Abrupt Climate Change, Oceans, and Us

Sixth Annual Roger Revelle Commemorative Lecture

Smithsonian National Museum of Natural History

November 10, 2004

5:30 pm

Contents

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Welcome

Dear Lecture Participant:

On behalf of the Ocean Studies Board (OSB) of the National Academies, I would like to welcome you to the Sixth Annual Roger Revelle Commemorative Lecture.

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College and at U.C. Berkeley. Then, in 1936, he received his Ph.D. in oceanography from the Scripps Institution of Oceanography. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950-1961, 1963-1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He calculated the first continual measurement of atmospheric carbon dioxide, leading to a long-term record that makes present-day discussions on research on global warming possible and very valuable. Revelle kept the issue of increasing carbon dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change.

Revelle was a proponent of daring programs, like Mohole and the International Indian Ocean Expedition. This expedition addressed fundamental scientific questions and pioneered international cooperation. In 1960, Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961-1963 and as the first Director of the Center for Population Studies at Harvard (1964-1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences (NAS) to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea-level change.

Smithsonian
National Museum of Natural History

This year marks the first time that the Academies has partnered with another organization and held the lecture outside the National Academies. The Smithsonian National Museum of Natural History was the perfect venue to host the lecture as it is the most visited natural history museum in the world. Opened in 1910, the museum is dedicated to maintaining and preserving the world's most extensive collection of natural history specimens and human artifacts. It also fosters critical scientific research, as well as educational programs and exhibitions that present the work of its scientists and curators to the public.. The Museum is part of the Smithsonian Institution, the world's largest museum and research complex. It is directed by Dr. Douglas Erwin.

Ocean Science Initiative

The National Museum of Natural History is building upon its substantial foundation in marine science to establish a comprehensive Ocean Science Initiative that will:

- Engage, educate, and inspire the public through state-of-the-art displays in the Museum's exciting and ambitious new Ocean Hall.
- Extend access to the exhibition, collections, and research through the integrated and dynamic Ocean Web Portal.
- Expand understanding of our oceans through the scholarly, multi-disciplinary Center for Ocean Science.

The Ocean Hall

In the Ocean Hall, visitors will find a one-of-a-kind interpretive exhibition, extraordinary in scale and presenting the oceans as never before: over time and in three dimensions. When complete in 2008, it will span more than 26,000 square feet to become the Museum's most prominent hall. Initial funding of $16 million has been provided by the U.S. National Oceanic and Atmospheric Administration (NOAA), whose mission is to understand and predict changes in Earth's environment and to conserve and manage coastal and marine resources. Since NOAA uses the Museum's basic science on biodiversity to build models of ecosystem dynamics and resilience, this partnership in public education is a natural fit.

This lecture was created by the Ocean Studies Board in honor of Dr. Roger Revelle to highlight the important links between ocean sciences and public policy.

I hope you enjoy the lecture.

Nancy Rabalais
Chair, Ocean Studies Board

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Dr. Richard B. Alley is Evan Pugh Professor of Geosciences and Associate of the EMS Environment Institute at The Pennsylvania State University, University Park, PA, USA. There he teaches and conducts research on the paleoclimatic records, dynamics, and sedimentary deposits of large ice sheets, as a means of understanding the climate system and its history, and projecting future changes in climate and sea level. Dr. Alley has spent three field seasons in Antarctica and five in Greenland. He is a Fellow of the American Geophysical Union, and has been awarded a Packard Fellowship, a Presidential Young Investigator Award, the Horton Award of the American Geophysical Union Hydrology Section, the Easterbrook Award of the Quaternary Geology and Geomorphology section of Geological Society of America, the Wilson Teaching Award of the College of Earth and Mineral Sciences and the Faculty Scholar Medal of the Pennsylvania State University. His book on abrupt climate change, The Two-Mile Time Machine, was the national Phi Beta Kappa Science Award winner for 2001. Dr. Alley chaired a recent National Research Council study on Abrupt Climate Change, and serves, or has served, on many other advisory panels and steering committees.

Synopsis

Modern climate science indicates that rising carbon dioxide levels in the atmosphere and the effects of other human activities will cause large climate changes requiring significant adaptation by human societies around the globe. Climate records and human history provide insight to the nature of climate change and the types of challenges a shifting environment will pose for human societies. Past records show that climate sometimes changes abruptly, but this aspect of climate history has received relatively little attention in efforts to understand the consequences of future changes in climate. Although a major, potentially rapid change in climate poses a daunting prospect, I am convinced that today's students, if given sufficient support, will be able to address the challenges of the future.

Introduction: A Challenge

How should we handle our climate future? In trying to decide what if anything to do about climate change, policymakers may consider a wide range of future scenarios, with larger or smaller, scarier or more acceptable changes. But almost all those scenarios postulate change that occurs smoothly and gradually, leaving the government and the governed plenty of time to respond.

This is surprising since the Earth's climate history is anything but smooth. Variability is the rule, not the exception. However, only in the past decade or so has the broader scientific community recognized that variability includes very large and widespread abrupt climate changes. The relatively recent revelations gleaned from the climate record tell us that change will occur in fits and starts, with potentially large and rapid jumps and detours along the way.

After presenting some of the evidence for abrupt climate changes and describing the likely causes, I will discuss whether the past has anything to tell us about the future (the answer is *yes*). Then I will offer a few opinions on the future based on the science of climate, my impressions of recent environmental history, and the potential of this generation of students.

Mired in Mud

The Earth's history is recorded in sediments. Because plants and animals that grow in warm environments can be readily distinguished from those that grow in cold environments, variation in the plant and animal skeletons found in sediment layers indicates that there were shifts in the climate at that location. For instance, planktonic skeletons that accumulate on the sea floor beneath the warm waters of the Gulf Stream are readily distinguished from those of nearby cooler waters. Similarly, pollen that accumulates on a tundra lake bed has little in common with pollen from a temperate or tropical forest. Sediment cores have revealed alternating accumulations of layers of cold- and warm-water organisms. Sometimes these layers occur close together, suggesting sudden shifts in conditions.

Of particular interest, European bogs showed that warming since the ice age staggered back to cold conditions several times, with one especially prominent reversal. This most recent major cold interval (about 12,800 years ago) was called the Younger Dryas after a tundra flower (*Dryas octopetala*) that appears in the mud record from that time, but disappears when European conditions become temperate. Conditions characteristic of cold periods, such as the regrowth of glaciers, appear to have started and ended abruptly during the Younger Dryas (1).

