fluorescence equipment and neutron activation analysis. Facilities for the latter are rarely found on oceanographic vessels.

I had missed the survey of Polygon I, located at Lamont Guyot, a complex volcanic structure in the western Pacific south of Marcus Island, but I was given two detailed maps and a free choice of manganese-oxide crust samples from the area for later study. Many samples had cracked badly upon drying out on board, and I suggested that a method perfected in our laboratory—impregnating the samples with gelatin—be used on fresh samples to prevent dessication. The method was enthusiastically adopted. I supplied some U.S. reagent-grade gelatin, and when that ran out, we raided the entire supply of cooking gelatin for our samples.

From Hilo, we headed south to Polygon II, at about 14 degrees North latitude, 153 degrees West longitude, where the crustal structures known as the Hawaiian Ridge and the Clarion Fracture Zone intersect. It was here, in the 1970s, that scientists on *R/V Valdivia*, owned by an international industry consortium, reported a deep-water positive temperature anomaly. They measured temperatures of 8.9 degrees and 28 degrees Celsius within 20 meters of the seabed at two closely spaced stations on two different cruises. Generally, bottom-water temperatures in this region of the Pacific range from 1 degree to 4 degrees Celsius.

We soon ran into heavy weather on the edge of a tropical storm. For six days, all loose equipment had to be tied down, and roll boards were needed on the bunks. We heard an

THE 1986 EXPEDITION OF *R/V AKADEMIK ALEKSANDR VINOGRADOV*



occasional loud crash as things broke loose in labs and in the pantry. The crew tried the old trick of soaking the tablecloths in the dining room, but still some dishes slid onto the carpet. Many people lost sleep because of the rough seas. Nonetheless, the survey and sampling programs were completed successfully. No anomaly in water temperature was found.

We set our course for Polygon III to explore the rich manganese nodule deposits in the vicinity of the Clarion and Clipperton Fracture Zones, immense structures in the bedrock that stretch for thousands of miles east of Hawaii.

Time Out for Tropical Juice

I had set up shop in the lab equipped for research in economic geology, a field devoted to the study of mineral resources. Several stereo microscopes were available, and I was given a good ore 'scope lent for the cruise by the famous nodule worker N. S. Skornyakova. I shared the lab with two friendly phosphorite geologists and a mountain of unused gear left over from previous cruises. The first few days were uneventful, but one day I found myself in a crowd of shipmates rushing down the ladders to the ship's hold. Had the rough seas caused a leak? No, it was "Tropical Juice Day!" I was told. According to custom, while the ship was in the tropics, everyone lined up at the ship's cooler once a week to get a ration of Bulgarian fruit juice. Some of the containers were two-liter wide-mouthed jugs, and I wondered out loud where we would keep them once the cover was pried off. Lev Gramm-Osipov, deputy head of the expedition and my guide, told me that many of the senior staff's cabins had refrigerators, as did some labs. My cabin did not.

He offered to let me store my juice ration in the refrigerator in his cabin, which was right next to mine. Later he told me that Stashchuk was embarrassed to learn that my cabin had neither a refrigerator nor a bath, and suggested that I bathe in a vacant hospital room with a tub and toilet. I agreed and promised not to lose the key, which Lev said was the only one they had. Finally, he asked if I had a short name and I told him that people call me Ron. Soon I was on a first-name basis with all the scientists.

It also turned out that my hosts were concerned about my laundry, and Lev suggested that one of the cleaning women take care of it for me. I understood that the only payment expected was a small gift before I left the ship. Later it was my turn to be embarrassed when I learned that everyone on the ship, from the head of the expedition on down, does his own laundry, often by hand.

Wet laundry and clothes soaked by rain were dried in the upper part of the engine room, where clothes lines had been rigged and where

A metal dredge bag with bottom samples is unloaded on deck as scientists eagerly wait for their specimens.

Shipboard recreational activities include (from top) musical evenings, volley ball, and parties for foreign visitors (with interpreter Lena at far right front).

there was always a strong, warm updraft. As luck would have it, my newly assigned bath facilities were only a few doors away from the engine room, and the upper level also was an excellent place to dry my hair.

During the surveys of Polygons III and IV, I was on deck for most of the sampling. When the ship was under way, I worked on manganese nodules in my lab or someone else's. I often took a break by chatting with the crew in the pilot house and checking charts and the navigation computer screens in the plotting room next door. Each day at 1130 hours the ship's bell and horn sounded and the current position was announced over the public address system. Also announced were such notable events as the sighting of dolphins, sharks, turtles, and whales—or the results of a chess tourney in Moscow.

Seminars were held in the dining room about once a week to discuss recent research results or new plans. My contribution was to instruct a small group in some of my micro-mineralogy techniques, a task I found worthwhile and even entertaining. I was also given a more urgent assignment. We had been at sea two days when I was asked to write radio messages in English to encourage more American scientists to enlist. I was told they could board ship in San Francisco when we made port there in about six weeks. I sent messages to a number of colleagues but received only one favorable response. Bill Siapno, a pioneer ocean miner, agreed to meet us in San Francisco. His vita was radioed to the Soviet Union and, to Stashchuk's delight, his candidacy was approved.

I was also asked to check whether we had been granted a port permit for either Portland, Oregon, or Vancouver, British Columbia. The ship wanted to make a short stop in the Pacific Northwest after working Juan de Fuca Ridge, Polygon V, before heading back to Vladivostok. But Stashchuk had not yet received confirmation of these port calls from Moscow, and was getting anxious.

Dreaming of San Francisco

To help out, I sent an inquiry to the State Department, which evidently led to direct contact between Washington and Moscow on the stopovers. On 30 July, Stashchuk received word from back home that *Vinogradov* would be allowed to dock in San Francisco on 2 September—but for only one day, not the five or six days everyone on board expected. Moreover, we learned that no permits had been given for Portland or Vancouver. Everyone spent the next month hoping that our stay in San Francisco would be extended. "It is our dream," said a lab partner.

Weeks later, I found out that the water chemists had a special reason to dream of San Francisco. They had run short of several key reagents and asked if I knew of a source in San Francisco from which they could purchase new supplies. I sent an appeal to the U.S. Geological Survey (USGS) at Menlo Park. There was no reply. But on our arrival at the Army Street Terminal, I telephoned from the dock and learned that the survey would rush most of the needed reagents to the ship.

Most of the ship's company, dressed in their best, headed straight for town on the

The author, holding a gift bottle (above left), prepares to take a launch (above) for a visit at sea to another Soviet oceanographic vessel R/V Akademik Msistlav Keldysh *(left).*

nearest bus. They rode the cable cars, shopped, and visited the parks. There was no sign of Siapno. To our surprise, the Russians' wish for a longer stay was granted—on whose authority I never learned. We could remain until 4 September. That let the Russians give a nice party and tour of the ship for the small contingent from the USGS. It also meant a reporter from the *San Francisco Chronicle*, Charles Petit, could visit the ship twice, and my son Keith could fly up from Los Angeles and spend a night on board in a guest cabin. Keith, a hotel food executive, pronounced the cuisine excellent. The meals he had were just our everyday fare.

On 4 September, at 1400 hours, we cast off, as required. The Russians were very happy with their visit but said it was still too short. As we approached Alcatraz Island, we received a message that Siapno was following us in a small boat. The master ordered a 180-degree turn at controlled harbor speed, a rare maneuver for a large ship, and we got our new recruit aboard.

