FOIA Number: 2012-0769-F

FOIA MARKER

This is not a textual record. This is used as an administrative marker by the William J. Clinton Presidential Library Staff.

Collection/Record Group: Clinton Presidential Records

Subgroup/Office of Origin: Council on Environmental Quality

Series/Staff Member: Kathleen (Katie) McGinty

Subseries:

OA/ID Number: 2615

FolderID:

Folder Title:
Oceans Hearing

Stack:	Row:	Section:	Shelf:	Position:
S	61	5	7	1

MEMORANDUM
MAY 18, 1992

TO: DEMOCRATIC MEMBERS, SENATE COMMERCE COMMITTEE

FROM: ANTHONY SOCCI AND MIKE NELSON

RE: MAY 20 HEARING ON GLOBAL WARMING AND THE OCEANS

On Wednesday, May 20, 1992, the Full Committee will hold a hearing on global climate change and the oceans. The hearing will be held at 2:00 p.m. in SR-253, the Commerce Committee hearing room. Senator Gore, Chairman of the Science, Technology, and Space Subcommittee, will preside. Rather than following the usual hearing format, witnesses and Committee Members all will join in a roundtable discussion.

BACKGROUND ON GREENHOUSE WARMING

There is a growing consensus among researchers that human activities are enhancing the Earth's "greenhouse effect," inevitably leading to an increase in the Earth's average temperature. Scientists have been studying the greenhouse effect for more than one hundred years, and there is general agreement on the main point of the theory--that small concentrations of so-called "greenhouse gases" in the air, most notably carbon dioxide (CO_2) and water vapor, absorb infrared radiation from the sun, trapping heat in the Earth's atmosphere that otherwise would radiate back into space. The natural greenhouse effect keeps the Earth almost 35^o C (63^o F) warmer than it would be otherwise.

The burning of fossil fuels and deforestation have been adding billions of tons of carbon dioxide to the atmosphere every year, and if present trends continue, the concentration of carbon dioxide in the atmosphere will double by the year 2030. To study the effects of increased concentrations of carbon dioxide and other greenhouse gases, atmospheric scientists have constructed computer models. Most of these models predict a warming of between 1.5^o and 4.5^o C (3^o-8^o F) for a doubling of CO_2 concentration, although how quickly this warming would occur is still debated. A global increase of even two degrees Celsius would lead to significant changes in regional climate and have huge economic and societal impacts. Eliminating the threat of global warming would necessitate major changes in energy use and agricultural practices in the United States and worldwide.

Various agencies within the Committee's jurisdiction have responsibility for research on global warming. The National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the National Oceanic and

Atmospheric Administration (NOAA) are responsible for most of the Federal government's effort to understand and assess global warming and other aspects of global change. They are the principal participants in the multi-agency U.S. Global Change Research Program, for which the Administration is requesting $1.37 billion for fiscal year (FY) 1993.

OCEANS AND CLIMATE

Covering almost 70 percent of the Earth's surface, the oceans act as a giant flywheel in the planet's climate machinery. Coupled with atmospheric circulation, ocean currents are a transport system that carries heat from the Atlantic to the Pacific Ocean and from the equator to polar regions. This redistribution of heat by the oceans and atmosphere determines global climate patterns. The temperate climate of northern Europe, for example, is a result of heat released from Atlantic surface waters as they move northward. The ocean current system acts as a huge global conveyor belt, containing 20 times as much water as all the world's rivers combined.

Over the past 10 years, oceanographers have greatly expanded our understanding of the oceans and their complexity. Using satellite imagery, more sophisticated sensors on boats and buoys, and supercomputers to collect and model their data, researchers are developing the ability to predict ocean circulation and how it influences world climate. Still, many uncertainties remain, and numerous research programs to collect and model more data are underway or in the planning stages.

PREDICTING CLIMATE CHANGE AND OCEAN ACTIVITY

To provide predictions of the amount and rate of greenhouse warming, researchers have developed elaborate computer models which attempt to mimic the complex processes that influence climate. Early computer models of greenhouse warming developed in the 1970s and 1980s modeled how the atmosphere alone would respond to an increase in the concentrations of greenhouse gases. For the most part, these models used an extremely simplistic approach to predicting how the oceans would change in response to increased greenhouse gas concentrations and increased atmospheric temperatures. This shortcoming led many to question the results of the models and caused researchers to work on developing more realistic computer models of the oceans which could be combined ("coupled") with the models of the atmosphere.

It is much more difficult to model the oceans than the atmosphere because, although many of the equations and computer algorithms are similar, ocean circulation and ocean chemistry vary in terms of the length of time associated with change, depending on where the activity occurs. For instance, while conditions at the ocean surface can change in just a few hours, change in the deep ocean is more likely to take centuries. Incorporating this complexity into computer models, even with the largest supercomputers, is very challenging, and as a result, models of the oceans are less realistic and less reliable than those of the atmosphere.

Models of how the oceans will respond to greenhouse warming must incorporate both how it stores and transports heat and how it influences atmospheric concentrations of greenhouse gases like carbon dioxide. This requires taking into account a host of physical, chemical, and biological processes.

THERMAL INERTIA OF THE OCEANS

Because water absorbs much more heat than air, the oceans act to moderate the Earth's climate. This is why coastal cities tend to have much more mild climates than cities further inland. As the atmosphere warms due to increased concentrations of greenhouse gases, the oceans' "thermal inertia" (resistance to being heated or cooled) will tend to slow down global warming, just as the thermal inertia of brick buildings tend to keep the air inside cool in the summer.

Many who question the reality of greenhouse warming ask why the 25% increase in the concentration of greenhouse gases during the 20th century has not resulted in an immediate increase in global temperature. The explanation is probably that the oceans' thermal inertia has delayed much of the warming predicted by earlier calculations. However, eventually the oceans will warm since they cannot absorb heat indefinitely.

OCEANS AS A SOURCE AND SINK OF GREENHOUSE GASES

The oceans also can influence the rate and amount of greenhouse warming by absorbing or releasing greenhouse gases like carbon dioxide, nitrous oxide, or methane. Of these gases, carbon dioxide is by far the most important with respect to global warming.

In all, the oceans contain more than 50 times as much carbon as the atmosphere. Thus, one would assume that a small change in the amount of carbon in the oceans can have a major impact on the concentration of carbon dioxide in the atmosphere. If this were the case, the oceans would be able to absorb most of the carbon emitted by the burning of fossil fuels. However, this is not entirely accurate. Most of the oceans' carbon dioxide is dissolved in water of the deep ocean where it is essentially isolated from the atmosphere. It typically takes thousands of years for water in the deep ocean to circulate to the surface.

In contrast, there is a constant exchange of carbon dioxide and other gases between the atmosphere and the upper 100 meters of the oceans. This so-called "mixed layer" acts as a "sink" for carbon, absorbing roughly 2 billion tons (30%) of the approximately 7 billion tons of carbon added to the atmosphere each year by the burning of fossil fuels and deforestation. However, the processes by which this carbon is absorbed are very complex and not well quantified. Many factors -- including temperature, wind speed, and biological activity -- influence the amount of carbon dioxide absorbed.

Researchers are working to determine how increased temperatures due to global warming will influence the absorption of carbon dioxide. As the temperature of water increases, the amount of gas it can dissolve decreases (as when soda warms up on a hot day). Thus, all other factors being equal, researchers expect the oceans to absorb less carbon dioxide as temperatures rise, and there is the possibility that, if temperatures rise enough, there will come a point where the oceans will be unable to absorb any more carbon.

OCEAN CIRCULATION

Ocean currents play a key role in the climate system by moving heat from the equator to the poles. They also redistribute salts and gases dissolved in the oceans, both vertically and horizontally. The composition of sea water, particularly the concentration of oxygen, carbon dioxide, and nutrients, controls the growth of plant and animal life, which in turn can affect the composition of the atmosphere and oceans. Improving our models of global warming will require taking into account ocean circulation on all scales. This consideration will require both more sophisticated computer hardware and software and more data on the temperature and composition of the oceans.

The ocean is subdivided into three distinct layers: 1) a mixed layer at the surface, mixed largely by wind and housing most of the plant and animal life of the ocean (including the plankton which form the base of the oceanic food chain and constitute most of the biomass of the oceans) -- this is also the zone of photosynthesis, below which light cannot penetrate; 2) an intermediate zone of warm water extending down several hundred meters; and 3) the colder deep ocean which makes up roughly 80% of the oceans' volume -- the deep-ocean layer has a relatively constant temperature of about 2^{o} C.

Each of these layers varies in temperature and salinity. These variations drive currents, including the so-called "great ocean conveyor" in which cold, salty surface water in the North Atlantic sinks into the deep ocean. The details of oceanic circulation are not well known, and are currently being investigated as part of the World Ocean Circulation Experiment (WOCE) Program and other international research programs.

NON-LINEAR BEHAVIOR OF OCEANS

It is now becoming increasingly clear, both from computer models of ocean circulation and from studies of the Earth's past climate ("paleo-climate") as recorded in the geological record, that ocean currents can change quickly and dramatically in seemingly unpredictable ("non-linear") ways. Apparently, ocean circulation can re-organize itself totally on a global scale, within less than 100 years, with profound effects on climate.

Using data on past climate derived from ice cores, researchers have argued that in the past changes in wind patterns have affected the rate of ocean circulation at the surface, triggering a wholesale restructuring of the chemistry of the upper ocean. During the last Ice Age, it is thought that such a reorganization led to a 30% decrease in the atmospheric concentration of carbon dioxide.

KEY QUESTIONS

How much will the thermal inertia of the oceans slow the onset of greenhouse warming? According to most calculations, the oceans can slow global warming by 20-100 years. This time lag means that even if the Nation were to reduce dramatically its energy use, and the concentration of greenhouse gases stopped increasing, global temperatures probably would continue to rise for at least 50 years.