But how abruptly? How much cooling occurred? How much of the world was affected? The discoverers of the Younger Dryas lacked the technology to find out, but now we are learning that the changes were rapid and dramatic, with local temperatures changing as much as 10^{o}C (18^{o}F) or more. Additionally, the climate shift moved quickly, spreading around much of the globe within a decade or so, possibly as quickly as a single year.

Into the Ice

Although sediments from ocean, lake, and bog floors have provided important evidence of past climate changes, it is difficult to resolve how rapidly events occurred because sediments often accumulated very slowly and burrowing animals can literally stir up the past, disrupting parts of the record. Ice provides higher resolution and better preservation of past events, inspiring scientists to seek ice cores from Antarctica, high mountains, and, for my story, the ice sheet of Greenland (2).

Snow that falls on an ice sheet is gradually squeezed into ice, which piles up over time. The ice in Greenland is now hundreds of kilometers across and three kilometers (about two miles) thick in the middle. The ice spreads slowly under its own weight like pancake batter on a griddle, dripping off the edges of Greenland to form icebergs or melting in low-elevation coastal regions. The rate of ice loss has been close to the rate of snowfall, keeping the volume of the ice sheet relatively constant over the last millennia.

Summer sunshine changes the physical properties of the snow, providing a seasonal marker in the ice like the rings of a tree. As snow falls it traps bits of dust, sea salt, smoke from forest fires, volcanic ash, and other materials from the atmosphere. Bubbles get trapped when the snow is squeezed into ice, thus capturing a time capsule of air that can be analyzed for gases that fluctuate with climate, such as methane and nitrous oxide. Measurements of subtle isotopic indicators and trapped gases have been used to determine the temperature in Greenland when the snow fell. The actual temperature of the ice today also provides evidence of past cooling—the ice is coldest 1-2 km down (about a mile) because of the lingering chill from the ice age. By reading the records in a Greenland ice core—temperature and snowfall in Greenland, wind-blown dust from Asia (fingerprinted by its unique chemical composition and minerals), methane from the world's wetlands—one can learn much about the climate in Greenland and other parts of the world. Also, because changes in the sun or in the Earth's magnetic field affect the cosmic rays that make some of the odd isotopes found in the ice, and volcanic ash blocks sunshine before falling on the ice sheet, ice cores provide some information on the causes of climate changes .

Several deep ice cores have been collected from Greenland and analyzed over the past 40 years. I was fortunate to participate in GISP2 (Greenland Ice Sheet Project 2) between 1989 and 1993, near the center of the ice sheet.

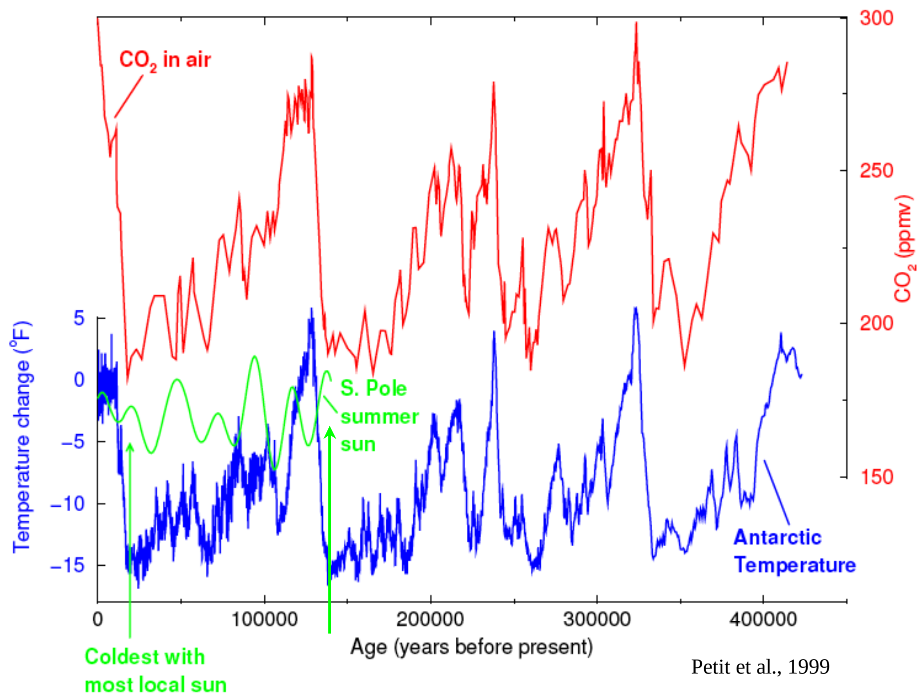
FIGURE 1:
Ice Cores, Such as These from GISP2 in Central Greenland, Produce Wonderful Records of Climate Change

Source:

Results from the many Greenland ice cores are spectacular and agree closely with previous studies from other locations. The cores tell us that Greenland and the rest of the world cooled over tens of thousands of years into the great ice age that peaked about 20,000 years ago. The ice ages were paced by slow changes in Earth's orbit. Remarkably, the orbital changes had little effect on the total energy received from the sun, serving instead to move sunshine around the planet. Cooling occurred worldwide when sunshine dropped in the far north because of the affect on atmospheric carbon-dioxide concentrations and thus global temperatures—Antarctica experienced especially cold temperatures although the sunshine was especially high, as shown in Figure 2 (3). When sunshine shifted from the south to the north, carbon dioxide rose in the atmosphere, Greenland warmed with the rest of the world and has remained warm to the present (Figures 2, 3). Many other hypotheses have been suggested for ice ages, but so far have failed. The only plausible explanation of what happened requires that global average temperature increases with increasing carbon-dioxide concentration in the atmosphere. And as shown in Figure 3, future changes in carbon dioxide concentration are likely to be large compared to those involved in the global ice ages.