We steamed northward about 300 miles off the coast. At my request, the chief engineer gave me a thorough tour of the engine room. Early on 7 September, we began our survey of Polygon V. After mapping the southern part of Juan de Fuca Ridge by echo-sounder, we carried out an intensive program of hydrochemical and benthic sampling, on and off the ridge. The positive manganese anomaly in the water over the areas of thermal vents was verified, and tons of glassy basalt, speckled with zinc sulfide minerals, were dredged. Sediment coring off the ridge was very successful. On 15 September, we took a break for "Group Photo Day" and to prepare for a rendezvous with another Soviet vessel, *R/V Akademik Msistlav Keldysh*, the flagship of the fleet of the P.O. Shirshov Institute of Oceanology in Moscow.

A core of sediment from the sea floor is quickly cut up for paleomagnetic study (right), then given a preliminary look with a hand lens.

The next day, we visited *Keldysh* by launch. It is said to be the most highly automated Soviet oceanographic ship in service, with computerized steering as well as satellite navigation. We had a lavish lunch (caviar, cheese and fruit, sausage, Georgian mineral water) and a tour of the ship, which has a computerized seismic survey lab and a multichannel laser spectrograph, then in use for a "gold in seawater" project. (The availability of this sensitive new instrumentation has apparently rekindled among the Russians the old hope of extracting economic quantities of gold from the seas.) But the ship lacked the neutron activation analysis capability found on *Vinogradov*. Two Canadian-built Pisces IV manned submersibles and two unmanned deep-tow vehicles were in use to make a detailed survey on Juan de Fuca Ridge. We had a chance to examine live tube worms and sulfide mineral samples collected the day before and were given a set of excellent color photographs taken in the vent area. The head of the expedition, Aleksandr P. Lisitzin, said he would like to see an international research preserve established on the ridge, where he had already deployed an array of acoustic transponders and "luminescent lamps" for bottom navigation.

A Better Opinion of Americans

While on Polygon V, we received word that Canada had granted a port permit for Prince Rupert, British Columbia. We headed there 20 September and were welcomed off the Queen Charlotte Islands by a large and active pod of whales. En route, I was busy packing my samples and gear but gladly took time out to attend an extravagant farewell party given for me in Stashchuk's comfortable lounge, where we were served the only whole roast of beef seen on the entire cruise, along with many Russian delicacies. All the chief scientists were there, and the affair was festive, but also sad, for by now we were all good friends. One of the geochemists said, "Since you have been aboard, I have a much better opinion of Americans."

I left the ship at Prince Rupert on 22 September with four cartons of samples and a large collection of maps, notes, photographs, and farewell gifts, and a very positive feeling. I have kept in contact with Stashchuk and Gramm-Osipov since then. Both hope to get Soviet support for a professional visit to my lab at Washington State University by 1990. It will be a pleasure to repay their hospitality at sea (said to be typical of Vladivostok, the Russian Far East) with some of the American Far West.

When American scientists ask what it is like to work on a Soviet ship, my answer is this: If you like the sea and have enjoyed your work on other ships, you will almost surely be equally pleased sailing with the Soviets. I found day-to-day life on *Vinogradov* much like that on the American research vessels and industry-owned ships I have worked on, except that the cabins and the dining room were more comfortable. Most of the scientific equipment was modern and worked as well as similar units on other ships. There was plenty of time and space for

Positioning a hardrock sampler for retrieving pieces of cobalt- and manganese-rich crust.

recreation, and friendly efforts were made to be sure that a visitor did not feel left out. And they did not have to give me first prize in the photo contest!

Specific recommendations: Bring a small portable radio, a camera and plenty of film, a calendar with some beautiful American scenes, and a Russian phrase book. Yes, you will have a language problem, but your attempts to learn some Russian greetings and other words will be much appreciated. And many shipmates will be eager to hear you speak English, American style.

By all means, avoid misunderstandings, which can happen anywhere. Before you accept the invitation to join a Soviet expedition, be sure that you and your hosts agree on what your research goals and opportunities will be, what kind of equipment and supplies are available. And put it all in writing. No one will be offended, and major surprises will be kept to a minimum.

A final note: If you enjoy fishing off the fantail when the ship is on station, be sure to bring your backpacking rod and some tackle. You will be surprised to see how many Russians share your enthusiasm as they use their "spinnik" to get the squid jig out there where the big ones are. □

Acknowledgment

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expeditions

In the Wake of a Modern Jason

Robert Ballard (left background) looks over his notes prior to a live broadcast from the Jason Project control van aboard the Star Hercules. *(Photo by Joseph H. Batley © 1989, National Geographic Society)*

by Diane Herbst

When Hagen Schempf began his graduate studies in mechanical engineering at the Woods Hole Oceanographic Institution (WHOI), he never thought that his years of work would be lost, albeit temporarily, on the bottom of the Mediterranean Sea.

But that's exactly what happened when a cable snapped during a test of the 2,400-pound robot Jason and its 8,000-pound garage Argo, the stars of the Jason Project, the brainchild of WHOI senior scientist Robert D. Ballard—who hopes to turn on school children to science by using live television broadcasts from the sea floor.

"When we lost the system my heart sunk into my pants. I saw all chances of graduating before the age of 40 slip away," said the 28-year-old Schempf, who expects to finish his studies within a year.

"We all were pretty shocked to see the hard work we'd put in just disappear," said project engineer Andrew Bowen.

But the Jason team aboard the mother ship *Star Hercules* pulled together like the mythical Jason and his Argonauts, and within three days—despite high swells and winds—retrieved the virtually undamaged system from 2,100 feet of water on their first attempt. "It was an incredible feat," said project coordinator David Gallo.

Actually, the Argo/Jason recovery two days before the first broadcast was only one of many incredible feats in a two-week, $8 million scientific extravaganza. The Jason Project successfully used, for the first time, the virtually untested undersea technology of Argo/Jason with its 13,000-foot fiber-optic cable. It utilized a complex telecommunications network involving two satellites to bring the discovery of hydrothermal

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Jason is gingerly hoisted to the deck after recovery from 2,100 feet deep in the Mediterranean. (Photo by Joseph H. Batley ©1989, National Geographic Society)

vents and artifacts from a 4th-century Roman shipwreck to about 250,000 students at 13 sites around the United States and Canada during the first two weeks of May. And the project opened a new era of oceanographic exploration by enabling researchers to observe as never before the activity beneath the sea while sitting comfortably on land.

Hoping for Lasting Influence

Has Ballard succeeded in his aim to interest more students in science by showing them, as he repeatedly said "that science is a contact sport," that the field requires "teamwork, physical fitness, and leadership," and is not a world for "nerds or dweebs"? And can interest generated by the 84 live broadcasts and subsequent Jason quests translate into a commitment to science?

Local students and educators gave the project an almost unanimous thumbs-up as Jason Project personnel awaited more feedback from students nationwide. "I'm waiting with my wet finger in the air," said Fred Douglass, a Falmouth High School teacher and curriculum coordinator/ educational liason for the the project.