Will the oceans continue to absorb a large portion of man-made greenhouse gases, especially carbon dioxide? Researchers are trying to determine whether there is a limit to the oceans' capacity to absorb carbon dioxide. Unfortunately, scientists are still not sure how and where the oceans absorb carbon dioxide. Even less is known about the behavior of methane and nitrous oxide, two other important greenhouse gases, although the work that has been done indicates that the oceans are minor sources of both.

How will changes in ocean temperature and ocean circulation affect marine ecosystems, and how will that in turn affect global climate? Marine ecosystems are very sensitive to the temperature and concentration of nutrients and gases like oxygen and carbon dioxide. Changes in ocean circulation due to global warming could decimate important marine fisheries. Potentially even more important, they could decrease the productivity of plankton, which play a role in absorbing carbon dioxide from the atmosphere. The ability of ecosystems to deal with the effects of global warming may be further compromised by marine pollution, especially in coastal oceans.

Is it possible that the oceans might begin to give up some of their carbon dioxide, thus exacerbating global warming already in progress? What are the climate model predictions? If the surface of the oceans warm, a release of carbon dioxide from the oceans would be consistent with calculations because, as the oceans warm, gases become less soluble and are therefore released into the atmosphere.

How sensitive are the oceans to changes in climate, and what is the likelihood of dramatic changes in ocean circulation? The history of the oceans and climate suggests that the oceans, and hence climate, are extremely sensitive to disruption, often with unpredictable and abrupt consequences.

Are Federally-funded research programs sufficiently funded and focused to answer the key questions regarding the oceans and greenhouse warming? Both NOAA and NSF play an important role in funding oceans research. Unfortunately, for the last two years, Congress has been unable to provide the requested increase in funding for NOAA's global change research program, which many researchers believe has affected adversely U.S. research on oceans and global change.

WITNESSES

There will be one panel of witnesses. Each witness will provide a three-minute summary of his or her research and its implications. All the participants then will join in a roundtable discussion.

Dr. James Kasting, Department of Geosciences, Pennsylvania State University, has modelled the changes in the composition of the atmosphere and investigated geochemical cycles relating to climate changes. **Dr. Scott Lehman**, Department of Geology and Geophysics, Department of Geology and Geophysics, Woods Hole Oceanographic Institute, has been investigating the oceanic history of abrupt circulation and climate changes. **Dr. James McCarthy**, Director of the International Geosphere-Biosphere Program and Chairperson, Department of

Organismic and Evolutionary Biology at Harvard University, is a biological oceanographer doing research on oceanic carbon and life systems, particularly as they relate to climate. **Dr. Michael McElroy**, Chairperson, Department of Earth and Planetary Sciences, Harvard University, has been investigating ocean-atmosphere climate interactions for many years, and is well-versed in the paleo-climate record as well. **Dr. Thomas Stocker**, from Switzerland and presently a Visiting Research Associate Scientist at the Lamont-Doherty Geological Observatory of Columbia University, is an ocean circulation modeller with particular expertise in rapid changes in circulation and their climatic implications. **Dr. John R. Toggweiler**, from NOAA's Geophysical Fluid Dynamics Lab at Princeton University, has developed coupled models of the ocean and atmosphere with which to investigate the effects of circulation changes on climate. **Dr. Xiao-Hai Yan**, Associate Director, Center for Remote Sensing, College of Marine Studies, University of Delaware, has been investigating a so-called "hot spot," a region of unusually warm water that has formed recently in the western Pacific ocean.

M E M O R A N D U M

DATE: May 15, 1992

TO: Al, Katie

FROM: Tony Socci

SUBJECT: Summary of oceans hearing as it presently stands

Breakdown of witnesses and testimony which I think they will deliver:

Dr. James McCarthy - Harvard Univ., Dir. of the International Geosphere-Biosphere Program. Jim is a biological oceanographer. He will focus in on the possible role of the biosphere within the ocean in climate change. He will also be capable of discussing the role of oceans as a sink and as a source for CO-2. Politically he and Wally Broecker do not see eye to eye on many things. There's no love lost bewteen the two. Wally considers the role of the biosphere in absorbing or giving up CO-2 two is minimal. McCarthy strongly disagrees, but it's personalities as well. However, Wally will not be present anyway, but there is something called a Lamont-Doherty perspective on oceans, etc., which is not nec. shared.

Dr. Michael McElroy, Harvard Univ., Chair, Dept. of Earth and Planetary Sciences - Mike will be in a position to do many things. He has broad knowledge of the climate history of the oceans and is an atmospheric chemist by training, in addition. He can specifically address the rapidity with which oceans can change completely, and the climatic implications of such convulsions. Mike will also be able to lay out, in some detail, Ed Boyle's alkalinity hypothesis on circulation-rate driven changes in ocean chemsitry (chemical restructuring of the oceans), the rate at which this appears to have occured (does occur), and the exchange of gases between the oceans and the atmosphere, which takes place, hence climate change.

Mike and others present will be able to address the fact that this mechanism involves an initial, rapid (a couple of hundred years) exchange of some volume of greenhouse gases between the atmosphere and the oceans (appx. 30 ppm CO-2), followed by a longer term. additional drawdown of from the atmosphere due to the chemical restructuring of the oceans and the consequent dissolution of deep-sea/shelf carbonate rocks/limestone/coral, etc.. This dissolution utilizes some volume of available dissolved CO-2 in the ocean, thus the need for that CO-2 to be replaced by a transfer of about 15 ppm of additional CO-2 from the atmos. to the oceans, bringing the total CO-2 exchnaged up to appx. 45ppm. The exchange driven by the dissolution, involving 15 ppm, appx., takes on the order of 2000 yrs. to 6,000 yrs. And there's more which Wally Broecker has added to Boyle's picture, as well as what Mike himself has added, especially most recently.

Robert Toggweiler, Coupled ocean-atmosphere-deep-sea sediment climate modeler at The Geophysical fluid dynamics lab at NOAA. Robert will be in a position to address many aspects of the ocean as a climate driving system and as a response to climate, with additional feedbacks. He, as others, will address the oceans paleo record of abrupt changes in circulation and the climatic consequences. He, as others, will also address the extreme sensitivity of oceans to any climate forcing/approaching thresholds, and the consequences with respect to climate and life. Robert has also extended the work of Boyle and Broecker, in suggesting that circulation changes alone (density and/or wind-driven) can, and may have, produced many changes in the ocean, including the exchnage of gases with the atmosphere, and therefore climate, again quite rapidly as well. This is a very bright person. Robby can also be in a position to discuss the history of ocean/climate models and the evolution of these models as a consequence of knowledge gained from the ice-core records. This historic chronology is extremely important Al to understand the whys of the present generation of models and thinking. I reiterate that I think this chronology is vitally important to lay out cold. It ties many things together. He, like others on this panel, will also address the uncertainty and multiplicity of potential and real feedbacks here, all with climatic implications.

Robby will lay out the work of Sarmiento as well, who recently stated that the so-called missing sink of C may not be as large as was originally thought, and that much of the missing C is not in the oceans. He can also address the point that there is no reason why any natural systems will uptake, naturally, all of the so-called excess, anthropogenic carbon. The oceans could, in fact, give up carbon, particularly if warmed, thus be a source of atmos. C as well, a positive feedback to warming.

Robby is also in a position to talk about the work of Manabe at Princeton's GFDL, perhaps the world's premier and brightest climate modeler of coupled systems. Manabe has recently played the following game which has significant implications in my mind:

Manabe recently decided to look at the non-equilibrium response of the oceans to the loading of the atmosphere with CO-2 (loading of the atmosphere by industrial output exceeds rate at which oceans can achieve equilibrium on this scale of time), taking one of the IPCC climate change scenarios for the next two hundred years or so. In this model run he incrementally added CO-2 in small amounts per year, for two hundred years. The non-equilibrium climate response was that the ocean surface gradually warmed and the climate got warmer. Additional water vapor was added to the atmosphere by this warming, as other GCM's have already indicated.

However, sometime after 200 years of this model run, the ocean began to equilibrate with the loading of greenhouse gases and the climate forcing due to greenhouse gases. The warming led to increased warming at poles, consistent with GCM's, and melting of polar ice sheeets, and s.l. rise. However, because of this new volume of available fresh water from this melting ice, of lower density than sea water, the ocean circulation stops (an extension of Broecker's so-called conveyor belt/heat pump). This leads to a stratification of the oceans (not all circulation need stop). It is however this configuration which leads to the sequestering of C from the atmosphere into the oceans, as others have described the consequences of the turn-on and off of the NADW system during glacial stages of the past. Thus he is describing a negative feedback to climate warming via this mechanism. How much C will be drawn down? According to ice-core records, appx. 90 ppm, but who really knows because of our charging the atmos. with so much greenhouse gas? Eventually, if climate cools enough and ice sheets expand the NADW starts up again, implicitly with the reverse of the above. Thus you see, there is a transient, non-equilibrium response to climate forcing here, followed by an equil. response. The feedbacks are many and complex, and largely unknown, especially the magnitude.

[illegible]

[illegible]

To the above I would add the following. Given the volume of greenhouse gases in the atmosphere, it is not clear, even if this heat pump is started again, whether it can overcome the warming effect of the greenhouse gases at all. Secondly, as the ocean surface warms, since gases are more soluble in cold water than in warmer, there is an outgassing of some gases from the ocean to the atmos. - positve feedback to warming. Third, if oceans truly stratify, the recycling within the oceans of that volume of nutrients responsible for the 30% C which the ocean biosphere represents, sinks to the bottom and is no longer available. This means that the carbon held by the biosphere can now return to the ocean floor as organic C or go off into the atmos. as CO-2, or both, thus warming again, and huge implications for food and life. These are valid concerns about the feedbakcs here Al.