FIGURE 2:

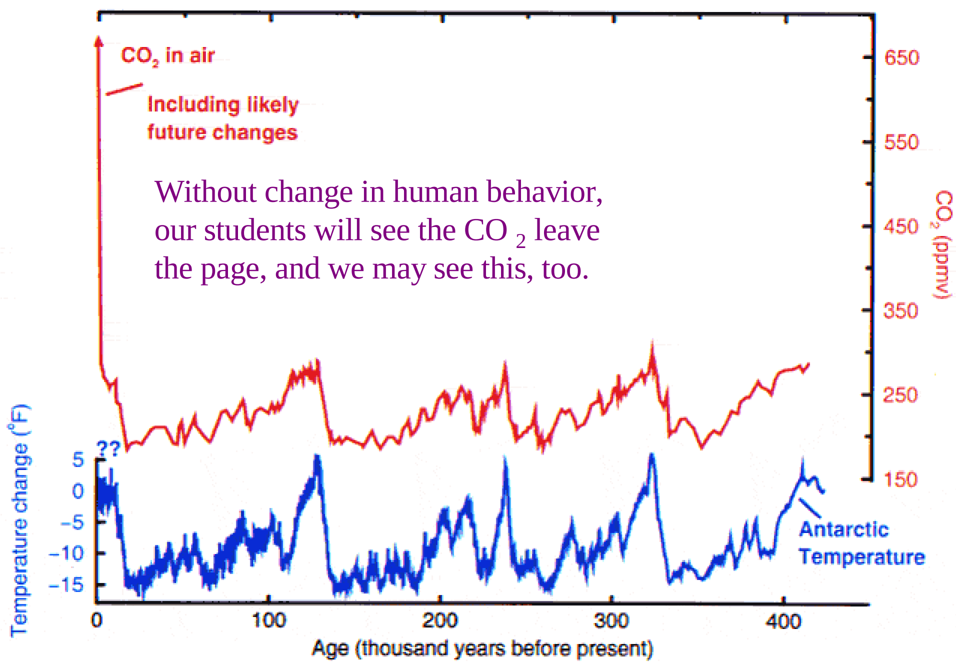
The Last 440,000 Years of Climate In Central East Antarctica, From the Vostok Ice Core (Petit Et Al., 1999). Today is on the Left, and 440,000 Years Ago on the Right. The Lower Curve Shows The History Of Temperature Estimated from the Isotopic Composition of the Ice. The Large, Approximately 100,000-Year Cycle of Ice Ages is Evident. This Basic Pattern is also Evident in Most Climate Records from Anywhere on Earth. The Bottom Curve Also Shows the Variation in Local Sunshine in Antarctica Over The More Recent Part of the Record, Calculated From Knowledge of Orbital Physics. Peaks in Antarctic Sunshine are Spaced about 20,000 Years Apart, and Occur When Northern Sunshine Was Especially Low, Including the Antarctic Peak In Sunshine About 20,000 Years Ago When Antarctica Was Especially Cold. The Only Explanation of this Behavior that "Works" is that the Carbon-Dioxide Concentration of the Atmosphere Followed Northern Sunshine, As Shown by the Upper Curve, and that in Turn Carbon Dioxide Was More Important for Southern Temperature Than Was Southern Sunshine.



Source: Modified from Alley, R.B. 2000. *The Two-Mile Time Machine*. Princeton University Press.

FIGURE 3:

As in Figure 2, but the Curves Have Been Compressed to Show the Likely Future Trend in Carbon Dioxide if We Do Not Change Our Behavior. Nature Indeed Has Changed Atmospheric Greenhouse Gases Greatly in the Past, but Humans are now "in control" and Moving out of the Natural Range of Variability Over at Least the Last 440,000 Years.

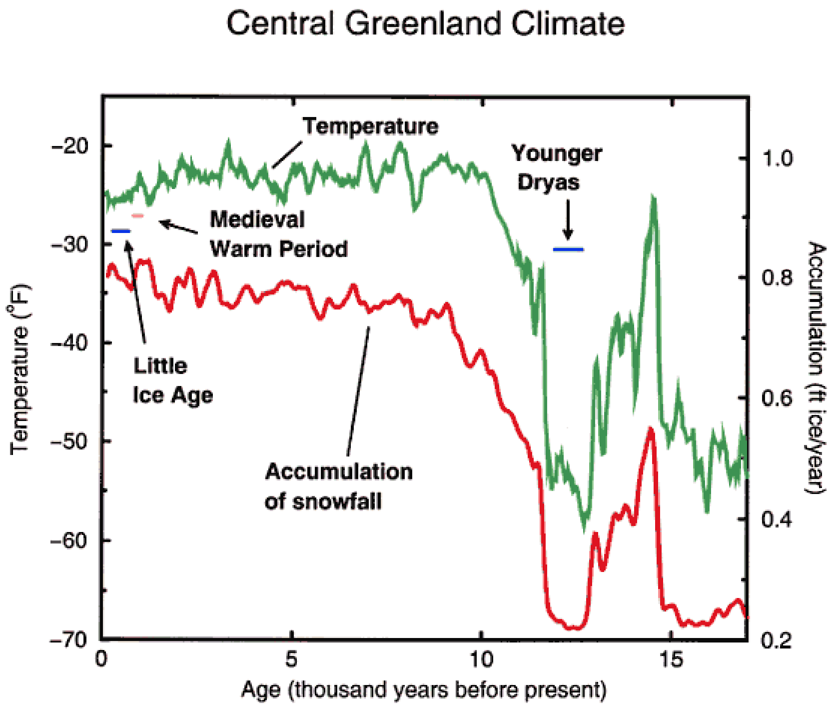


Source:

Riding on the back of these slow, large changes are the abrupt climate changes that have caught so much recent attention. Numerous times, Greenland's temperature jumped many degrees (as much as 16ºC or 28ºF) in decades or even just a few years (Figures 4, 5). These jumps were accompanied by order-of-magnitude changes in dustiness and almost twofold shifts in atmospheric methane. When Greenland was cold and dry, more dust and less methane reached Greenland, indicating generally cold, dry and windy conditions across much of the globe. Greenland's snowfall seems to have doubled in a single year at the end of the Younger Dryas. Abrupt, indeed.