In WHOI's Redfield Auditorium, students from the Cape and Islands filled the 200-seat room for six live shows each weekday, with other viewers watching the live weekend and taped evening shows. Surrounded by three, 10-foot-high screens, the audience was led by the entertaining and indefatigable Ballard, the show's human star. Ballard, who also hosted six shows each weekend day, introduced viewers to "telepresence," as he led them through Jason's navigations and sea-floor discoveries.

After watching Jason and its manipulator arm pick up a centuries-old amphora—a double-handled jug used as a shipping container during Classical times, the name literally means "carry-all"—Falmouth Academy seventh grader Bethany Ziss exclaimed, "This is fantastic, it's just amazing what they can do!" Tenth-grader John Mayo said he was impressed with the technology involved and that the Jason team actually found the artifacts in the 2,100-foot deep waters. "This definitely makes me more interested in science," he said. A two-way audio hook-up at Redfield and the 12 museum sites allowed students to query Ballard or other team scientists. "I was nervous," said Falmouth High School freshman Bryan Loughead after he asked Ballard about the evolution of vent life.

Science teacher Nancy Twichell of Falmouth Academy said the response has been very positive. "I think it's been a very beneficial experience for students. It really allowed them to see oceanography in action. We'd like to see this every year," she said.

Twichell and colleague Allison Ament had a special treat when they accompanied two students for a day in the "black room"—the telecommunications center at WHOI's Deep Submergence Laboratory. There they viewed the action on 24 television sets, listened to personnel speak with scientists aboard the mother ship, and gained a sense of the endeavor's continuity as they watched one amphora after another rise to the surface via an elevator.

"You could just see the excitement grow on the boys hour after hour," Ament said. "None of us even wanted to leave for lunch."

Many elementary school children would have liked more time to watch Jason, and observe life on the sea floor, according to Falmouth's Mullen-Hall School principal Michael Ward.

The earlier segments of the event, which the Mullen-Hall students attended, focused more on Ballard and the crew, and gave a

A Falmouth, Mass. schoolboy considers the path of Jason Project telecasts from the Mediterranean to WHOI's auditorium. (Photo by Tom Kleindinst)

technological background way beyond the scope and interest of the children, Ward said.

"The scientists have to be more attuned to what a nine-year old is thinking. While a high school student might be interested in what the crew is doing, these kids wanted to see more of Jason and more shots of fish."

A Robot Becomes a Friend

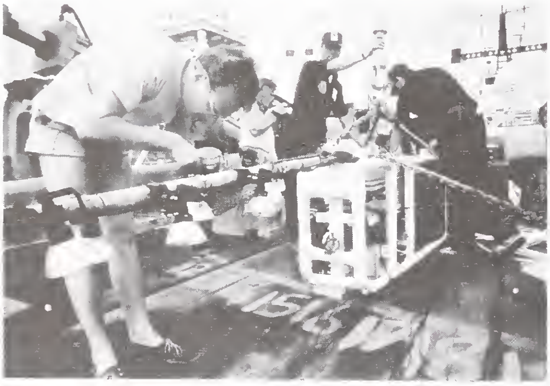
In fact, Jason became more like a friend than a robot, as a curriculum—prepared by the National Science Teachers Association—was taught in schools participating in the project during the weeks prior to the broadcasts. Ward said that when Jason was lost, "the whole fourth grade was depressed. They anthropomorphized the robot—he became a living, breathing thing. Their expectations were so high and they weren't prepared for the tedium of science."

Douglass, who wrote the curriculum section on ancient shipbuilding and trade for high school students, said this kind of feedback is important for planning future Jason curricula. The Jason team will soon be turning their sights northward as they plan their next journey, to the Great Lakes in search of wrecks from the French and Indian War, the American Revolution, and the War of 1812.

How long-lasting and far-reaching will be the enthusiasm of the kids who enjoyed the shows remains to be seen, said Jake Pierson, Assistant Dean of WHOI's Education Department. "I think the concept is great, and all the feedback I've gotten is very positive," he said. "But it's one thing to watch a show, it's another to translate that enthusiasm into making the committment to study a field."

Pierson said that in recent years, there has been a steady decline in the number of American applicants to the graduate program. "It's worrisome," he said. Although the quality of applicants accepted remains the same, the depth of the applicant pool is shallow, with chemistry, geology and geophysics experiencing the greatest decline. "But we're not going to compromise our standards," he said.

Andrew Bowen and an accessory, called "Knuckles," to Jason's mechanical arm. It was used to cradle amphoras on their trip to the surface. (Photo by Joseph H. Batley ©1989, National Geographic Society)



Hagen Schempf secures a light to Argo's understudy, the robot Medea. (Photo by Joseph H. Batley ©1989, National Geographic Society)

"We applaud the project. It's exciting and it'll take a long time to know the results. But it's sure been worth the try," he said.

The Argo/Jason technology, developed by the Deep Submergence Laboratory, enabled the team to find the first known—and quite active—vents in the Mediterranean, at the Marsili Seamount, and to recover scores of amphoras from a 4th-century Roman shipwreck. And the use of telepresence, with its clear, crisp images, may have opened a new window on the world of the ocean bottom, enabling researchers to observe as never before activity beneath the sea.

On 5 May, biologist Cindy Van Dover (*Oceanus* Vol. 31, No. 4, pp. 47–52) and geochemist Geoffrey Thompson, both of WHOI, sat in the black room helping Ballard to direct Jason's path in the active vent field among gold and green chimneys with shimmering hot water spewing from them. A computer alongside Van Dover displayed temperature, depth, and conductivity data from Jason's probe.

"The imagery is as good as being in a submersible, and I'm getting some better views than I would from *Alvin*'s port. I think it's fantastic to get this kind of live action and visual coverage," said Thompson, noting that the system allows scientists a more extended observation time than is available with research submersibles. The Argo/Jason technology is "the wave of the future for bottom sampling and observation," he said. "And this is just a prototype, it's going to be much better."

Project coordinator Gallo said that while telepresence certainly will not replace *DSV Alvin*, (*Oceanus* Vol. 31, No. 4), it is less costly and allows scientists from different fields to gather together at one site, view the bottom for days at a time, and discuss the finds immediately. "You rarely have a mix of disciplines on board a ship," he said.

Telepresence images greatly improve the level of visible detail, said Van Dover, who was able to identify bryozoans—microscopic animals whose colonies form fern-like mats. Thompson said that identification of the chimney composition, which either is of sulfides or iron oxides, will be confirmed after analysis of samples.

A young Red Sox fan queries Ballard via satellite on Mediterranean geology. (Photo by Tom Kleindinst)

A coral polyp retrieved by the manipulator arm was delivered to WHOI biologist Fred Grassle by institution director Craig E. Dorman, who spent several days with the Jason team aboard the *Star Hercules*. The coral, a Dendrophyllid, is not particularly a vent organism, said Grassle, who suggested an analysis of seawater to learn more about the vent fauna.

The site of the shipwreck contains a debris field with more than 100 amphoras, representing a period of about 500 years, with some dating to A.D. 3 or 4. One amphora might date back to 300 B.C., said Sonya Hagopian, project media coordinator. "That is a real find," she said. For a week after the television cameras stopped rolling, the Jason team continued to pluck amphoras from the sea, preserving them in seawater on board the mother ship. After their arrival in Woods Hole, scientists will begin the slow process of freshwater preservation, said Hagopian.