Dr. Xiao-Hai Yan, College of Marine Studies, Univ. of DE. He has reported the hottest spot in the ocean ever recorded, off in the western pacific. He has also monitored its temp.

and size/area over past 10 yrs., over which time he records a .35 degree C rise in sea surface temp. and an increase in size of heated area of water. The reason: I don't really know. He wants to attribute to global warming. Others suggest possible coupling to el nino southern oscillation.

Scott Lehman from Woods Hole Oceanog. Inst. He will reveal to us a new, highly resolved record of extremely rapid climate changes, changes in ocean system, on a timescale of tens of years to centuries. He reports many, abrupt chnages in ocean circulation/climate within a timespan of 40 years along, with great, tighlty calibrated records of time, synchronized with a new, more highly calibrated ice-core timescale as well. He can nail down the rapidity with which oceans turn and climate changes, and the danger of approaching thresholds which we know nothing about. He, as others, will address and re-address the enormaous sensitivity of the oceans to any climate forcing.

Scott will also bring to this hearing a new record of the calibration of temperature changes and CO-2 changes in the paleo record. In new, highly revised, highly resoved chronology within ice cores and deep-sea sediments now shows that there seems to be a very tight coupling between changes in atmos temp and changes in CO-2. And, contrary to the repeated assertions of Lindzen and others, that these ice core records show that temp changes often lead CO-2 changes, this new data says that's bullshit. ~~The~~ real problems with the chronology of the ice core records was the manner in which the calibration of the temporal record of ice was being conducted, as most scientists knew or sensed. Thus, anyone with sense was not willing to say, without qualification in light of these calibration problems, which lead which. Now its better resolved, at least in this study, which is not the work of Lehman. Lehman will nonetheless, be prepared to talk about it. I suspect we have not heard the last of the chronology of the ice core records, but this is a very tidy piece of research, and important at that.

Scott will also talk about his own records of the operation of a Broecker-like NADW heat pump. He also finds that in his record of multiple 40 year changes in ocean circulation, there are changes in the temp as well of 5 degrees C in either direction. These is some question of the extent of these climate signals globally, but Younger Dryas seems to show up virtually everywhere these days.

Thomas Stocker works with Broecker at Lamont. He is Swiss and a recipient of one of 5 science fellowships awarded in Switzerland, to work elsewhere. He willl lay out Broecker's heat pump and many variants of it, and much more. Broekers' heat pump mechanism is fairly well accepted and documented at this point, although that's not to say there is no disagreement. It works as you know, by density changes (changes in temp. or salinity of water or both). When it's in full swing and warm water is carried north, poleward in the Atl., there is melting of polar ice (circulation now is accelerated). When not in operation, shut down, there is no heat transported to pole and therefore, ice accum. This operates on scale of less than 100 years. There is lots of debate of whether this systems also causes exchanges of gases with the atmos., and if so, whether it resides in atmos. long enough to cause another kind of climate change involving greenhouse gases. He will also address the rapidity of ocean changes and the sensitivity of oceans to any forcing.

I am trying to get ahold of Ray Hayes regarding an update on coral bleaching.

I am also awaiting a call from Peter Schlosser who's been in Texas. I doubt we can expect him.

The above witnesses are definitely on board if you feel comfortable with this.

Could I have put together a fuller, deeper panel with more time, at a different time? Yes, I could think of a so-called ideal panel. However, I believe this group of six can do a very good to excellent job, if you are comfortable.

I thought about the seals, etc., and did some background reading as well. It does not tie neatly together, particularly if we cannot put a finger on a very likely climate connection. Many of theses may be UV-B and/or toxic affects, seemingly compound, but difficult to pull apart. Likewise, I did some background work on the algal blooms. Many have ascribed their greater and new presence as function of some non-descript changes in their ecological niches. Others have suggested a higher incidence of ship discharge (I'm not sure I give this latter any credence). I am not certain how to fit it into this hearing,nor am I certain that we want to, even though I think it would make a great hearing, but a different kind of hearing perhaps.

Lastly, I thought of trying to get Jim Kasting to come in, or James Walker, to discuss the planet's natural scrubbing mechanism for CO-2. They have recently stated that they estimate that it will takes thousand of years, perhaps up to 10,000 yrs. for the earth to naturally scrub CO-2 out of atmosphere by weathering process, which is the scrubber. Interestingly enough, Gerry Mahlman is coming to realize that the scrubbing of CO-2 and it's climate effects, from the atmosphere, will be a surprisingly long venture, moreso than most have thought.

Thoughts and Comments?

..., pp. 35-40, 5 November 1987

North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature

Edward A. Boyle* & Lloyd Keigwin†

* Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
† Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA

During a surface cooling event 10,000 to 12,000 years ago, higher Cd/Ca and lower $^{13}C/^{12}C$ ratios are observed in benthic foraminifera shells from rapidly accumulating western North Atlantic sediments. Data from sediment cores show that marked nutrient depletion of intermediate waters occurs in association with reduced glacial North Atlantic Deep Water flux. It is proposed that cold high-latitude sea surface temperatures enhance intermediate-water formation at the expense of deep-water formation.

THE transition from latest Pleistocene glaciation to the Holocene interglacial period occurred over thousands of years[1-4]. In the North Atlantic Ocean and continental Europe, this long-term warming trend was interrupted by a brief return to glacial temperatures ~10,000-12,000 yr ago referred to as the 'Younger Dryas'[5,6]. The relative abundance of cold- and warm-water fossil fauna in oceanic sediments shows that the surface North Atlantic was also cooler then. Recent accelerator radiocarbon dating of single-species foraminifera from a high-accumulation-rate sediment core indicates a terrestrial-equivalent radiocarbon age of ~10,300 yr[7]. Oxygen isotope studies from ice cores demonstrate that deglacial warming in Greenland was also interrupted by a brief period of near-glacial temperatures[8]. Recent counting of annual $\delta^{18}O$ and dust cycles indicates that this event ended 8,770 chronological years ago[9] (equivalent to 9,050 conventional radiocarbon years). These events are synchronous within the uncertainties in the ages; a climate model study indicates that synchroneity is to be expected[10]. The sudden reversal of the warming trend is not seen in ice-volume indicators, except perhaps as a pause in melting[2].

This event is one of the shortest well-documented extreme climate reversals, occurring over ≤1,000-2,000 yr. The rapidity of this fluctuation can help determine the response time of other climate subsystems. For example, the Younger Dryas can be used to test the response of deep-ocean circulation to a short climate event. The duration of the Younger Dryas climate reversal is short compared to Milankovitch (orbital) cycles, implying that other mechanisms can generate large climatic changes. A number of models have been proposed to account for the Younger Dryas, but no consensus has been reached yet[6].

No convincing evidence for a deep-ocean response to Younger Dryas cooling has been obtained from high-sedimentation-rate cores. Given normal deposition at 2-3 cm kyr^{-1} (and typical biological stirring of the upper sediment layer down to 8 cm), it is unlikely that such a short-duration event could be reliably recorded in most deep-sea sediment cores. The north-east Bermuda Rise, a feature created from transport of fine-grained detritus, has high deposition rates, of >10 cm per thousand yr[11,12]. We present data from a Bermuda Rise core which document the deep-ocean response to Younger Dryas cooling.

The sediment core and its timescale

Core EN120 GGC1 is a large-diameter (10 cm inner diameter) gravity core. It was raised from 4,450 m depth (33°40′ N, 57°37′ W) on RV *Endeavor* cruise 120, 31 August 1984. The core site is near that of core KNR31 GPC5 for which previous stratigraphic work has been undertaken[11,12].

The timescale for this core is estimated by cross-correlation with features that have been radiocarbon dated in other cores from the North Atlantic basin. This correlation assumes that ice volume is the dominant factor controlling changes in benthic foraminiferal $\delta^{18}O$, with a lesser contribution from deep-ocean temperature[13]. The ice-volume signal must be globally synchronous within the mixing time of the ocean (<1,000 yr[14]); part of the temperature contribution to $\delta^{18}O$ variability is likely to be correlated with ice volume as well (W. F. Ruddiman, in preparation). The estimated timescale is based on the following assumptions. (1) The sample with most positive $\delta^{18}O$ is assigned the conventional glacial maximum age of 18,000 yr. Because benthic foraminifera are scarce in the glacial section of the core, there is some uncertainty as to the true depth of the glacial maximum (Fig. 1). The following discussion will not rely on the details of the chronology preceding deglaciation. (2) The first rapid shift of ^{18}O towards interglacial values ('Termination Ia') is very clear in this core at 145 cm, with an uncertainty of no more than a few cm. This feature has been dated at 14,000 radiocarbon years using the accelerator radiocarbon technique in another North Atlantic sediment core[15]. (3) After a brief $\delta^{18}O$ plateau, a second rapid shift to full interglacial conditions (Termination Ib) occurs which has been accelerator radiocarbon dated at 8,500 radiocarbon years[15]. This transition is less clearly defined than Termination Ia, but it occurs somewhere between 80 and 95 cm in EN120 GGC1. The Termination Ib level was chosen at 90 cm. (4) There is a regional $CaCO_3$ minimum (at 17 cm depth in this core), as well as several other $CaCO_3$ cycles in the Holocene section of this core (Fig. 1), that are identical to cycles observed in nearby core GPC5 (L. D. Keigwin and G. A. Jones, in preparation). Planktonic foraminiferal carbonate from the youngest carbonate minimum has been radiocarbon dated at 1,900 yr in KNR31 GPC5[11]. (5) The core top is assigned an age of 0 years. In view of the characteristics of the corer, similarity of the chemical data for the core top and Smith-McIntyre box-core sample, and the high sedimentation rate, this assignment appears reasonable and is unlikely to be low by more than a few hundred years.