FIGURE 4:

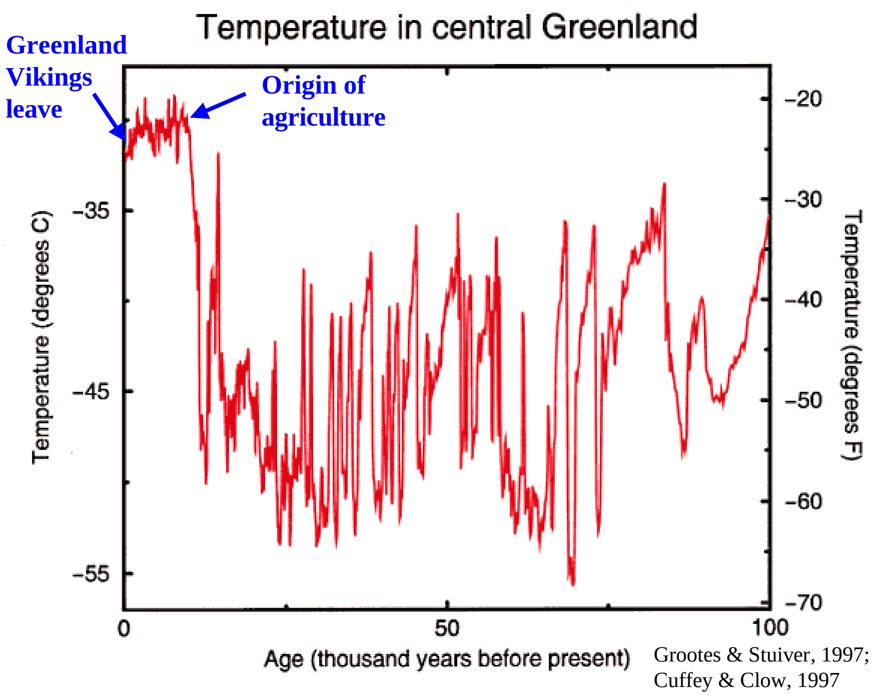
History of Snowfall (Bottom) and Temperature (Top), Somewhat Smoothed, for Central Greenland from the GISP2 Core. Large and Surprising Changes Have Occurred, Including the Younger Dryas Event, Indicated.



Source:

FIGURE 5:

A Longer View of the History of Temperature in Greenland, Showing the Numerous Large and Abrupt Changes (to 16ºC or 28ºF) Riding on the Back of the Ice-Age Cycle.

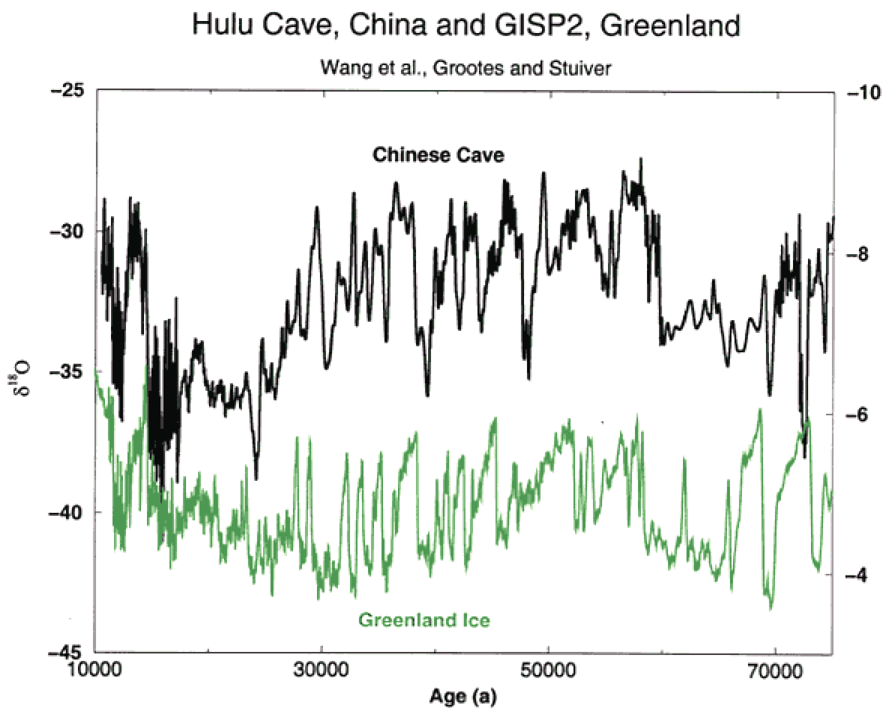


Source: Grootes & Stuiver, 1997; Cuffey & Clow, 1997

While we were working in Greenland, colleagues were still coring into the ocean muds and lake sediments, into trees and cave formations, and developing wonderful new records that confirmed and extended the ice-core data. When Greenland was cold, the monsoons were weaker, causing large areas of Asia (Figure 6) and Africa to dry out. Tropical weather patterns shifted south in the Americas, changing precipitation (4). Importantly, the cold north brought warmth to the far south – providing an essential clue to what had happened.

FIGURE 6:

Cave-Formation of Water Availability in China and of Temperature in Greenland Showing that Cold in Greenland Has Occurred with Dryness in China.



Source: Wang, Y.J., H. Cheng, R.L. Edwards, Z.S. An, J.Y. Wu, C.C. Shen, and J.A. Dorale. 2001. A high-resolution absolute-dated Late Pleistocene monsoon record from Hulu Cave, China. *Science* 294(5550):2345-2348.

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So What?

The evidence is really remarkably clear. Large, abrupt changes across much of the Earth happened repeatedly in the past. Among the many consequences, plants and animals living across most of the Earth were forced to move, often great distances. After an abrupt climate change, life did not continue as usual. The lesson should be obvious – if such a change were to happen today, even our modern society would be affected. We cannot simply pick up and move, because people already live where we would want to go. And other living things can't move easily, either, because our farms and highways are in the way.

The huge ice-marginal lakes that triggered many past cool periods are long gone. Nonetheless, we cannot easily dismiss the record of the past because human activities and natural processes could potentially affect the North Atlantic and the many other “switches” in the climate system.

The North Atlantic switch has been flipped by the supply of freshwater; if there is too much, the waters freeze before they sink, causing cold, dry and windy conditions to prevail in the region. Human society is now conducting a vast experiment with the climate by rapidly pumping carbon dioxide and other greenhouse gases into the atmosphere. Each week, a typical American driver spends $30 or so to put nearly 100 pounds of gasoline into a car, and then turns that gasoline into about 300 pounds of CO_2 that go into the atmosphere. Compared to solid trash, this waste is huge, but we don’t see it or smell it. CO_2 traps heat and warms the planet, just as a blanket traps the warmth of your body in bed. By turning the 500-million-year accumulation of carbon in coal, oil and natural gas into 500 years of easy energy and CO_2 emissions, we are exceeding the planet’s capacity to soak up CO_2. The result will be a high-CO_2 atmosphere (7).