'Contact Sport' a Team Effort

The unexpected loss of Argo/Jason, and its swift recovery, was just the beginning of two weeks of other exciting experiences for the crew, particularly the satisfaction of seeing the new technology work. Schempf integrated the manipulator arm into the Jason system, spending months on the project—which up until broadcast time was still having a few difficulties. He recalls: "When the arm worked, it was very exciting. There was a lot of screaming and yelling. And it was the most exciting thing to see Jason pick up the amphoras. Just picture perfect."

Bowen, pleased with the vehicle's performance, said that this cruise, under the constant eye of the television cameras, was much different from the rigors of the usual scientific cruise. "Our priority was to hold the kids' interest—that's what this whole thing was about," he said. Schempf said the novelty of working before television cameras to put on a show six times a day was a constant challenge. "It's amazing how much cooperation there is" between the scientists and television personnel, he said. "This is for kids, and we hope it's entertaining."

For many of the Jason Project scientists, the cruise was the culmination of six months of 14- to 16-hour days, said Gallo. "This whole thing happened only because they're dedicated. I think the Woods Hole community has a lot to be proud of," said Gallo. Dana Yoerger, who worked with the vehicles' control systems, had to leave his wife and their new baby girl the day after her birth. "Those guys deserve a hero's welcome back here. They have made the institution even more important in science, technology, and education," Gallo said.

But the entire Jason team, on land and at sea, needs to be recognized, said Schempf. "This whole effort would not work if you took just one person away, it would have just ground to a halt. Everyone deserves credit." □

book reviews

***100 Years Exploring Life, 1888–1988: The Marine Biological Laboratory at Woods Hole* by Jane Maienschein. 1989. Jones and Bartlett Publishers, Boston, MA. 192 pp. + xvi. $22.95.**

The summer of 1988 marked the centennial of a revered research institution, the Marine Biological Laboratory (MBL). To commemmorate this occasion, Jane Maienschein, a science historian at Arizona State University, has put together a generously illustrated biography of the laboratory.

Drawing from archival records and old-timers' recollections, Maienschein introduces us to a cast of colorful characters. For this is a story not of the research performed at the lab but of the people involved: the scientists and students doing the hands-on work, as well as the administrators, librarians, specimen collectors, and caretakers who make the work possible, not to mention the benefactors who have helped pay the bills. Vintage photographs selected by MBL archivist Ruth Davis bring these people to life.

The author moves back and forth in time, often using present-day events to draw us into earlier happenings. She explores themes that have as much relevance for today's investigators as for those of years gone by: the inspirational mixing of minds, the restorative powers of recreation, and the all-too-familiar scarcity of funding and housing.

MBL began primarily as a summer training ground for biology teachers. Such a scheme had been tried in 1873 on nearby Penikese Island by the famed Swiss-born naturalist Louis Agassiz of Harvard, and, the next year, by his son Alexander (after Agassiz's sudden death). The school's brief life and locale made lasting impressions on its students. Based on his earlier experiences there, Alpheus Hyatt, who had gone on to run a teachers' school of natural history in Annisquam, Massachusetts, was easily convinced by Spencer Fullerton Baird, founder of the Woods Hole Fisheries, that Woods Hole was an ideal site to set up a new teaching laboratory. Charles Otis Whitman, who had also attended the Penikese school, was chosen to become the first director. Despite the complete absence of salary, he kept the position from that summer until 1908.

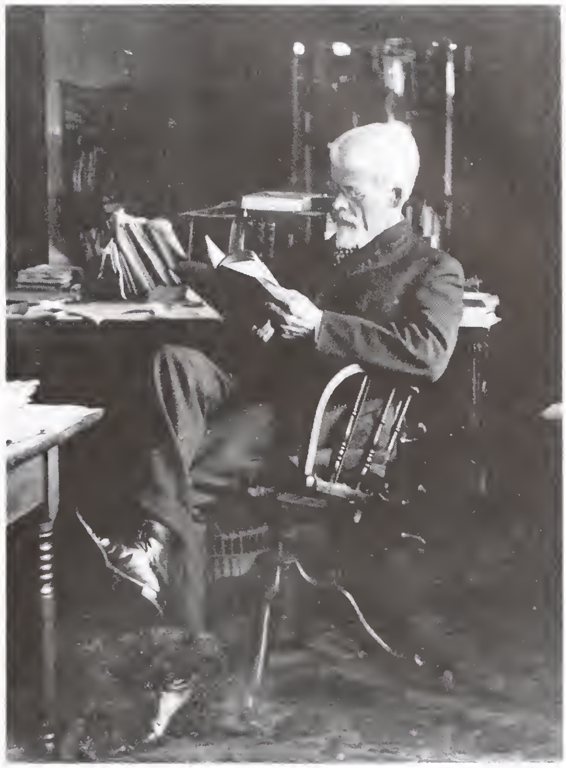
Today MBL retains its commitment to education, drawing to its advanced summer courses in cell physiology, embryology, neurobiology, and ecology top-notch students from around the world. But another side has also developed, separate from formal training: pure research. Many scientists flock seasonally to this seaside village—some to collaborate with colleagues from other institutions. A few stay year-round.

From the start, investigators were drawn by the abundance of life in local waters. (Another factor in Woods Hole's favor was cheap land; the local guano processing company had only recently closed down, and its presence still lingered in the air.) But as the years went by, scientists didn't necessarily use local organisms, let alone marine ones. For example, Whitman, who studied the behavior of pigeons that he normally kept in his backyard in Chicago, hauled his birds to the MBL several summers. And geneticist Thomas Hunt Morgan brought fruitflies from his "fly room" at Columbia.

Since the 1960s, a seasonally abundant marine organism—the squid—has become the star attraction. Squid contain two unusually long nerve fibers, or giant axons. Unlike most nerve cells, these are large enough to insert electrodes into and are thus ideal for studying nerve impulses. Presently, one-third of the demand for marine organisms at the MBL is for squid, and, as I can attest from my four years as a graduate student in the joint MBL-Boston University Marine Program, many a summer feast is prepared from their remains.

The MBL has always been highly respected and influential, and has hosted at one time or another, more than its fair share of Nobel laureates—35 to be exact—whose names are listed at the back of the book. When Japanese Emperor Hirohito, a practicing marine biologist, was planning his 1975 tour of the United States, MBL was the one place he insisted on visiting.

But there have also been a few rough spots in the MBL's history. During its formative years there was much debate about just how the MBL should be run and by whom. Whitman resented the efforts of nonscientist trustees living in Boston to exert power. Some of them, on the other hand, felt that Whitman was trying to build his own empire. A reorganization soon changed the constituency of the board of trustees, making the MBL an autonomous body, mainly



Clockwise from top left: a collecting party at Cuttyhunk Island, 1895; the first director, Charles Otis Whitman; the original laboratory, 1888; the 1897 embryology class, with Gertrude Stein, front row, second from left. (Courtesy of MBL Archives)

controlled by and for the scientists.

The lab has since gone through many other changes, notably the great increase in scientific specialization. This is reflected by the famous summertime Friday evening lectures. Originated by Whitman as a public forum for the day's important scientific questions, they now tend to leave many listeners, even scientists, behind in a dust of jargon.