With these control points, other depth intervals are assigned ages by linear interpolation (and extrapolation beyond the glacial maximum). Preliminary results from accelerator radiocarbon dates in this core and nearby core GPC5 support the timescale used here. In particular, in GPC5, the Younger Dryas interval is bracketed by radiocarbon dates of 9,210±150 yr (*G. ruber*) at 175 cm and 11,150±310 years (*N. pachyderma*) at 202 cm (L. D. Keigwin and G. Jones, in preparation). The $CaCO_3$ cross-correlation indicates that these intervals in GPC5 are equivalent to 100 cm (interpolated age 9,500 yr) and 115 cm (interpolated age 11,000 yr) in EN120 GGC1. It is unlikely that

Table 1 Data from sediment core EN120 GGC1

Depth (cm)	Cd species	Cd/Ca (μmol mol^{-1})	$\delta^{18}O$ (‰ PDB)	$\delta^{13}C$ (‰ PDB)
0	umb	0.072		
	wue	0.073		
5	umb	0.088		
7	umb	0.080		
9	umb	0.087	2.36	0.33
11	umb	0.075	2.48	0.52
13	umb	0.082		
	wue	0.085		
15	umb	0.080	2.37	0.66
17	umb	0.076	2.49	0.39
18	umb	0.088		
19	umb	0.080		
	wue	0.083	2.48	0.59
21	umb	0.073		
23	umb	0.076	2.24, 2.48	0.32, 0.03
25	umb	0.081	2.43	0.86
	wue	0.093		
27	umb	0.072		
	wue	0.127	2.33	0.76
29	umb	0.106	2.57, 2.39	0.49, 0.39
31	umb	0.104	2.41, 2.40	0.53, −0.08
33	umb	0.082	2.47	0.39
35	umb	0.093	2.32	0.74
37	umb	0.094	2.24	0.65
39	umb	0.082	2.54	0.45
41	umb	0.078	2.52	0.88
43	umb	0.099	2.54	0.51
45	umb	0.114		
47	umb	0.097	2.40	0.37
49	umb	0.070	2.40, 2.40	0.77, 0.19
51	umb	0.077		
	wue	0.098	2.43	0.61
53	umb	0.086	2.46	1.10
55	umb	0.073	2.52, 2.49	−0.34, 0.01
57	umb	0.084	2.45	1.03
59	umb	0.086	2.43, 2.35	−0.18, −0.14
61	umb	0.096	2.59	0.93
63	umb	0.111	2.37	1.02
65	umb	0.077		
66			2.69	1.01
67	umb	0.086		
69	umb	0.105		
71	umb	0.086	2.48	1.10
73	umb	0.075	2.54	0.61
75	umb	0.076	2.54	1.20
77	umb	0.090	2.53	0.90
79	umb	0.075		
	wue	0.106	2.49	0.86
81	umb	0.069		
83	umb	0.077	2.50	1.05
85	umb	0.072	2.45	1.10
87	umb	0.077	2.71	0.99
89	umb	0.071	2.40	0.79
91	umb	0.075	2.56, 2.69	0.38, 1.04
93	umb	0.075	2.39	0.60
95	umb	0.089	2.46	0.70
97	umb	0.095		
	wue	0.097	2.47	0.47
99	umb	0.095		
	wue	0.127	2.97	0.24
101	umb	0.093		
	wue	0.127	2.65	−0.68
103	umb	0.123		
	wue	0.137	2.80	−0.49
105	umb	0.104		
	wue	0.140	2.95	−0.19
107	umb	0.129		
	wue	0.139	3.19	−0.10
109	umb	0.124		
	wue	0.143	2.84	0.32
110	wue	0.135		
111	umb	0.133		
	wue	0.129	2.49	−0.17
113	umb	0.125		
	wue	0.128	3.05	0.32
115	umb	0.109	2.98	−0.55
116	wue	0.115		
117	umb	0.081	3.23	0.22
119	umb	0.100	2.89	0.61
121			2.80	0.41
123	umb	0.076	3.31	0.33
125			3.01	0.89
127	umb	0.086		
	wue	0.111		
129			3.17	0.50
138	umb	0.089		
139	umb	0.094		
143			3.21	−0.14
147			3.35	−0.54
149	wue	0.110		
151	wue	0.158	3.59	−0.78
152	wue	0.156		
153	wue	0.135		
155	wue	0.131		
157	wue	0.120		
159	wue	0.130		
161			3.70	−0.57
163	wue	0.125	3.73	−0.68
165	wue	0.127		
167	wue	0.105	3.74	−0.52
169	wue	0.133	3.80	−0.67
171	wue	0.111		
173			3.77	−0.55
176	Uvi	0.149		
177			3.76	−0.51
179			3.79	−0.39
181	Uvi	0.170	3.96	−0.31
183			3.77	−0.28
186	Uvi	0.222		
199	Uvi	0.177		
204	Uvi	0.125		
213	Uvi	0.149		
217	Uvi	0.140		
226	Uvi	0.124		
232	Uvi	0.153		
238	Uvi	0.155		
242	Uvi	0.194		
245			3.74	−0.41
248	Uvi	0.216		
256			3.99	−0.02
260			4.05	−0.55
264			4.02	−0.08
273			3.71	0.04

All isotope data is from *C. wuellerstorfi*. '0'-cm sample is from Smith-McIntyre surface sediment sampler; all other depths refer to distance along core liner (sediment surface in core is at 4 cm). In the species column the symbols are: wue, *C. wuellerstorfi*; umb, *N. umbonifera*; Uvi, *Uvigerina*.

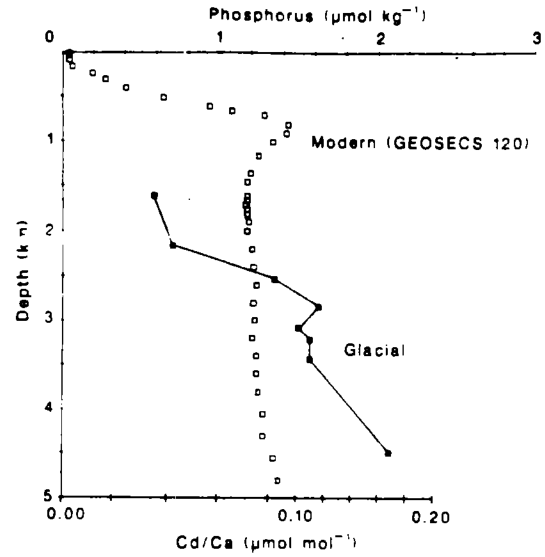


Fig. 4 Glacial depth profile of phosphorus in the modern western North Atlantic (GEOSECS station 120) compared to glacial profile. The glacial profile is based on the cores shown in Figs 1-3 as supplemented by two others whose glacial section is determined from percentage CaCO3 curves (CHN82 Sta30-1 Core9PC, 41°50.6′ N, 26°27′ W, 2,830 m, glacial sample at 30-40 cm; CHN82 Sta23 Core3PC, 41°38′ N, 27°20′ W, 2,525 m; glacial sample at 36-42 cm). The actual data for the glacial profile are Cd/Ca ratios in benthic foraminifera (bottom scale). The phosphorus scale is estimated assuming that the Cd-P relationship in the glacial ocean is similar to that of today, and assuming that the distribution coefficient for Cd/Ca in foraminifera relative to sea water is 2.9. Note the change in the Cd scale, which is based on observation of a significant 'kink' in the Cd-P relationship (ref. 23). Actual glacial P is uncertain to the extent that this relationship may have been slightly different during glacial times and to the extent that the distribution coefficient is uncertain (it is known to no better than 15%). Despite these uncertainties, the important feature is the relative vertical homogeneity in the modern North Atlantic compared to the marked depth gradient in the glacial ocean. This qualitative difference depends neither on the assumed Cd-P relationship nor on the assumed distribution coefficient.

temperatures. Essentially, water 'distills' off the warm North Atlantic and is transported by the atmosphere to 'condense' onto the cool North Pacific[6].

Proxy climate data show that the glacial high-latitude North Atlantic was much colder than at present[32,33]. An analysis similar to Warren's[30] for the modern and glacial North Atlantic from 40 to 65 °N and from 10 °E to 70 °W indicates the consequences of that cooling (Table 3). Neglecting the effect of changes in the wind speed and relative humidity over the glacial North Atlantic, cooler glacial temperatures would tend to reduce the rate of evaporation by a factor of two. This difference is comparable to the contrast between the modern North Atlantic and Pacific. This effect is reinforced by diminished northward transport of saline water from lower latitudes. Processes tending towards lower surface salinities are countered in part by increased wind strengths which enhance evaporation[34]. Furthermore, dry catabatic winds cascading off continental ice masses would have reduced atmospheric relative humidity near the ice edge and contributed to the formation of cold saline water (J. Reid, personal communication). Hence, although it is plausible on the basis of temperature changes that the salinity of the Atlantic north of 45 °N tended to lower values during glacial times (which has already been surmised qualitatively[32]), it probably did not attain the state of the modern North Pacific.