Rising CO_2 will likely bring increased precipitation and melting ice to high latitudes, increasing the freshwater supply to the North Atlantic. Could this extra freshwater change the conveyor circulation? Possibly. Most complex climate models project a slowdown in ocean circulation, without a complete collapse. The slowdown would occur over decades or longer. Most model outcomes suggest that warming would occur in the North Atlantic, but more slowly than elsewhere in and near the Arctic, with higher CO_2 replacing the heat lost as warm ocean currents slow. However, when these models are tested for their ability to replicate past climate changes, they show much skill but tend to underestimate the size or rate of change. When simpler models are used to project future climate, they sometimes produce greater change that includes local cooling around the North Atlantic as the rest of the world becomes warmer. One complex model was programmed recently to simulate a complete shutdown of the North Atlantic circulation. The results included widespread drying, with strong shifts in precipitation patterns much like those of the past and projected reduction in total plant growth on Earth. Although we do not know if the threshold for shutdown of North Atlantic circulation is being approached, we do know that the expected speed-up in fresh water supply from precipitation and ice melt is occurring, with changes in ocean conditions that have surprised oceanographers (8).

Hence, there is a possibility that our activities could shift the North Atlantic circulation and cause large impacts on ecosystems and economies. Most likely, the change will not be as large as past events identified in ice cores, but a change almost as large is not unthinkable. Accurate predictions are not yet possible, but monitoring efforts are underway to detect early indicators of change.

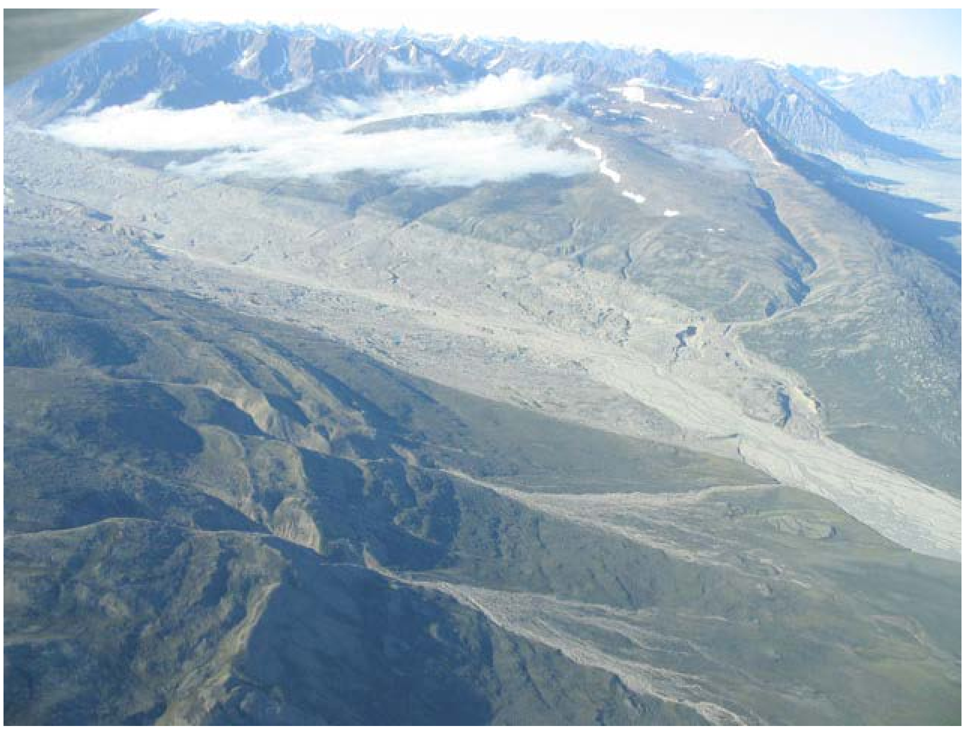
Could there be other surprises out there in the climate system, thresholds that, if crossed, will rapidly switch us into a new and very different pattern? Again, the answer appears to be yes. Consider briefly two of the possibilities: collapse of an ice sheet, and onset of persistent droughts. Both have happened in the past, both could happen in the future, and both are linked again to the oceans.

The ice sheets are perhaps the easiest to understand. At the end of the last ice age, about 30% of the current land area was under ice sheets and sea level was more than 100 m (nearly 400 feet) lower than today. The ocean had retreated far from the modern coastline, and many islands and continents were connected by land bridges. Then, with a change in the earth’s orbit, sunshine rose in the north and atmospheric CO_2 increased (from changing oceanic chemistry and perhaps biology), causing much of the ice to melt. Sea level rose rapidly, averaging about 1 cm per year for nearly 10,000 years and rising much faster at times. About as much land was flooded as was exposed when the ice melted.

Today, about 10% of the land is under thick ice sheets holding enough water to raise sea level more than 70 m (about 230 ft). About a half meter of sea-level rise is locked in mountain glaciers, about 7 m in the Greenland ice sheet, nearly as much in the West Antarctic ice sheet, and the remainder in the largest, coldest ice sheet in East Antarctica. The mountain glaciers have been melting as the world has warmed over the last century (Figure 7), and together with the thermal expansion of the ocean, this has contributed to a sea-level rise of about 2 mm/year (nearly an inch per decade) over the last century. That rate of sea-level rise, though far slower than the peak rates during the last ice age, has contributed to the loss of beaches on the east coast of the U.S., to flooding in Venice and Bangladesh, and to the growing problem of how to keep the ocean out of New Orleans the next time a hurricane strikes (7).

FIGURE 7:

Small Glacier Beyond the Main Ice Sheet, Stauning Alps, East Greenland. During the Ice Age, Everything Shown Was Under Ice. Readvance of the Glacier During the Younger Dryas Produced Prominent Sediment Piles (Moraines) Outlining the Glacier's Extent, Including Those Seen Clearly in the Lower Left of the Photograph. At the End of the Little Ice Age about 100 Years Ago, the Glacier Occupied the Light-Colored Region. Today, the Glacier is Much Reduced, and is Barely Visible in the Upper Left of the Photograph. Water from the Melt-Back Since the Little Ice Age Has Contributed A Little To Sea-Level Rise, As Have Numerous Other Glaciers Melting Around The World..



