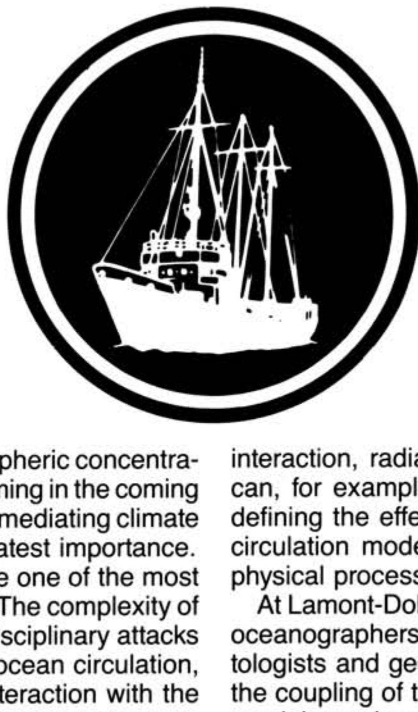
The Center for Climate Research

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY OF COLUMBIA UNIVERSITY IN COOPERATION WITH GODDARD INSTITUTE FOR SPACE STUDIES (NASA)

Among the most baffling and complex of any natural phenomena are the workings of the Earth's climate. Intensive research by scientists in dozens of specialties now suggests that in fact climate may truly become predictable. If so, it will be one of the most dazzling scientific accomplishments of this century, and one that will have a most profound impact on how we maintain the viability of Earth as a suitable environment for the human race.

There are critical moments in the progress of scientific discovery, points of rapid take-off marked by the confluence of new technology or new observations and a visionary idea. Lamont's first Director, Maurice Ewing, took the technology of continental geophysical exploration to sea with the powerful conviction that the ocean basins somehow hold the key to the enigmas of the geological evolution of the continents and the past and future climates of the Earth.



As Ewing suspected, the oceans turned out to hold the key to the origin of the continents. It is probable that the answers to the fundamental questions of climate also lie there. It is almost certain, for example, that the disastrous climate perturbations of 1982 and 1983 are linked to the extraordinary El Niño of those years. The normal pattern of the currents of the southeastern Pacific underwent a dramatic change that was coupled to a major shift in the normal pattern of atmospheric pressure over the Pacific.

The ocean is also the principal medium for redistributing the global heat budget and the carbon dioxide whose increasing atmospheric concentration promises to produce a major global warming in the coming decades. The detailed role of the oceans in mediating climate still remains a scientific enigma of the greatest importance.

These questions have begun to stimulate one of the most remarkable scientific efforts ever mounted. The complexity of climate problems has prompted new interdisciplinary attacks on such aspects of climate as the world's ocean circulation, past climates, tropical oceans and their interaction with the global atmosphere. In these efforts the planning and execution of the observational and theoretical work is carried out by physical oceanographers, geochemists, marine biologists, atmospheric physicists and chemists, paleontologists and experts in computer modeling.

At the same time the conventional experimental tools of the ocean scientist are being revolutionized. The most important is the parallel and equally striking developments of the remote sensing of the Earth from satellites, and the digital computer. Satellites have become vehicles for instrumental arrays that detect ocean currents, wind stress on the ocean surface, chlorophyll concentration in the oceans, sea-surface temperature, and they promise to provide measurement of atmospheric chemistry and changes in the biota of the land's surface. The prodigious volume of data that result can now be reduced by modern computers, permitting interpretation and, more important, global modeling of the ocean-atmospheric physicochemical system. Long-range prediction is now within reach.

The success of this global enterprise depends on the resourcefulness and long-term commitment of the best minds in the earth and ocean sciences. Lamont-Doherty and the Goddard Institute for Space Studies which is a division of the Space and Earth Sciences Directorate of the Goddard Space Flight Center, Md.), cooperating in the new Center for Climate Research, together represent a unique combination of resources to meet the challenge of modern climatology.

At GISS, the team of atmospheric physicists and chemists and specialists in such subjects as sea ice, ocean/atmosphere interaction, radiative heat transfer and numerical modeling can, for example, perform vital computational experiments defining the effects of CO_2 in the atmosphere. Their global circulation models take into account much of the array of physical processes that control climatic variations.

At Lamont-Doherty ocean chemists, physical and biological oceanographers, dendrochronologists, palynologists, paleontologists and geologists conduct research on past climates, the coupling of the oceans and the atmosphere, the oceans as sinks and sources of heat, the time scales for exchange of heat and gases between the ocean and the atmosphere and a variety of related topics. Their observations and theoretical studies provide parameters needed to improve the computer models at GISS, which in turn suggest new experiments and observations. The synergistic combination of Lamont and GISS will be critical to the nation's climate enterprise.

Lamont-Doherty and NASA's Goddard Institute for Space Studies in New York together represent an unparalleled treasury of climate expertise. The Center for Climate Research provides a focus of excellence in research for those outstanding scientists with a career interest in climate studies. It is a powerful source of the fundamental scientific work needed to support the efforts of those who must make decisions in planning for the best use of the world's natural resources. The Center for Climate Research is at the forefront of this great new scientific adventure.