This decrease in salinity would have made it more difficult to form very dense waters in the North Atlantic. It would have favoured more production of intermediate waters. The palaeochemical evidence shows that the glacial North Atlantic

Table 2 Data from two cores

Depth cm	Cd/Ca (µmol mol⁻¹)	$\delta^{18}O$ (‰ PDB)	$\delta^{13}C$ (‰ PDB)
CHN82 Sta 41 Core15PC			
2	0.051	2.46	0.63
6	0.040	2.43	1.28
9	0.049	2.77	1.24
12	0.054	2.64	1.31
16	0.037	3.36	1.21
19	0.043	3.18	1.27
22	0.053	2.93	0.87
25		3.55	0.88
27	0.038	3.19	1.02
29	0.036	3.96	1.17
31	0.047	3.92	1.19
33		3.95	1.27
36	0.050	3.74	1.21
39	0.043		
41	0.048	3.42	1.18
KNR65 Sta5 Core5PG			
7		2.17	0.96
8	0.073	2.41	0.89
9		2.54	1.09
11	0.095	2.19	0.77
12	0.061	2.05	0.76
13	0.074	2.24	1.15
15	0.065	2.11	1.03
17	0.050	2.73	0.90
18	0.055		
19	0.057	2.87	0.86
21	0.048	3.01	1.11
22	0.035	2.75	0.83
25	0.042	3.32	1.23
29	0.048	3.34	1.32
32	0.030	3.27	1.28
35	0.041	3.18	1.13
39	0.038	3.10	1.39
41	0.034	3.50	1.12
43		3.44	1.23
47	0.038	3.10	1.18
49		3.21	1.10
51		3.28	1.05
52	0.046		
53	0.035	3.06	0.84
55		3.30	1.04
55	0.048		
57	0.041	3.10	1.11
59	0.053	3.23	1.20

Cd data from *C. kullenbergi* and *C. wuellerstorfi*. Isotope data from *C. wuellerstorfi*. The time interval is verified as isotope stages 1 and 2 by the presence of excess ^{230}Th (ref. 38) and the absence of *G. flexuousa* (ref. 39).

did not fully attain the conditions of the modern North Pacific; some deep water must have been forming to maintain the Atlantic at lower nutrient levels than the Pacific[16,24]. The North Atlantic probably shifted towards a state more like the North Pacific, with less deep-water production and more intermediate-water production. This model predicts that glacial North Atlantic intermediate waters would have been colder and fresher (and perhaps relatively more depleted in ^{18}O).

An alternative model

Another intermediate-water source for the modern Atlantic is the outflow of nutrient-depleted saline water from the Mediterranean. Zahn, Sarnthein and Erlenkeuser[35] studied the carbon isotope composition of sediments from intermediate depths in the eastern Atlantic from Gibraltar southwards. They found evidence for enhanced nutrient depletion of these mid-depth waters during glacial times. This evidence was interpreted as indicating an increased flux of nutrient-depleted Mediterranean

Lamont-Doherty Geological Observatory of Columbia University

Palisades, N.Y. 10964

Tel.: (914) 359-2900
Telex: TWX-710-576-2653
Fax: (914) 365-3183

Dr. Thomas F. Stocker
ext. 705
May 19, 1992

Tony Socci

Dear Tony,

Thank you for the letter of invitation and the regulations. Please note that I am employed as a **Associate Research Scientist** at Lamont-Doherty. Enclosed is a draft of my statements for the discussion tomorrow. If you have any comments, please let me know by fax or phone.

Your Sincerely,

Thomas

Thomas Stocker

EARN/BITNET: thomass@lamont.ldgo.columbia.edu Telemail: [LDGOCHEM/OMNET]Mail/USA

Modes, Stability and Variability of the Deep Ocean Circulation

Thomas F. Stocker

Lamont-Doherty Geological Observatory of Columbia University
Palisades, New York, 10964, USA

20 May 1992

Of all the water that takes part in the hydrological cycle, only one part in 100,000 can be found in the atmosphere; the storage of carbon in the ocean is 30 times larger than in the atmosphere and biosphere together, and the ocean accounts for more than 70% of the planet's surface allowing for the exchange of energy, water and greenhouse gases with the atmosphere. Essential to our modern climate is the transport of heat and moisture from the low to the high latitudes of which the atmosphere and ocean carry roughly equal parts.

Paleoclimatic records from sea sediment and ice cores have revealed that the ocean circulation has not always been in its present-day state. Altered wind regimes due to the presence of massive continental ice sheets during the Last Glacial Maximum have influenced the wind-driven surface circulation. More important, the deep circulation was also different implying that the entire world ocean is sensitive to changes at the interface with the atmosphere. While the atmosphere tends to respond smoothly to changes of the external forcing, it is now clear that the ocean can exhibit drastic re-organizations that can fundamentally modify our climate on very rapid time scales. The reason lies in the nature of the deep or thermohaline circulation and the surface processes that influence it. Changes in the density field caused by local temperature or freshwater anomalies, among others, can alter the stability and the convective properties of the water column. While the cause may be local, the effect can have basin-wide and even global implications by altering the geographical location and strength of oceanic heat release.

Water properties are distinctly different in the major ocean basins due to the structure of the modern thermohaline circulation. This flow operates like a global conveyor belt cycling water masses through the ocean basins and represents an important link between the surface of the ocean and the deep. The thermohaline circulation is maintained by a net freshwater loss in the Atlantic basin due to excess evaporation and is crucially important for the climate of the areas adjacent to the North Atlantic. Any process that changes the atmospheric branch of the hydrological cycle or the surface heat budget of the ocean is likely to alter the thermohaline circulation.

Numerical ocean circulation models suggest that the modern mode of operation has only a limited stability to perturbations of the heat and freshwater budget at the ocean's surface. Once such changes are initiated, transitions to different regimes of flow can be completed within a few decades. Changes involve primarily the Atlantic Ocean which appears to be the most sensitive area, but they can also be triggered in other parts of the ocean as well. Deep circulation can stop and so interrupt the meridional transport of heat; surface waters become cooler and fresher, and net evaporation decreases. This is a positive feedback mechanism which results in a further freshening. While we have not experienced such fundamental changes during the last 8000 years, these are evident in the records covering the most recent termination of the Last Glacial, for example during the Younger Dryas event about 10,700 years ago. The hydrological cycle in the atmosphere is a major component in determining the stability of the thermohaline circulation in the modern ocean. A decrease of the Atlantic-to-Pacific freshwater transport through the atmosphere is able to decrease stability and drive the system over the critical threshold.

Decadal to century time scale variability is an important element of the climate system, because anthropogenic modifications also evolve on these time scales. The thermohaline circulation can exhibit natural variability with periods ranging from less than a decade to a few hundred years. These self-sustained oscillations are due to the fact that the processes of atmosphere-ocean heat exchange are fundamentally different from those of freshwater exchange. It is important to note that the dynamic behaviour, whether or not such oscillations are present, and the time scales involved depend on the state of the thermohaline circulation itself.

It is the dynamic behaviour of the ocean and its potential to undergo rapid changes that calls for a better and deeper understanding of this component of the climate system. Long-term and basin-wide in situ monitoring, numerical models, both process studies and fully 3-dimensional models, and the careful analysis of records of past changes from the high-latitude regions in both hemispheres are the necessary tools for the advancement of our knowledge of how the ocean is operating.

University of Delaware

THE GRADUATE COLLEGE OF MARINE STUDIES
ROBINSON HALL
NEWARK, DELAWARE 19716

Fax: 302-831-6838

TO: Mr. A. Socci
202-224-1892 Fax
202-224-9360 Voice

DATE: 5-19-92

TIME: 12:00

MESSAGE:

First Draft of the statement. Please call if you have any question or suggestions.

FROM: X. H. Yan
302-831-6838 Fax

NUMBER OF PAGES (including cover sheet) 17

IF TRANSMISSION IS NOT COMPLETE, PLEASE CALL:
302-831-3694 Voice

Statement of

Dr. Xiao-Hai Yan
Associate Director

Center for Remote Sensing
Graduate College of Marine Studies
University of Delaware

Before the

U.S. Senate Committee on Commerce, Science, and Technology
A Full Committee Hearing on Global Climate Change and the Oceans

May 20, 1992

Washington, D.C.

Statement of

Dr. Xiao-Hai Yan
Associate Director

Center for Remote Sensing
Graduate College of Marine Studies
University of Delaware

Before the

U.S. Senate Committee on Commerce, Science, and Technology
A Full Committee Hearing on Global Climate Change and the Oceans

May 20, 1992
Washington, D.C.

Mr. Chairman, members of the Senate Committee, I am Xiao-Hai Yan, Associate Director of the Center for Remote Sensing, Graduate College of Marine Studies, University of Delaware. I am pleased to speak before you today on the importance of satellite remote sensing in understanding global climate change, ocean dynamics and the remote sensing research being done on the Western Pacific Warm Pool and its implication in global climate change. I am testifying on behalf of myself and on behalf of the Center for Remote Sensing, University of Delaware.

The scientific community has made substantial strides towards understanding a wide variety of complex ocean processes in response to Global Climate Change. These include studies of the tropical ocean and the unusual hot spot called the Western Pacific Warm Pool found in the tropical Pacific Ocean. The satellite image shown on the screen confirms ground observations of this vast warm pool in tropical Western Pacific Ocean. The tropical ocean and this warm pool play a key role in regulating the earth's climate. The fact that they store and transport both heat and greenhouse gases must be taken into account in any discussion of global climate change. The scientific community has been aware of the hot spot, but it is the first time vivid images from satellite data agree so well with observation data gathered at sea level. Such time series of satellite images will constitute a powerful tool for tracking the warm pool as its temperature and size fluctuate from time to time. They will also contribute toward understand the El Niño phenomenon and global climate change as well.