Source:

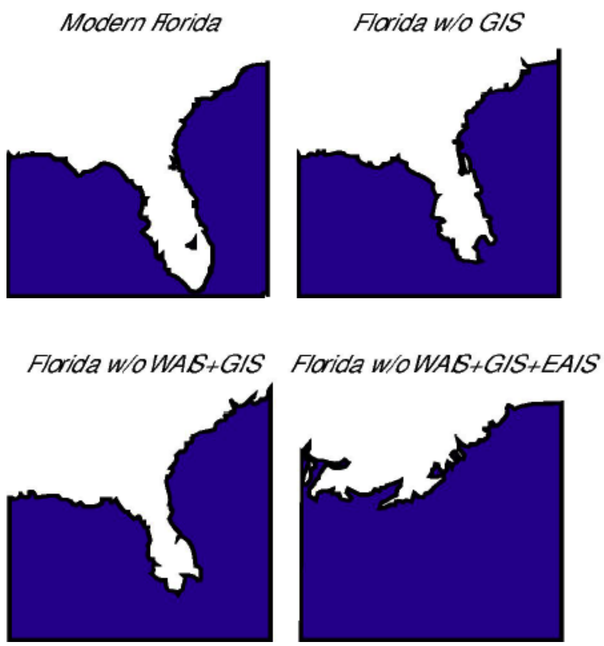
Just a few years ago, it appeared that the great ice caps were not contributing to sea-level rise, but more-recent research shows an acceleration of ice loss from important coastal regions of Greenland and West Antarctica. In Greenland, some of the change appears to have come from increased melting of low-elevation ice near the coast. Also, the extra meltwater may have accelerated ice flow by draining through holes in the ice to the glacier bed and lubricating the ice so it skates more easily over the rock beneath. Both in Greenland and Antarctica, some of the accelerated ice loss has been attributed to the impact of the ocean on ice-sheet margins (9).

Typically, flow from a big ice sheet will not produce icebergs at the site where the ice begins to float. Instead, ice remains attached to the ice sheet and flows out over the ocean to make an ice shelf, with icebergs breaking off at the end of the ice shelf. In many places, these ice shelves exist in embayments; the moving ice must shove past slower-moving ice before making icebergs. In other places, the ice shelves run aground on islands before reaching the calving front. The flanking land and islands help slow the ice flow, pushing back on the non-floating ice. At the same time, ocean water is circulating under the ice shelves. If this ocean water warms, the ice shelf will melt from below and become thinner. Thinner ice may lose contact with islands and weaken at the sides, allowing the ice sheet to spread and make icebergs more rapidly. New research shows that over the past decade, the small ice shelf that helped restrain Jakobshavn ice stream in Greenland has thinned, accelerating what was already the fastest sustained flow of any ice-sheet region on Earth. The same seems to have happened to several glaciers that drain vast regions of the West Antarctic ice sheet into Pine Island Bay, with thinning and speed-up penetrating far into the ice sheet. Along the Antarctic Peninsula, ice-shelf melting from below was augmented by surface meltwater which wedged open crevasses in part of the Larsen ice shelf. The shelf fell apart quickly, over only a few days or weeks, freeing the ice behind it to flow more rapidly.

The total contribution of these events to sea-level rise is not large. But if warming continues and accelerates in the future, larger increases in sea level are possible. In West Antarctica, much larger ice shelves closer to the South Pole appear stable, but could become vulnerable in a warmer world, releasing much more ice into the ocean. In Greenland, if the ice spreads and thins enough, the cold upper reaches will move down into warmer regions where melting occurs. A threshold may be crossed beyond which the ice sheet cannot maintain itself. Loss of an ice sheet such as Greenland or West Antarctica could occur over millennia, but possibly in as short a time as a few centuries. Considering the populations, land area, and value of coastal land (all of Florida south of the Everglades, for example), loss of even part of one of the big ice sheets of Greenland or West Antarctica would be a major event (Figure 8). The most important factor may be the rate at which ocean currents deliver heat to the waters beneath the ice shelves. Note the interesting dilemma in Greenland—rapid melting could be self-limited if the increased fresh-water flow slowed the ocean conveyor, but this could trade sea-level rise for other costly climate changes.

FIGURE 8:

Graphic Illustration of What Might Happen if Greenland Ice Sheet (GIS), West Antarctic Ice Sheet (WAIS), and East Antarctic Ice Sheet (EAIS) Were to Melt. This is Not a Prediction, But Interesting.



Source: Byron Parizek.

Large, abrupt-onset droughts also might be caused if the climate system is pushed across a threshold. Although somewhat less global in impacts than a conveyor shutdown or ice-sheet collapse (and further removed from my primary expertise), droughts are of great interest. Droughts have afflicted humans in the past, often causing serious reversals of fortunes. Collaborations between paleoclimatologists and archaeologists have uncovered links between drought and the decline of earlier civilizations including the ancestral Puebloan (Anasazi) peoples of Mesa Verde and other enclaves in the southwest U.S., the Mayans of Central America, and the Akkadians in the Middle East. Weather has not been monitored with sophisticated instruments long enough to understand the extent and lengths of droughts, but tree-rings and other records indicate that mega-droughts in several regions have lasted decades or centuries. The Dust Bowl of the North American Great Plains during the 1930s appears as a short, small event in some drought records, compared to the much longer and larger events centuries or millennia earlier. (10)

Some aspects of droughts are easy to understand. Random variability can cause a drought in a region that on average gets just enough rainfall. When the climate warms, evaporation is higher and the time from the last rainfall to the onset of plant wilting and drought is shorter. This is observed in many climate models which project that drought will become more common and severe in grain-growing regions even though rainfall is likely to increase globally. Much of the rainfall in regions such as the Great Plains originates from water evaporated from plants, water that was drawn out of the soil by plant roots. If plants wilt, there will be less evaporation, with water instead seeping through the soil and eventually reaching streams. Hence, when plants wilt due to heat and lack of rain, the reduced evaporation further diminishes rainfall.

An important observation is that the oscillations in the Pacific Ocean associated with the El Niño phenomenon are major causes of droughts. Changes in sea-surface temperatures affect the paths followed by storms. Under La Niña conditions, warm waters amass in the western equatorial Pacific and bring drenching rains to Indonesia and parts of Australia, while cold waters off Peru suppress evaporation and storm formation, bringing dry conditions. But if the trade winds slacken, the warm waters spread east, and South American rain is joined by Indonesian and Australian drought. Furthermore, circulation patterns shift southward to the Antarctic and northward into the U.S., affecting weather patterns and bringing droughts to some regions and floods to others (11).

During past centuries, El Niños have come and gone, without getting stuck in one mode for more than several months or a year or two. Paleoclimatic records indicate that the size and persistence of El Niños have varied over geologic time, and vigorous research is now directed towards learning what is possible and likely in the future.