The author touches on other issues as well, including the effort of women to make their mark in a male-dominated institution. Ironically, the photographs show that women played a significant role in the earliest days. The author also makes passing reference to the struggles of Ernest Everett Just, one of the few blacks in American science in the 1920s. Only the MBL would provide a scientific home in the United States for this talented researcher.

The author does not go into great detail on such issues. She prefers to give us an overview, providing a feeling for the people and atmosphere at the MBL rather than an in-depth account. This may whet the appetite of readers who can go to other sources, some of them listed at the end of each chapter. (Frustratingly, however, there is no index.)

Despite the book's lack of analyses, its easy-flowing text and candid illustrations make it a fine introduction to the history and achievements of one of our oldest marine research institutions.

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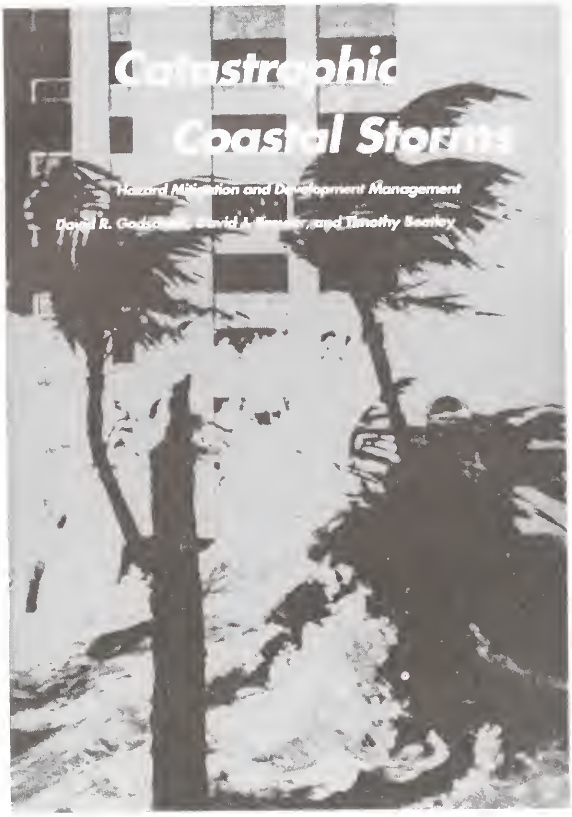

Catastrophic Coastal Storms by David R. Godschalk, David J. Brower, and Timothy Beatley. 1989. Duke University Press, Durham, NC. 275 pp. + x. $47.50.

The specter of accelerating climate change accompanied by higher sea levels and increased storm activity has many coastal towns worried about their future. What impact will these potential events impose on communities' infrastructure and tourism? What is the best management policy for these areas, and how does a coastal town obtain guidance and financial help with coastal management? These driving questions are among those addressed by the authors in their study of catastrophic coastal storms.

The book is well written in general and presented at a level not so specific as to lose the nontechnical reader. It addresses the accepted natural hazard management model, which consists of a four-stage process: mitigation, preparedness, response, and recovery. The primary focus, however, is on mitigation, the one element of the natural hazard model that has been most neglected in the past. The emphasis is on "bottom-up" mitigation—starting with a local disaster mitigation program—developed in the context of the overall intergovernmental framework.

The most effective mitigation strategy, in the view of the authors, is one that manages growth and development to keep infrastructure away from the areas where storm forces will be greatest. While this position is tenable for undeveloped coastal regions, it's not clear how this strategy would be applied to coasts that are already heavily developed. The authors focus on development management as the primary mitigation (alteration of the shoreline, strengthening buildings and facilities, and evacuation, for instance). While this slant may not have been intended by the authors, it does detract from the completeness of the presentation, particularly for heavily developed coastal areas. However, the general theme, that of managing growth and development in hazard-prone areas, is a laudable one that must form the basis for much of our coastal mitigation program.

Although the theme of development management has been making the rounds of the policy circuit for a long time, this book goes beyond simple platitudes and offers some solid recommendations: establishment of a comprehensive set of storm hazard mitigation performance standards; reorientation of federal expenditures related to mitigation, to reward state and local programs that meet the performance standards; and incorporation of the mitigation standards into state and local development management plans and programs that actually guide coastal development. The authors conclude with a detailed description of how to derive effective local mitigation strategies, including ways to overcome local adoption and implementation obstacles.

Federal policy support for local hazard mitigation is discussed, including the need to overcome the cycle of build-destroy-rebuild presently fostered by federal programs. Unfortunately, the book was published just as the Upton-Jones amendment to the Flood Emergency Act (FEMA) was passed, so this positive advance made by the federal sector is acknowledged only by footnote at the end of the final chapter. The amendment encourages local government to declare structures as imminently endangered. This allows structure relocation to become an eligible insurance loss claim if relocation occurs sufficiently far from the hazard area (for instance, behind the 30-year coastal set-back line—that is, the projected shoreline 30 years in the future, based on the current rate of local erosion). If relocation were not performed soon enough, and the structure suffered subsequent damage, the insurance claim could not exceed 40 percent of the insured value. This policy thereby minimizes the costs of future claims by encouraging timely relocation. It is also funded through insurance premiums, and therefore does not require new appropriations.

The authors recommend that the National Flood Insurance Program, administered by FEMA, be reoriented to encourage operations more similar to a conventional, private insurance company, with variable rates tied to the relative risk of various policy holders, even to the point of canceling insurance for policy holders in zones where the risks are too high. Finally, they discuss how to implement coastal mitigation management most effectively on a local level, including arguments to overcome some of the common objections to mitigation planning.

This volume provides a useful management tool for coastal communities. It reviews the development of coastal emergency management, and provides appropriate guidelines for local mitigation of coastal flooding (due to storms, rather than potential longer-term sea-level rise). Coastal communities that feel a need for guidance in mitigation management should benefit from its insights.

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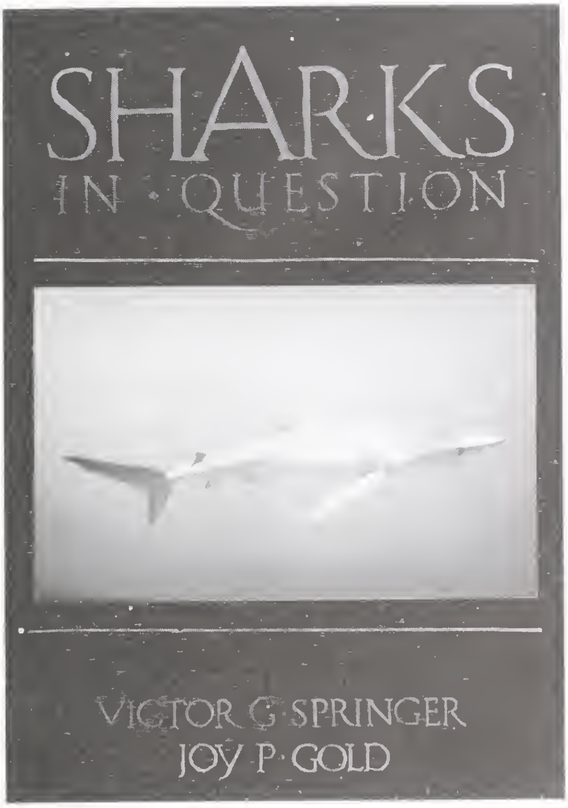

***Sharks in Question: The Smithsonian Answer Book* by V. G. Springer and J. P. Gold. 1989. Smithsonian Institution Press, Washington, DC. 187 pp. $39.95.**

For those marine biologists, amateur naturalists, museum docents, and so many others who have always felt a certain queasiness when attempting to answer questions like: "Why are sharks unchanged over time? Won't the shark die if it stops swimming? How smart are sharks? What should I do if I'm attacked by a shark?" and the ever-favorite, "How are sharks different from fish?" your prayers have been answered.