The mysterious Western Pacific Warm Pool, which covers more of the earth's surface than the continental United States, stands out vividly as the orange and red area in our newly processed image of long-term average sea-surface temperature obtained from satellite data (Figure 1). This swath of ocean near New Guinea which has a temperature consistently higher than 28° Celsius -- 2 to 5 degrees above other equatorial waters, is the largest single expanse of warm water on our planet. This warm pool is a region of net freshwater input to the ocean because of the heavy precipitation (nearly 5 meters of rainfall annually) and because of the reduced evaporation usually associated with light winds. This mass and buoyancy flux significantly affects the dynamics and thermodynamics of the mixed layer of the warm pool[1,2]. Direct thermal effects, associated with precipitation, may act as a negative feedback on convection that releases large amounts of heat to the upper atmosphere and produces clouds that block some incoming energy but trap outgoing energy[3]. Precipitation caused density stratification affects the upper ocean's ability to absorb and mix thermal energy, which in turn influences the transfer of heat and moisture back to the atmosphere. Interannual variabilities over the extent and duration of this intense exchange of energy between the warm pool and the overlying atmosphere appear to induce climate variations over the entire Pacific Ocean and beyond.

In recent years, significant international efforts have been made to understand the coupled ocean atmosphere system in the equatorial ocean. However, most oceanographic studies have focused on the eastern and central Pacific Ocean and less effort has been given to the Western Pacific Warm Pool, even though the early stages of the El Niño Southern Oscillation (ENSO) phenomenon may first develop there[4]. El Niño events, which occur about every four to five years, appear to disrupt climate in distant places. They have been accompanied by droughts in Australia, India and Africa; floods in South America and China; and severe winter storms in the United States and Asia. Climate variations such as El Niño have serious impacts on human affairs, including loss of life, crop failures, and depletion of fisheries. Therefore, it is extremely important to track the warm pool as its temperature and size fluctuate from year to year, and to understand the relationship between the warm pool dynamics and El Niño events and global climate changes.

Conventional oceanographic observations usually constitute the basis of large oceanographic research programs. However, ship observations are often limited in both space and time, and are more expensive than remote sensing methods. Satellite images, with their large areal coverage and frequent sampling potential, bridge the spatial and temporal gaps between hydrographic surveys and moored instruments and are less expensive than field observations. It is well known, that there are biases in satellite derived sea-surface-temperature data[5]. However, there are also biases in field observations, for example, expendable bathythermographs (XBT)[6,7]. Therefore scientists should not be discouraged from using satellite SST and XBT-SST, provided a careful data processing method is applied.

A multi-channel sea surface temperature (MCSST) data product derived from the TIROS-N/NOAA series AVHRR (Advanced Very High Resolution Radiometer) by Otis Brown, Rosenstiel School of Marine and Atmospheric Science (RSMAS), University of Miami is distributed by the Distributed Active Archive Center (DAAC), formerly the NASA Ocean Data System (NODS), at the Jet Propulsion Laboratory (JPL). This MCSST product consists of a weekly composite for the globe at approximately 18 km resolution as well as regional subsets. In this study, the weekly MCSST for the tropical Pacific Ocean from 1982 to 1990 has been analyzed to compute monthly mean SST, annual mean SST and long-term mean SST.

The TIROS-N/NOAA series polar orbiting satellites carry four channel (TIROS-N, NOAA-6, NOAA-8, NOAA-10) or 5 channel (NOAA-7, NOAA-9) AVHRR sensors as part of their payload. The primary objective of the AVHRR instruments is to provide cloud top and sea surface temperatures with passively measured visible, near infrared, and thermal infrared spectral radiation bands. The AVHRR sensor has an instantaneous field of view (IFOV) that corresponds to a ground resolution of about 1.1 km at nadir, and a total scan field of view (FOV) of ± 55.4 degrees from nadir (approximately 2240 km). The five spectral bands measured are: Channel 1, visible, 0.58-0.68 microns; Channel 2, near infrared, 0.725-1.10

microns; Channel 3, infrared, 3.55-3.99 microns; Channel 4, thermal infrared, 10.2-11.5 microns; and Channel 5, a second thermal infrared channel at 11.5-12.5 microns (NOAA-7 and NOAA-9).

MCSST products are derived from the NOAA/NESDIS Global Retrieval Tapes which contain MCSST, retrieved with latitudes and longitudes. MCSST values are binned into a 2048 by 1025 pixel grid. For each grid point, the average of all MCSST measurements available for one week is computed. Open areas are interpolated using an iterative Laplacian relaxation technique until all such areas connected to valid observations are filled. A first guess for open areas is provided by computing the mean of horizontal bounding "good" data-filled pixels. The original global weekly MCSST data set is 16 bits, the temperature is the value divided by 10. Thus the resolution of MCSST is 0.1°C with an RMS error of 0.6°C. The spatial resolution of the original data set is 18 km. To conveniently display and print it out, the 16-bit data set is reduced to 8 bits so that the resolution of the temperature is 0.2°C. The spatial resolution is also reduced to 72 km. The weekly MCSST is first averaged into monthly mean MCSST. The annual mean MCSST and long-term mean MCSST are then averaged again from monthly mean and annual mean MCSST.

From Figure 1, we can clearly see the vast Western Pacific Warm Pool where the highest open ocean water temperatures in the world are found. Comparing Figure 1 with Figure 2, which shows the long-term mean SST based on field observation[8], we can see that the pattern of the long-term mean SST from satellite AVHRR data is very close to that of the Levitus climatological compilation, especially in the Western Pacific Warm Pool region.

Figure 3 shows an enlarged Western Pacific Warm Pool region for a nine year (1982-1990) period. We can track the warm pool from Figure 3 as its temperature and size fluctuate from year to year. We can see a slow warming trend of the warm pool water and a gradual increase of the warm pool area. In order to analyze the trends observed from nine years of satellite data, we compute and plot the time series of warm pool temperature and size. In Figure 4, the Western Pacific Warm Pool is defined as an area where sea-surface temperature was larger than 28°C inside a rectangular box from 120°E to 150°W and from 20°S to 20°N. From Figure 4, an increase of 8.1×10^5 km^2 per year of the warm pool area is calculated.

In a similar fashion, area averaged warm pool temperature is computed and plotted as a function of time in Figure 5. This Figure indicates that the sea-surface temperature in the warm pool area increased by 0.03°C per year over the nine year period between January 1982 and December 1990.

Further support for the view that the warming trend of the Western Pacific Warm Pool in the satellite data is real comes from the research of Nitta, a scientist from the Japan Meteorological Agency. Nitta[9] performed Empirical Orthogonal Function (EOF) analysis by using global sea surface temperature data for 38 years from 1950 to 1987 to examine year to decade-scale variations of SST. He found that the SST averaged in the whole tropics between

20°S and 20°N was warmer by about 0.3-0.4°C in the 1980's than in the 1970's -- with a trend of 0.03-0.04°C per year, which is very similar to our satellite data analysis result for warm pool.

In summary, by taking advantage of the unprecedented temporal and spatial coverage of satellite MCSST observations, we have been able to conduct a year to year SST and area variability analysis for the Western Pacific Warm Pool. Warm pool temperature and area time series generated in this study reveal that there is a slow warming trend of the warm pool water and a gradual increase of the warm pool area. We believe that such satellite image analysis represents a powerful and economical tool for tracking the warm pool, as its temperature and size fluctuate from year to year. These satellite observations may provide new insight into the mechanisms responsible for the initiation and development of El Niño. They may also improve our understanding of upper ocean processes, air-sea exchanges, and the global atmosphere as well. To explore these new insights and new understandings, the further integration research of multi-satellite and multi-sensor data for modeling and process studies is urgently needed.

Mr. Chairman and members of the Senate Committee, I am pleased to have had this opportunity to talk to you today about our new findings and about what additional research is needed to improve our understanding of coupled ocean atmospheric system. In your deliberations, we urge you to consider the critical importance of an investment in science and technology for our nation's future, and that of our planet as we seek to utilize the remote sensing and space technology in the global change study in a responsible manner. We believe that adequate funding support from the Federal government agencies is crucial if we want to continue to make advances in this research area.

Finally, thank you again for the opportunity to testify today. I would be pleased to answer any questions the Senate Committee may have.

References

1. Ostapoff, F. & Worthem, S., *Science*, 180, 960-962 (1973).
2. Miller, J., *J. Phys. Oceanogr.* 6, 29-35 (1976).
3. Greenhut, G.K., *J. Phys. Oceanogr.*, 8, 1135-1138 (1978).
4. Lukus, R. & Lindstrom, E., Proceedings of the 'Aha Haliko'a Hawaiian Winter Workshop on the Dynamics of the Ocean Surface Mixed Layer, Hawaii Institute of Geophysics Special Pub., 67-94 (1987).
5. Reynolds, R., Folland, C. & Parker, D., *Nature*, 341, 728-731 (1989).
6. White, W.B., Meyers, G., Donguy, J.R. & Pazan, S., *J. Phys. Oceanogr.*, 15, 917-935 (1985).
7. Yan, X.-H., Niiler, P., Nadiga, S. & Stewart, R., *J. Geophys. Res.*, forthcoming (1992).
8. Levitus, S., Climatological Atlas of the World Ocean, NOAA Prof. Pap. 13, U.S. Government Printing Office, P173 (1982).
9. Nitta, T., Recent Warming of Tropical Sea Surface Temperature and Its Impact on the Northern Hemisphere Circulation, Interaction TOGA Scientific Conference, 16-20 July 1990.