In addition to El Niño, more subtle patterns of persistent sea-surface-temperature anomalies have been observed. Some might be linked in some way to El Niño, but the patterns are not as well understood. Recently, researchers have used measured patterns of sea-surface temperatures to force atmospheric models. The striking result is that the history of the Dust Bowl is simulated rather accurately and seems to result from subtle, degree-or-less anomalies in the Pacific temperatures. Similarly, African Sahelian drought of previous decades may be explained by sea-surface-temperature anomalies in nearby oceans, with a little help from the effects of pollution on weather patterns (12).

Now What?

So what is one to make of all of this? People are affected by climate, but still manage to live in climates ranging from the frozen Arctic to the steamy tropics. Humans survived past climate changes and will survive changes in the future, but those past changes often caused great difficulties, and we are justified in worrying about future changes. We are rapidly pushing the Earth’s climate in a new direction by fundamentally changing the environment through activities such as cutting forests, damming rivers, paving landscapes, and burning fossil fuels. We will not be able to precisely predict all the changes this will bring, but it is highly likely that average global temperatures will be higher, with consequent changes such as sea level rise. How much warmer probably depends mostly on whether we get serious about finding alternatives to burning fossil fuels to reduce the build-up of atmospheric carbon dioxide. Such alternatives might include energy conservation, switching to non-carbon-producing energy sources, and sequestration of carbon dioxide captured at the source or from the atmosphere (13).

Looking back, we find that temperatures have risen as carbon dioxide in the atmosphere has increased (eg., Figure 2). The greenhouse gas effect of carbon dioxide provides the best explanation of those temperature changes, supporting future projections of a warmer climate. But we also find that strange things have happened—huge and abrupt shifts in climate over much of the world, ice-sheet collapses speeding sea-level rise, persistent droughts, and more. Many abrupt changes can be explained by mechanisms that appear to have brought the climate system to a threshold, after which the climate changed rapidly, often in a surprising direction. As we face a future of great change, it is worth remembering this past strange behavior and the possibility that we might trigger an abrupt change that could present more of a challenge than gradual change. It also seems prudent to include the possibility of such strangeness, of abrupt climate change, in assessing what if anything should be done about the production of greenhouse gases.

The remarkably intertwined nature of the Earth system is illustrated clearly by the abrupt climate changes of the past. Even a simple discussion of climate change quickly raises numerous questions about everything from ocean mixing to plant roots. As a specialist in ice, the important role played by ice in causing, amplifying, and recording the past convinces me that there is much more to learn, and I encourage students to pursue research in this area. I am struck by how important the oceans have been in this story; putting a fresh-water and sea-ice cap on the North Atlantic has repeatedly arrested the Asian monsoon, and even subtle changes in Pacific temperatures have contributed to massive social disruption thousands of miles away.

I remain optimistic about society's ability to address the environmental challenges arising from climate change. We have faced a great range of previous environmental problems, responding globally to the ozone hole and regionally to phosphate pollution in Lake Erie. Good ideas have often had unexpected consequences (new refrigerants and ozone destruction, or better detergents and overfertilization of lake ecosystems). As I remember, a vigorous and often acrimonious public debate followed in which science only occasionally played the leading role. Those who advocated cleaning up the problem were usually opposed by arguments that: i) there really isn't a problem; and ii) if there is a problem, nature is doing it, not humans; and besides, iii) it would be too expensive to clean up the problem, anyway. Soon after, however, a novel solution appeared (low-phosphate detergents, or ozone-friendlier refrigerants), the problem was greatly reduced or eliminated at relatively low cost, new industries or products provided employment and contributed to the economy, and we are left wondering why we thought the problem would be so hard to fix. Other such environmental threats, including the effects of DDT on bird eggs, acid rain, and lead from gasoline, also have been reduced with much less pain and agony than some predicted. I even have the nagging suspicion that the solutions often came from industries that, until they had the solutions in hand, were busily arguing that solutions were neither possible nor necessary.

We would never consider going back to the old "look out below" system of dumping chamber pots out the window, but real investments were required to get indoor plumbing, sewers, and sewage-treatment plants – a sanitation system that remains scarce in some parts of the world. Nor are we likely to go back to previous high levels of lead, DDT, phosphate, acid rain, or chlorofluorocarbons.

Similarly, I am optimistic that our great-great-great grandchildren will control atmospheric carbon dioxide at levels to suit themselves. Professionals will prosper in new industries developed to meet the challenge of managing greenhouse gases. This is not a scientific judgment based on detailed study, of course; it is the opinion of one scientist who was fortunate enough to be given the lectern for an exciting hour.

But to get to this future, we should foster the genius of humanity to understand energy options and engineering, to devise new technologies, and to understand the climate system well enough to know what we want and how to get there. These are among the great challenges facing humanity, and they will be met better if our students are better supported in their endeavors.

Notes and References

1. Weart, S. 2003. The discovery of rapid climate change. *Physics Today* 56(8):30-36.

2. Much has been written about Greenland ice cores, spanning at least hundreds and perhaps thousands of scientific papers now. I am biased in favor of the popular account in:
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   The preface (Hammer et al., 1997) and articles in *Journal of Geophysical Research-Oceans* 102(C12) provide a more detailed starting point to the literature:
   Hammer, C., P.A. Mayewski, D. Peel, and M. Stuiver. 1997. Preface to Greenland Summit Ice Cores. *Journal of Geophysical Research-Oceans* 102(C12).

   The paper by Severing et al. (1998) is especially relevant in showing how widespread and abrupt the climate changes were.
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3. For some insight into controls on atmospheric carbon-dioxide concentrations over ice-age cycles, see:
   Broecker, W.S., and T.-H. Peng. 1998. *Greenhouse Puzzles*, 2nd ed. Eldigio Press, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY.

   One partial explanation of how reduced northern sunshine led to lower carbon-dioxide concentrations and global cooling, involves the ability of dust to fertilize the ocean, stimulating the growth of plants that remove carbon dioxide from the atmosphere. Most land, hence most dust, is in the northern hemisphere. The cooling and drying associated with reduced northern sunshine increase the delivery of dust to the ocean. For additional insights on ice-age cycles, see my book (2), or:
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   Cronin, T.M. 1999. *Principles of Paleoclimatology*. Columbia University Press, NY.

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National Research Council. 2001. Climate Change Science: An Analysis of Some Key Questions. National Academies Press, Washington D.C.