Like all museum professionals, the authors were besieged by the above-mentioned questions and so many more after a local shark attack, or the nearby discovery of a fossil shark tooth. (The phenomenon of besiegement by questions also peaks during Science Fair and when science term papers are due.) Springer, a distinguished ichthyologist with the Smithsonian's Fish Division, and Gold, a Technical Information Specialist in its Department of Vertebrate Zoology, decided to compile the typical questions and their answers in a novel format, along with just enough basic elasmobranch (shark and ray) biology to update a rusty biology graduate or challenge an interested novice.

Much has been learned about sharks in the last few decades, aided in part by the U.S. Navy's concern for their personnel and equipment, and subsequently by the public's interest in the subject since Peter Benchley's book and film *Jaws*. Several natural history films have recently brought scientists and filmmakers together to enter the shark's milieu at Hollywood's expense, and the result has certainly whetted the public appetite and occasionally added to the confusion. Current research has largely turned away from a search for shark repellents and directed itself more to the sensory modalities and abilties of elasmobranchs. The rising commercial market for shark flesh in a protein-short world has reminded us how little we know about the natural history of most (or any!) of today's 350 species of sharks. This book touches on each of these points, and answers—although not exhaustively—many more; and it properly culminates with the question: "What is left to learn about sharks?" (The answer: lots.)

The book is organized in five sections, followed by a useful glossary; bibliographies of general, popular, and technical literature; and an index. Numerous line drawings, as well as sixteen color plates of adequate quality (but modest size) illustrate various shark behaviors, species, and anatomical parts. The first part answers the basic anatomical, evolutionary, and behavioral questions, and ends with a synoptic description of the nine orders of living sharks. Part two focuses on the biology of "supersharks," the large, dangerous, and charismatic species. Part three is a brief but obligatory treatment of the danger of shark attack, beginning with "How serious is the threat?" (not great unless you are a victim—less than 100 annually reported worldwide, with about 30 fatalities); and continuing with "Which sharks are dangerous?" (only 21 species); "Why do sharks attack humans?" (biologists are not sure, but they have some good ideas—I won't give them away here); and "Are there any effective shark repellents?" (no). Part four concerns "sharks and us," and asks: "Of what use are sharks? How can I become a shark specialist?" and "What is left to learn about sharks?" Part five contains appendices of shark classification, common and scientific names, and maximum and minimum lengths of selected species.

The book has undergone a careful reading and editing by several experts in the field. Areas of controversy among elasmobranch biologists are identified and treatment is given to different points of view. Errors are few and trivial. In fact, the book is so complete that I'm afraid many high school students will use it as the sole source for their various papers. On the other hand, the good ones probably won't, and some may become inspired to pursue a career in this or a similar field.

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A Note to Teachers

We offer a 25-percent discount on bulk orders of five or more copies of each current issue—or only $4.12 a copy. The same discount applies to one-year subscriptions for class adoption ($17.00 per subscription).

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Shark, a Photographer's Story **by Jeremy Stafford-Deitsch. 1988. Sierra Club Books. San Francisco, CA. 200 pp. $16.95.**

I saw my first shark (an oceanic whitetip), while I was leaning over the rail of *R/V Atlantis* in the Windward Passage about 35 years ago. At that time you probably didn't need more than the toes on one foot to tally up all the available underwater pictures of sharks in the wild. Certainly, you would have found it next to impossible to have located any that had been taken close up, in focus, well composed, and in color. *Shadows in the Sea,* for example, a popular shark book first published 1963, didn't contain a single underwater picture, good or bad. By contrast, this book has dozens of superb photographs of sharks in their natural habitat.

We owe such photography largely to the great surge in professional and amateur underwater exploration in the 1960s and '70s, as well as to the advances in diving gear and cameras that accompanied and encouraged all this activity. But it is also a tribute to the energy, perseverance, skill, and courage of the photographers themselves who often seem willing to risk all in their quest of sharks.

But this book isn't just a collection of pictures. It's a natural history of sharks, principally of the larger and more conspicuous kinds that divers and other sea-goers are sometimes lucky enough to see. Author/photographer Stafford-Deitsch nicely weaves together zoology and his own considerable underwater experience with these much maligned animals.

Unfortunately, his fine photographs are ill-served by the book's design. Of the 70 or so photographs that occupy a page or more, at least 30 have been done substantial damage because they're cut in critical places by the margin between facing pages. For example, on pages 17 and 18, designer Nigel Partridge should have let the gutter sever the diver instead of the shark. And on pages 55 and 59, there's enough white space to the right of the eagle ray, a kin of the shark, so that this fine fish needn't have been beheaded.

One can only be left to wonder how many cold, wet, tired hours Stafford-Deitsch spent underwater before he got the wonderful picture of the mako on pages 132 and 133, only to have it butchered by somebody sitting warm and dry before a studio table on King's Cross Road in London, where the book was produced.

Stafford-Deitsch doesn't claim to be a scientist (he majored in philosophy at London University). But his biology seems correct to me and his field natural history is first-rate. Wherever he and I intersect in experience (mostly in dealing with oceanic sharks), he seems to be right on target, and I'm willing to believe what he tells me about those many things of which he knows so much more than I do. His sea stories are well tempered and ring true. He's a good writer, even poetic now and then, and I really enjoyed reading this reasonably priced book. It's too bad that both pictures and text are dragged down by the shortcomings of design.

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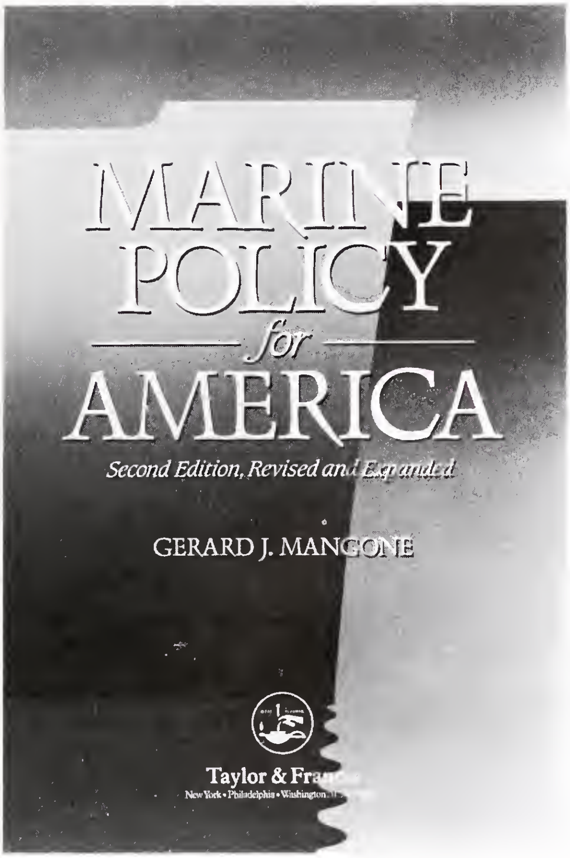
Marine Policy for America, Second Edition, Revised and Expanded, **by Gerard J. Mangone. 1988. Taylor & Francis, New York, NY. 365 pp. $40.00.**

"Marine policy is public policy." So begins the final chapter of Gerard Mangone's second edition of *Marine Policy for America*. Not theoretical, or even analytical in a disciplinary sense, the book is the *only* comprehensive, historical treatment of the field. Its structure is an accurate, sometimes precise, reflection of the institutions that create and carry out U.S. public policy near, on, or under the oceans, and of the issues they face. Those who believe that marine policy only emerged with the environmental movement in the late 1960s have a lot to learn from this book. For those who have allowed themselves to become caught up in the excitement of recent presidential proclamations extending U.S. ocean jurisdictions, this book is mandatory reading.