How the Components of Climate Operate and Interact

The great challenge faced by the climate community is to develop a reliable computer simulation of the Earth's atmosphere-ocean-ice-soil system. Before this can be done we have to learn more about the basic operation of the components of these systems and about the interactions among them. Scientists at Lamont-Doherty Geological Observatory and the Goddard Institute for Space Studies are heavily involved in this activity. Lamont scientists are leaders in the area of exploiting information provided by the distributions of natural and anthropogenic trace substances. Goddard Institute scientists use these results to test their computer simulations.

Tropical Air-Sea Feedbacks

The most economic and often sociopolitical havoc is caused by climate variations in the intermediate scale, the Biblical "seven years of famine" — too long to ride out and too short to make major adjustments to. The prediction of such climate variations is of vivid interest to both atmospheric and oceanographic scientists.

Two key factors, temperature and precipitation, are modulated by the ocean: the ocean is the globe's reservoir, and its heat storage acts as a massive flywheel. Great currents flow within and between the world's oceans, transporting heat and affecting evaporation, which is controlled by the temperature difference at the interface between the ocean and atmosphere.

Certain regions of oceans, in particular in the tropics and at the poles, are the prime areas for studying the possible causes of the interannual trends in climate fluctuation. The vertical exchanges which occur there, internally within the atmosphere and the ocean, and between the two, are felt everywhere. Interesting statistical relationships have been established between the sea surface temperature in certain tropical areas with subsequent flooding and droughts in non-contiguous continental areas. Such hindsight predictions suggest that if we can develop a dynamical model that adequately simulates the atmosphere/ocean system we may achieve a true predictive capability.

One Lamont program in physical oceanography is a study of the seasonal response of the upper waters of the tropical Atlantic Ocean to the annual wind cycle. In 1983 and 1984 a joint program of the U.S. and France collected a comprehensive data set to describe both the forcing and subsurface currents, sea surface temperature and heat storage in the upper hundreds of meters, height of the sea surface and the wind velocity over that surface. Analysis of this data is expected to continue for several years.

Oceanographers tend to focus on what are the consequences of a particular forcing field on the ocean circulation. The 1983-84 data set is expected to provide a good part of the answer to that question. However, the connection with climate variation will not be made until the subsequent questions are answered: How does a variation in oceanic circulation feed back into the atmosphere, in turn affecting the forcing of the ocean? How do the variations of one year influence those of the following year, causing the multi-year cycles of feast and famine?

Polar Sea-Ice Feedbacks

Though only found at high latitudes and only one to three meters thick, sea ice is a key variable in climate sensitivity. It is critical to numerous processes and feedbacks in the climate system.

Only a thin layer of sea ice is sufficient to decouple the cold atmosphere from the relative warmth of the ocean, attenuating exchange of heat, water and gases. The boundary zone between the ice-covered and ice-free regions, the marginal ice zone, can have large temperature gradients and strong heat fluxes.

Sea ice is particularly important to the dynamics of the top layer of the ocean, the mixed layer. The atmosphere/mixed layer momentum flux is larger when there is a broken, drifting ice cover than when no ice exists. Sometimes, the warmer and more salty water below can be upwelled or turbulently entrained up into the mixed layer. This affects the heat balance and convective stability of the mixed layer. Ice melting/freezing is a source of fresh water/salt that can lead to stratification/convection.

The formation of the deep water of the world ocean is linked to sea ice. Off-shore winds over parts of the shallow continental shelves of the Arctic and Antarctic can carry the ice-cover offshore. As these open areas rapidly re-freeze, a cold, dense brine is produced that contributes to deep water. Sea ice also has a role in the production of deep water by deep, open-ocean convection in the Labrador Sea and probably in the Greenland Sea as well. This relationship between the atmosphere and the deep ocean is likely to be significant for climate change on long time scales.

The interaction of sea ice with other parts of the climate system is complicated by feedbacks. In the ice-albedo (reflectivity) feedback, for instance, a small rise in air temperature over the sea ice increases ice break-up and drift, and lowers ice albedo. Still higher air temperatures result, and a positive feedback is established. This positive feedback is one of the key mechanisms of the atmospheric warming and the retreat of sea ice that is likely to accompany the increase in atmospheric CO_2.

U.S. Coast Guard ice-breaker at Ross Sea ice shelf barrier, used by Lamont scientists collecting oceanographic data.

A wide range of sea ice research is in progress at GISS and Lamont. In the numerical modeling effort there is a focus on refining of sea ice processes in the GISS Global Climate Model, which is used to investigate paleoclimates and the CO_2 warming. Both modeling and field work are used to study sea ice processes on the spatial scales of 1-100 km, particularly those of the marginal ice zones in the Arctic and the Antarctic. Research on the role of sea ice in deep water formation is now being initiated. These projects interact with research in such diverse fields as the atmospheric boundary layer and ocean eddy dynamics because of the numerous processes linking sea ice to the atmosphere and ocean.