8. The IPCC includes assessment of the future of ocean circulation. Also see:
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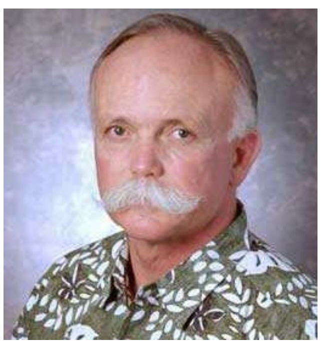
Admiral James D. Watkins
Chair, U.S. Commission on Ocean Policy
Our Oceans, 2003

Good science and good policy are inextricably intertwined. Nowhere is this more evident than in the area of ocean policy. Decisions are made every day with important economic and environmental consequences: How many fish should we catch? Where and how should we extract critical resources from the sea? How can we promote coastal tourism without damaging the very resources people come to enjoy? What kinds of climate change and fluctuations can we expect in the short and long term? None of these questions can be answered without a strong understanding of ocean and coastal processes and a robust observing system to monitor the ocean realm. Based on his lifetime of public service, his well-known passion for science and the sea, and his current role as Chair of the U.S. Commission on Ocean Policy, Adm. Watkins will discuss ways to strengthen the links between scientists, regulators, and policymakers for the good of the nation.

Sponsored by: The Office of Naval Research; The U.S. Geological Survey; The Scripps Institution of Oceanography.



Dr. Michael K. Orbach
Director, Marine Laboratory
Duke University
Beyond The Freedom Of The Seas: Ocean Policy for The Third Millennium, 2002
Up until the end of the first millenium anno Domini humans used the oceans primarily at their margins, lacking the desire or the ability to venture further out to sea. In the second millenium humans exploded in their exploration of the seas, crossing, charting and beginning to exploit the spaces and resources of most of the world's oceans, at least to the depth of a few hundred fathoms.

In the last half of this second millenium, the formal doctrine of mare liberum, "freedom of the seas", emerged under which most uses of the world's oceans remained unregulated within any common community except for the constraints of individual nation states upon their own citizens. This "freedom of the seas" doctrine emerged for a very practical reason: No single nation or group of nations could effectively either monitor or control activities on the oceans except within fairly close proximity to land, and thus the "freedom" approach emerged as the negotiated compromise. Incursions have been made into this "freedom", notably in the 200-mile extensions of jurisdiction among coastal nations in the 1970s and 80s and in such proposals as the Common Heritage of Mankind approach to ocean resources advanced during the United Nations Law of the Sea negotiations. However, most of the world's oceans still remain in a state of "freedom" as an unregulated commons.

This "freedom" has had tragic consequences for many of the living marine resources and for water quality and habitat of the world's oceans as well as promoting unnecessary competition and conflict over ocean space and resources. We now have the technological capability to monitor and, if we wish, control human activities virtually anywhere on the world's ocean. This presentation will present alternative futures for the governance of the world's oceans and their resources, "beyond the freedom of the seas" and into the third millenium.

Sponsored by: The National Science Foundation; The Office of Naval Research; The U.S. Geological Survey; The Scripps Institution of Oceanography.

Dr. Marcia K. McNutt
President and CEO
Monterey Bay Aquarium Research Institute
Ocean Exploration, 2001

The ocean is essential to life on Earth: it is Earth's largest living space and contains most of its biomass. The ocean moderates climate to keep Earth habitable, recycles our wastes, and provides an inexpensive source of protein to fee the global population. Yet 95 percent of the ocean remains unknown and unexplored. Now, thanks to a number of technological innovations, we have the tool necessary to undertake a systematic exploration of the ocean. Autonomous vehicles can be programmed to execute precise underwater surveys lasting up to week without pause. Remotely operated vehicles equipped with physical, chemical, an biological sensors function as our eyes, ears, noses, and hands in the deep sea. New data management systems permit the systematic archiving of information, allowing subsequent generations of researchers around the world to answer questions not contemplated at the time the data were collected. Much has been learned about the oceans through traditional research programs. But research is different from exploration. While research attempts to find answers, exploration inevitably uncovers new questions. Ocean exploration brings great, but often unpredictable, rewards: cures for diseases from novel biological compounds, untapped mineral, energy, and biological resources, new insight into how the ocean functions, geological and biological vistas of unsurpassed beauty, and renewed appreciation for mankind's maritime past. The time is ripe to launch a major international program of ocean exploration with all the benefits it will bring.
Sponsored by: The National Science Foundation; The Office of Naval Research; The U.S. Geological Survey; Scripps Institution of Oceanography; and Woods Hole Oceanographic Institution.

Dr. Shirley A. Pomponi
Director, Division of Biomedical Marine Research Harbor Branch Oceanographic Institution
The Oceans and Human Health: The Discovery and Development of Marine-Derived Drugs, 2000

The oceans are a rich source of both biological and chemical diversity. During the past two decades, thousands of novel marine-derived biochemicals have been identified. Many have the potential for development as new pharmaceuticals to treat diseases such as cancer and drug-resistant infections. The challenges facing continued discovery are both technical, such as developing new tools to explore habitats and collect and test organisms never before studied, as well as political, such as complying with regulations related to the rights of a country to its natural resources. Successful discovery and development of marine derived pharmaceuticals will depend on our ability to address a number of questions. What organism produces the bioactive compound, and why? Can we apply this knowledge to our rapidly increasing understanding of the human genome and human disease processes? Are there viable alternatives to harvesting for sustainable use of marine natural resources for drug development? And finally, what constitutes a fair and equitable sharing of revenues resulting from commercialization of marine resources, as mandated by the U.N. Convention on Biological Diversity? Addressing these questions will require the collaboration of marine and biomedical scientists and the cooperation of industry and government.

Sponsored by: The National Science Foundation; The Office of Naval Research; The U.S. Geological Survey; Scripps Institution of Oceanography; and Woods Hole Oceanographic Institution.

Dr. Peter Brewer
Senior Scientist
Monterey Bay Aquarium Research Institute
Contemplating Action: Storing Carbon Dioxide in the Ocean, 1999

Concerns about global climate change suggest that we should level off, or even decrease, atmospheric carbon dioxide. Recent advances in ocean science hint at the possibility of taking active steps to achieve this. Experiments have shown that it is possible to inject carbon dioxide directly into the deep ocean, where it forms a solid gas hydrate. Other options have also been explored, such as fertilizing seawater to speed up the growth of microscopic plants that consume carbon dioxide. If we want to hold carbon dioxide levels steady, large interventions will be necessary. Is this even possible? And would there be unforeseen environmental consequences? Forty-two years after Roger Revelle's analysis of the “greenhouse” problem, society may be ready to take action through active use of the enormous buffering capacity of the ocean.

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