Figure Captions

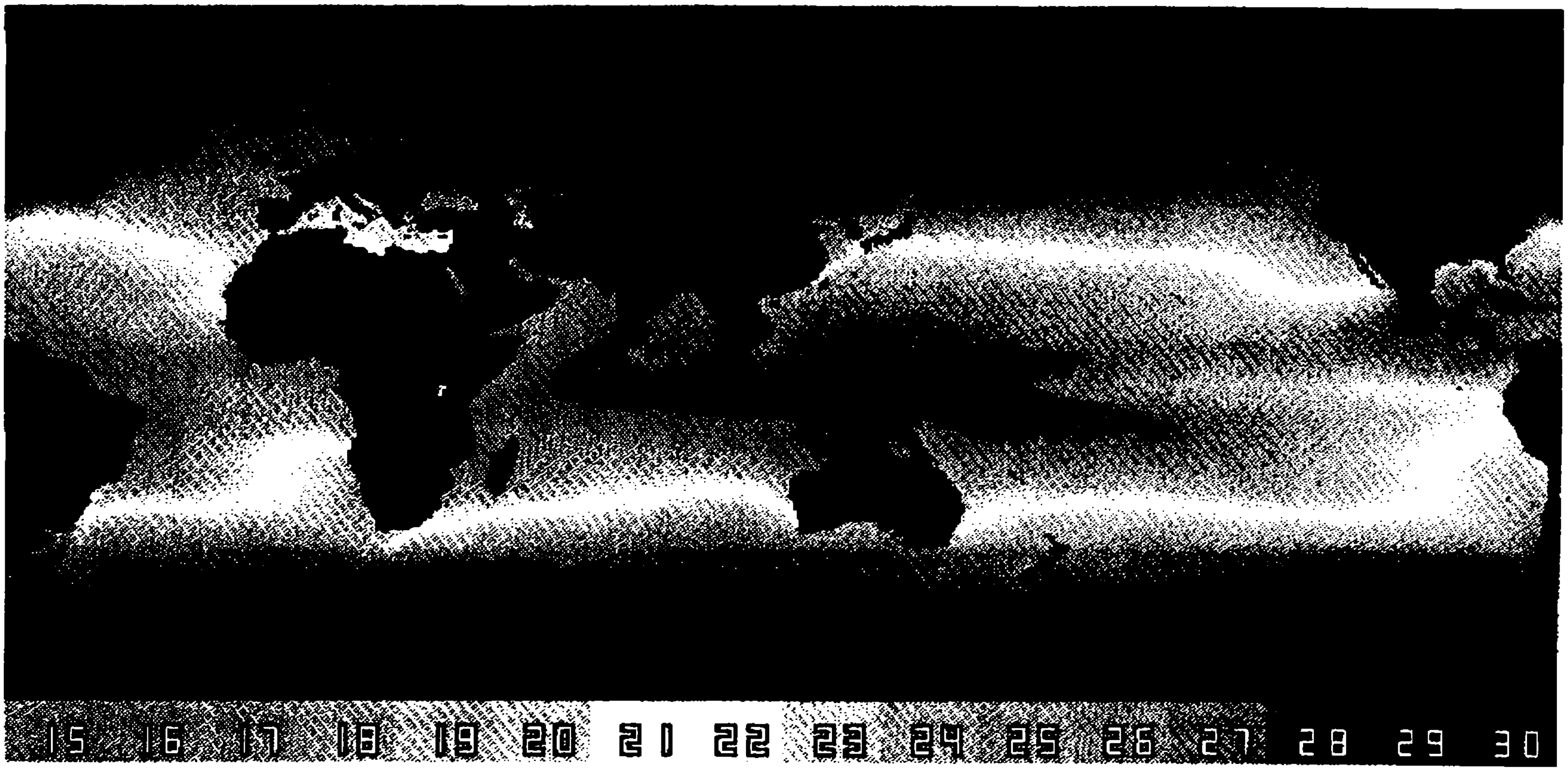
Figure 1. Color-enhanced image of nine year mean (1982-1990) sea-surface temperature from satellite data, with warmest surface temperature evident in the Western Pacific Warm Pool (orange and red).

Figure 2. Contour map of the long-term mean sea-surface temperature observations (adapted from Levitus, 1982).

Figure 3. Color-enhanced image of Western Pacific Warm Pool SST from 1982 to 1990.

Figure 4. Time series of warm pool area between January 1982 and December 1990.

Figure 5. Time series of warm pool SST between January 1982 and December 1990.