Mangone, director of the Center for the Study of Marine Policy at the University of Delaware, clearly is aware of the difficulties in characterizing a field with a scope as broad as marine policy. He writes:

> It is often asked whether the United States has a marine policy. In the sense of a single, comprehensive, integrated statement or formula, the answer must be "no." ... [There are] such a diversity of problems and issues, such a mix of constituents and public interest, and such a wide distribution of responsibility within the American government that any search for a single policy would be futile.

This statement must alarm those who seek simple solutions to persistent problems in ocean governance. Mangone reminds us that posing institutional solutions



is easy, but that achieving them is more difficult and often ephemeral. Indeed, he remarks bluntly that one of the common "solutions" to problems of marine policy—that of creating a single, national ocean agency—is a chimera. If such an agency were in fact established, it would merely "engender an octopus with fissiparous tendencies."

The absence of a single marine policy for the United States could have presented a problem for the author as well, but his treatment is well-organized and even. There are seven chapters, focusing respectively on: Early America and the Sea, The Navy and American Security, the Merchant Fleet of the United States, Fisheries and Foreign Policy, the Continental Shelf and Seabed Minerals, Marine Pollution, and Formulation and Administration of Marine Policy. Each chapter is completed with a section on "problems and issues," a synopsis of historical events in combination with some limited forecasts. Through a series of polished essays, *Marine Policy for America* largely succeeds in presenting an integrated view of historical events that frame future possibilities.

Indeed, any book on marine policy that includes both Herodotus and Henry Ford between its covers ought to invite considerable attention. We learn to attribute the late-18th-century concept of a territorial sea to Ferdinando Galiani, who was, appropriately, an economist. We discover that Alexander Agassiz, the successful copper magnate, was hauling up manganese nodules at the turn of the century, and that a long line of philosophers has been interested in the effects of man on climate. Among them: Hugh Williamson, who suggested in 1760 that climate might be altered to "gain more moderate temperatures and salubrious airs!"

The reader, however, is left asking for more. And a few statements indicate, almost by design, that there is more. Again, with regard to constructing institutions for governance, Mangone explains that:

> The game of organizational arrangements can be played by anyone, yet the principle of vertical specialization for the application of policy and the lateral review of performance by disinterested parties should not be forgotten.

Had this meaty thesis appeared in the first chapter, instead of the last, and been developed with the plethora of factual accounts that fill its pages, *Marine Policy for America* could have laid a paradigmatic foundation for the field.

But such criticisms are merely afterthoughts. Without Mangone's considerable effort, we would remain mired in ignorance, muddlers at best. This is a valuable work, well-referenced and indexed. The second edition includes more figures and tables than the first, and the new typeface and layout enhance readability. It should be within reach of any government official with even a tangential responsibility for ocean management, as well as research specialists who need to accelerate quickly on marine issues with which they have little familiarity.

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Marine Policy Center
Woods Hole Oceanographic Institution

The Crest of the Wave: Adventures in Oceanography **by Willard Bascom. 1988. Harper & Row, New York, NY. 317 pp. + xiv. $19.95.**

Willard Bascom has had (and is still having) a wonderful life. He has seen and been involved with many exciting things, most of which involve the ocean. In this charming book he shares some of his experiences with us. Parts of his story were almost déjà vu for me, involving similar people and events, but 15 years later in time.

Bascom's story starts in 1945 when, as a young mining engineer, he was attracted to oceanography by John Isaacs, who was then a young teacher at Scripps Institution of Oceanography in La Jolla, California. (As an aside, somebody should write a book about Isaacs, who has influenced so many people.) With Isaacs, Bascom made an amazing series of beach surveys risking life and limb to learn about waves off the West Coast of the United States. Later he was indirectly involved in the Bikini A-bomb tests, had a series of experiences with land-based mining operations, then became involved with oceanography at Scripps, in particular in the Capricorn Expedition in the Pacific Ocean. Along the way he successfully came through a bout with cancer.

Bascom spent a few years in Washington at the National Research Council where, among other things, he helped develop the Moho Project, and was one of the leaders of its successful first phase, the CUSS I expedition off San Diego. The Moho Expedition was an attempt to drill through the earth's crust to the mantle reaching the Mohorovičić discontinuity, or Moho, the boundary between the crust and mantle; it did not succeed because of political problems concerning the awarding of the drilling contracts. Subsequently he went off to mine diamonds off the coast of Africa, and formed the Ocean Science and Engineering Company (with several others).

Next he went looking for treasure ships in the Caribbean. Unsuccessful, he returned to California and headed up the Southern California Coastal Water Research Project. Finally, we find Bascom working back at the National Academy of Sciences with satellites and sailing vessels. One could get the mistaken impression that he cannot hold a job. Just the opposite: he leaves when things get boring or something more exciting beckons.

Along the way, the reader meets Bascom's compatriots, names well known in oceanographic circles. Besides Isaacs, there's Al Vine, Walter Munk, Roger Revelle, Russ Raitt, Giff Ewing, Art Maxwell, John Knauss, George Shor, Richard Von Herzen, among others, and it is a lovely trip. I only overlapped for a few minutes of Bill's career, and every second of that time is memorable. Read this book if you want to learn how oceanography was before scientists and engineers had to worry about mundane things like budgets, government regulations, department chairmen, and more.

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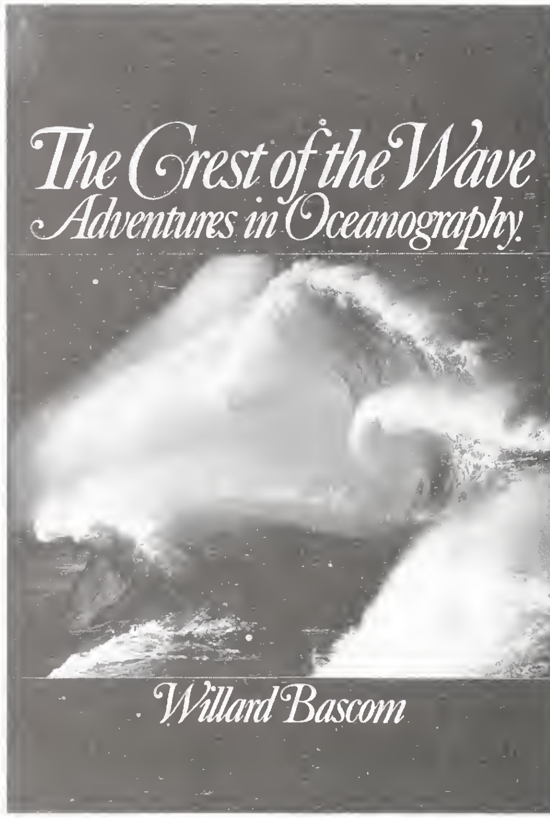

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Biology

The Coralline Red Algae by William J. Woelkerling. 1988. Oxford University Press, New York, NY 10016. 268 pp. + xii. $85.00.