Center for Remote Sensing, University of Delaware

Figure 1

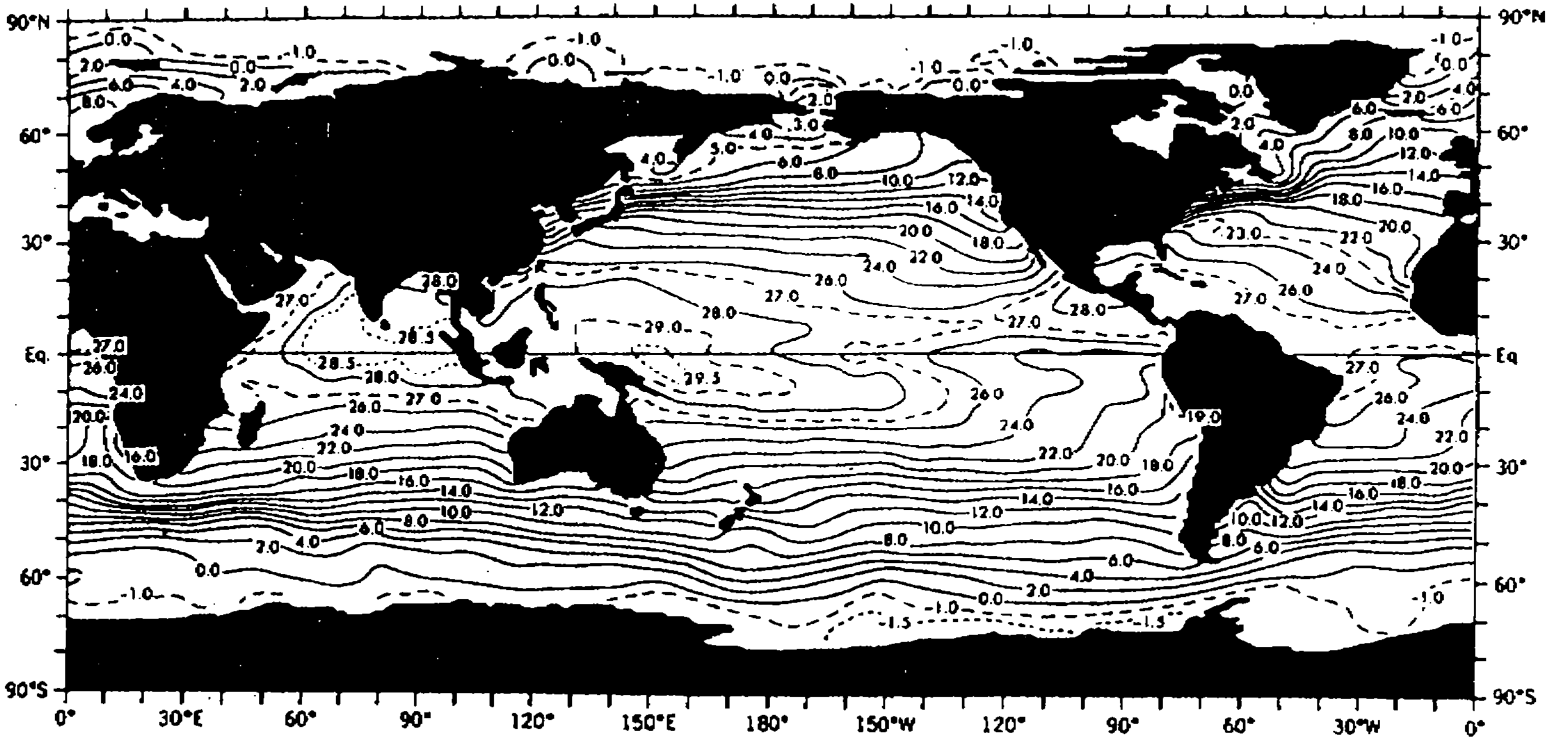


Figure 2

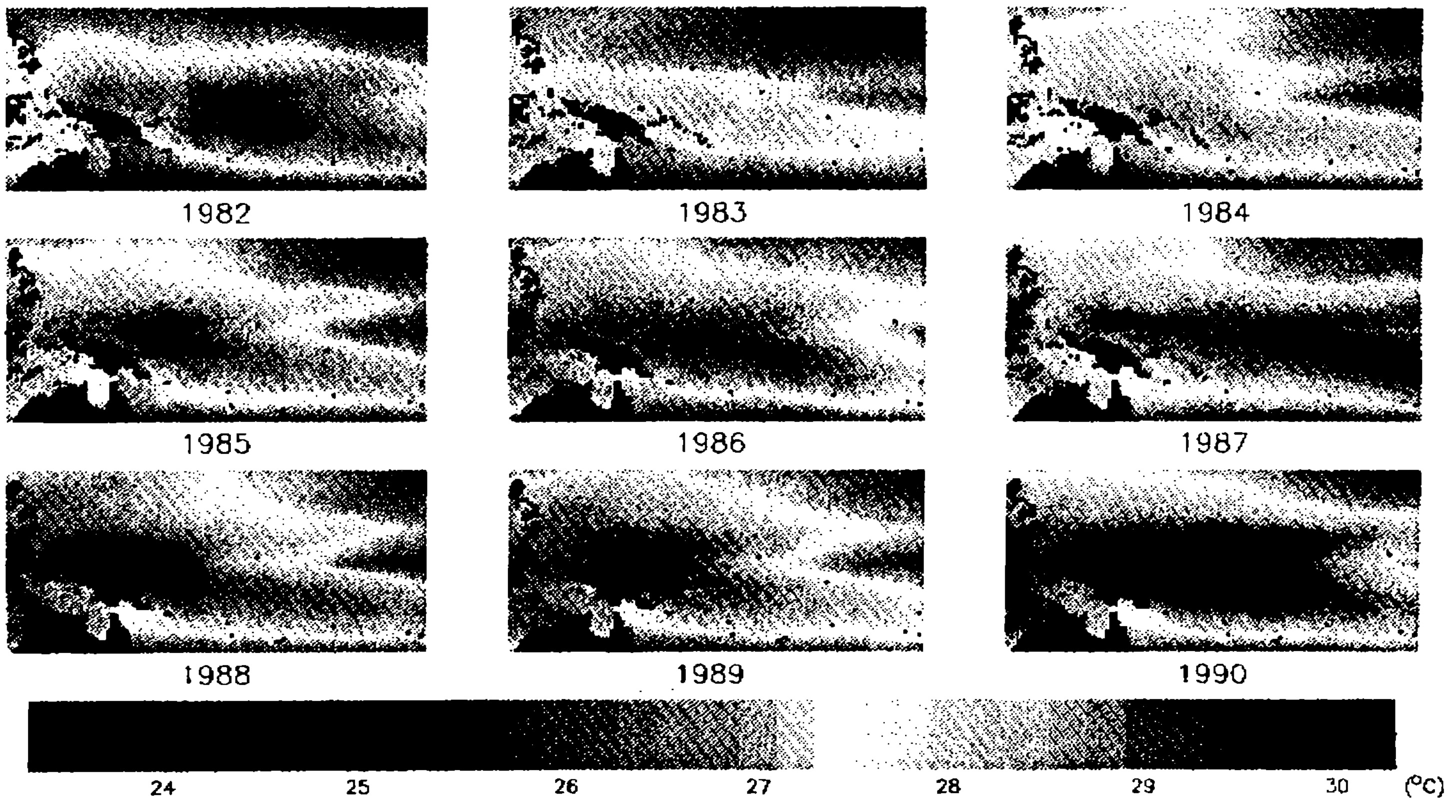

1982
1983
1984
1985
1986
1987
1988
1989
1990
24
25
26
27
28
29
30
(°C)

Figure 3

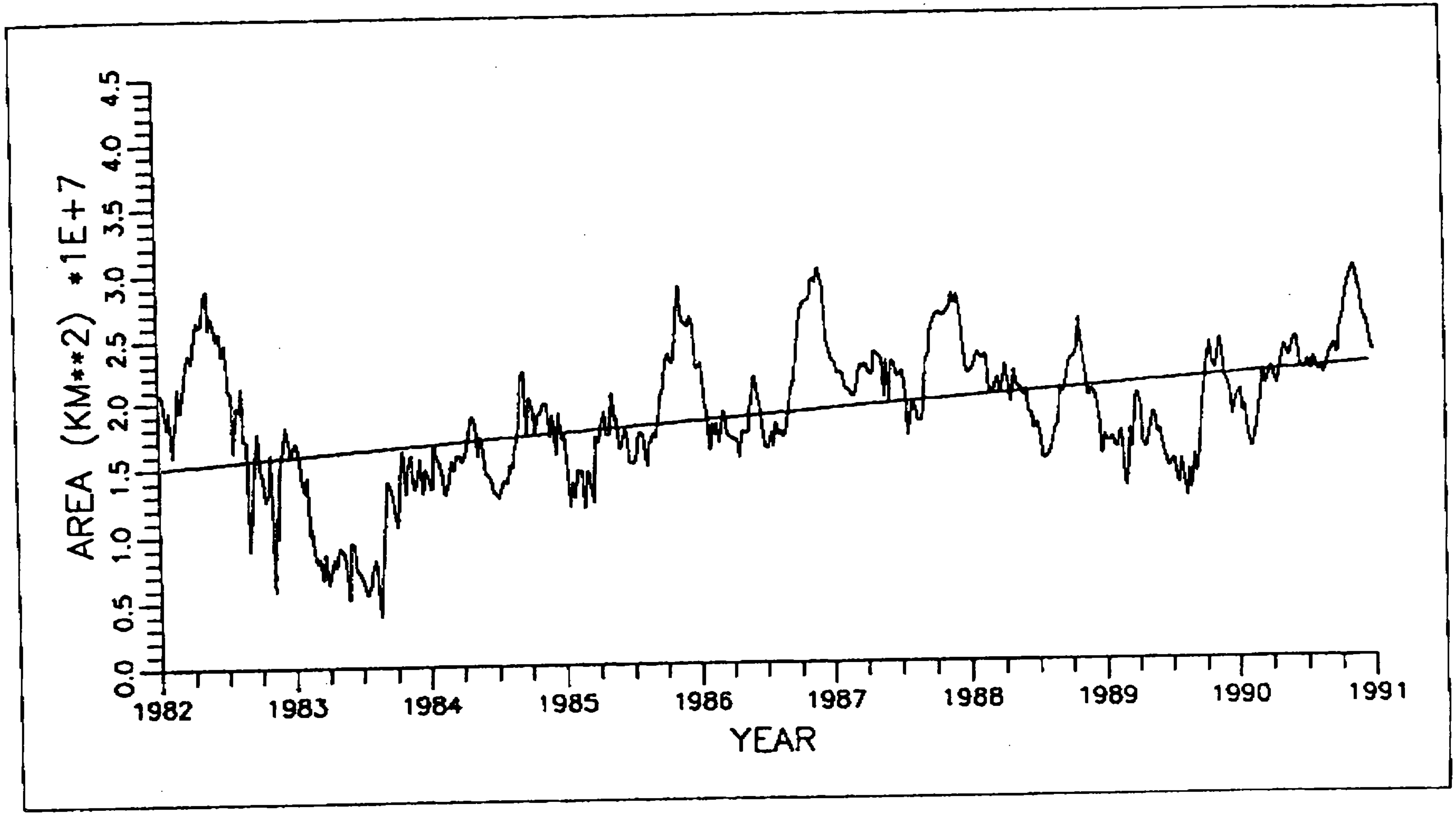

AREA (KM**2) *1E+7
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
YEAR

Figure 4

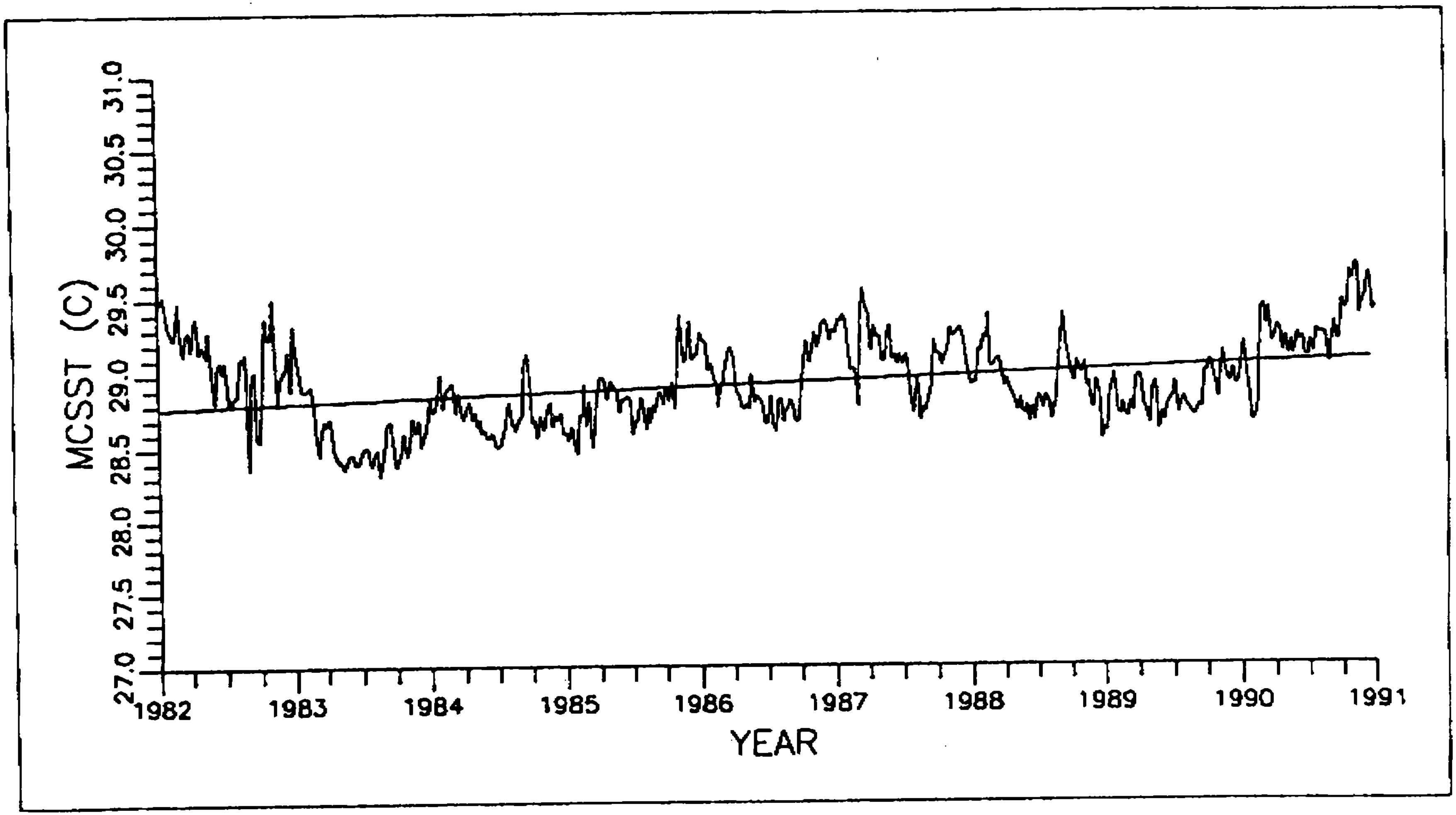

MCSST (C)
27.0
27.5
28.0
28.5
29.0
29.5
30.0
30.5
31.0
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
YEAR

Figure 5