Marine Microbiology by B. Austin. 1988. Cambridge University Press, New Rochelle, NY 10801. 222 pp. + xii. $59.50.

Microbial Ecosystems of Antarctica by Warwick F. Vincent. 1988. Cambridge University Press, New Rochelle, NY 10801. 304 pp. + x. $75.00.

On Lampreys and Fishes: A Memorial Anthology in Honor of Vladim D. Vladykov edited by Don E. McAllister and Edward Kott. 1988. Kluwer Academic Publishers Norwell, MA 02061. 162 pp. $83.00.

Peacemaking Among Primates by Frans de Waal. 1989. Harvard University Press, Cambridge, MA 02138. 294 pp. + xiv. $29.95.

Pelagic Snails: The Biology of Holoplanktonic Gastropod Mollusks by Carol M. Lalli and Ronald W. Gilmer. 1989. Stanford University Press, Stanford, CA 94305. 259 pp. + xvi. $49.50.

Sensory Biology of Aquatic Animals edited by Jelle Atema, Richard R. Popper, Arthur N. Popper, and William N. Tavolga. 1988. Springer-Verlag, Secaucus, NJ 07096. 936 pp. + xxxvi. $169.00.

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Tuna and Billfish: Fish Without a Country by James Joseph, Witold Klawe, and Pat Murphy. 1988. Inter-American Tropical Tuna Commission, La Jolla, CA 92093. 69 pp. + xi. $15.75.

Turtles and Tortoises of the World by David Alderton. 1988. Facts on File, New York, NY 10016. 191 pp. $22.95.

The Ultrastructure of Polychaeta edited by Wilfried Westheide and Colin O. Hermans. 1988. Gustav Fischer Verlag, New York, NY 10010. 494 pp. $77.00.

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The Ocean Alphabet Book by Jerry Palota with illustrations by Frank Mazzola, Jr. 1989. Charlesbridge Publishing, Watertown, MA 02172. 32 pp. $11.95.

The Rock Pool by David Bellamy, with illustrations by Jill Dow. 1988. Clarkson N. Potter, New York, NY 10003. 26 pp. $9.95.

The Scientific Kid: Projects, Experiments and Adventures by Mary Stetten Carson. 1989. Harper & Row, New York, NY 10022. 80 pp. $9.95.

Sunken Treasures by Gail Gibbons. 1988. Thomas Y. Crowell, New York, NY 10022. 32 pp. $12.89.

Earth Science

Basement Correlation Across the North Atlantic by Jean-Pierre Lefort. 1989. Springer-Verlag, Secaucus, NJ 07096. 148 pp. + xii. $59.00.

Drifting Continents and Shifting Theories by H. E. Legrand. 1988. Cambridge University Press, New Rochelle, NY 10801. 313 pp. + vi. $49.50.

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Balancing the Needs of Water Use by James W. Moore. 1989. Springer-Verlag, Secaucus, NJ 07094. 267 pp. + xi. $69.00.

The Delaware Estuary: Rediscovering a Forgotten Resource edited by Tracey L. Bryant and Jonathan R. Pennock. 1988. University of Delaware Sea Grant College Program, Newark, DE 19716. 144 pp. $20.00.

Living with Chesapeake Bay and Virginia's Ocean Shores by Larry G. Ward, Peter S. Rosen, William J. Neal, Orrin H. Pilkey, Jr., Orrin H. Pilkey, Sr., Gary L. Anderson, and Stephen J. Howie. 1989. Duke University Press, Durham, NC 27708. 236 pp. + xiv. $12.95.

Living with the Coast of Maine by Joseph T. Kelley, Alice R. Kelley, and Orrin H. Pilkey, Sr. 1989. Duke University Press, Durham, NC 27708. 174 pp. + xvi. $10.95.

Oceans of Plastic edited by Sue Keller. 1988. Alaska Sea Grant College Program, Fairbanks, AK 99775. 41 pp. + vi. $5.00.

Pollution of the North Sea: An Assessment Edited by Wim Salomons, Brian L. Bayne, Egbert K. Duursma, and Ulrich Förstner. 1988. Springer-Verlag, Secaucus, NJ 07096. 687 + xii. $113.00.

Using Oil Dispersants on the Sea edited by Andrea Corell. 1989. National Academy Press, Washington, DC 20418. 335 pp. + xvi. $29.95.

Field Guides

Beachcomber's Guide to the Gulf Coast Marine Life by Nick Fotheringham and Susan Brunenmeister. 1989. Gulf Publishing, Houston TX 77252. 142 pp. + x. $12.95.

A Field Guide to the Fishes of Galápagos by Godfrey Merlen. 1988. Wilmot Books, London England SW3 5EL. 60 pp. $12.00.

Florida's Fossils: Guide to Location, Identification, and Enjoyment by Robin C. Brown. 1988. Pineapple Press, Sarasota, FL 16008. 208 pp. $21.95.

Marine Plants of the Caribbean by Diane Scullion Littler, Mark M. Littler, Katina E. Bucher, and James N. Norris. 1989. Smithsonian Institution Press, Washington, DC 20560. 263 pp. $14.95.

Sea Life of Britain and Ireland edited by Elizabeth Wood, with foreward by David Bellamy. 1988. IMMEL Publishing, London, England W1X 3RB. 240 pp. £14.95.

General Reading

The Cosmic Blueprint: New Discoveries in Nature's Creative Ability to Order the Universe by Paul Davies. 1988. Simon & Schuster New York, NY 10020. 224 pp. + x. $8.95.

Genethics: The Clash Between the New Genetics and Human Values by David Suzuki and Peter Knudtson. 1989. Harvard University Press, Cambridge, MA 02138. 384 pp. $25.00.

Infinite in All Directions by Freeman Dyson. 1988. Bessie/ Harper & Row, New York, NY 10022. 319 pp. + vii. $8.95.

Koviashuvik: A Time and Place of Joy by Sam Wright. 1988. Sierra Club Books, San Francisco, CA 94109. 214 pp. $17.95.

Parallel Universes: The Search for Other Worlds by Fred Alan Wolf. 1989. Simon & Schuster, New York, NY 10020. 351 pp. $19.95.

A Pictorial History of Diving edited by Arthur J. Bachrach, Barbara M. Desiderati, and Mary M. Matzen. 1988. Best Publishing, San Pedro, CA 90732. 149 pp. $83.00.

Plants Beyond: Discovering the Outer Solar System by Mark Littman. 1988. John Wiley & Sons, Somerset, NJ 08875. 286 pp. + xvi. $22.95.

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Sea-Brothers: The Tradition of American Sea Fiction from *Moby-Dick* to the Present by Bert Bender with drawings by Tony Angell. 1988. University of Pennsylvania Press, Philadelphia, PA 19104. 267 pp. + xvi. $29.95.

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