Soil Moisture Feedbacks

In order to understand and model the climate system one must be able to partition the rainwater after it reaches the Earth's surface. When it rains some of the water infiltrates the ground, and seeps into deeper levels of the soil. Another fraction pools on flat surfaces. Some may collect on leaves. Finally, that portion of the rain that does not infiltrate or collect runs off into streams and lakes, and eventually into the ocean. The soil structure and vegetation determine how much water infiltrates and how much runs off. Water that collects within the ground is available to evaporate back into the atmosphere, either directly or through plants. The water vapor may condense again, providing more rain. However, if the water runs off intially, it is no longer available to evaporate at that location.

Thus climate research involves the study of how the soil texture and structure influences water movement within the soil, how plants draw moisture from the soil and lose moisture through their leaves to the atmosphere. We need to know the distribution of soils over the globe, and what vegetation grows in different regions. GISS climate modelers are involved in disciplines such as geology, soil physics, physical geography and botany — as well as the more traditional climate-related subjects such as meteorology and climatology.

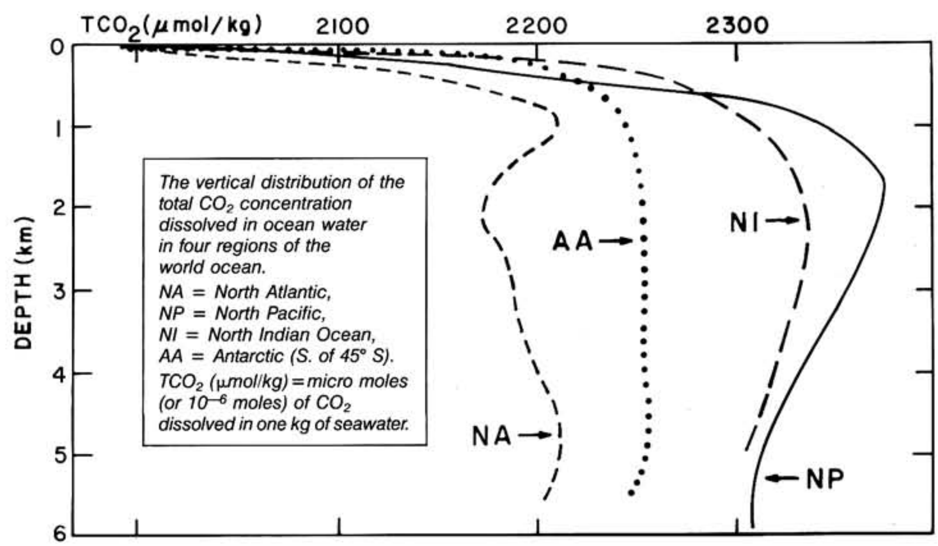
The Oceans as CO_2 Reservoir

The oceans are an active chemical reservoir for climatically sensitive gases such as CO_2. They contain as dissolved CO_2 molecules in seawater about 50 times as much CO_2 as the atmosphere, and they also exchange CO_2 with the atmosphere. A huge amount of carbon (about 50,000 times that in the atmosphere) is present in the lithosphere as limestone ($CaCO_3$), and organic residues. Through the combustion of fossil fuels and calcination of limestones for cement production this lithospheric carbon is being released into the atmosphere at a rate so rapid that the atmospheric CO_2 content could double the pre-industrial level by the year 2100.

The climatic changes anticipated include global warming and changes in the pattern of precipitation and wind, as well as a rise in sea level due to melting of polar ice. This in turn could alter the rate and pattern of the ocean circulation, changing the ocean's capacity to retain CO_2. If as a result the oceans discharged more oceanic CO_2 to the atmosphere there would be further and possibly dangerous "runaway" climatic change. Alternatively, the ocean's response might actually alleviate an increase in the atmospheric CO_2 content and inhibit further climatic changes.

A major scientific objective is to develop a capability for estimating and modeling the ocean's feedback to climatic changes. The first step is to understand how CO_2 is exchanged between the atmosphere and the oceans, and how it is transported and stored within the oceans.

Marine chemists at Lamont and elsewhere have determined the distribution of dissolved CO_2 in the world oceans (see figure). The concentration is lowest in the surface water, where the ocean is in direct communication with the atmosphere, and it increases with depth. The concentration in deep water differs in each ocean basin: Atlantic deep water is lowest and the Pacific deep water is highest. The observed distribution is only qualitatively understood. In the photic zone near the surface of the oceans, the CO_2 is fixed by photosynthetic plankton, thus reducing the dissolved CO_2 concentration. These plankton die and sink; they are decomposed by microbial activity and release CO_2 and associated nutrient chemicals (phosphate, nitrate and others) to the surrounding deep water. The CO_2 and nutrients released are carried by deep ocean currents, and eventually are brought back to the surface ocean through complicated water circulation paths. Thus the amount of CO_2 contained in the oceans is governed by complex interactions between the horizontal and vertical circulation of ocean water, as well as biological processes in the photic zone and in the deep ocean.



The vertical distribution of the total CO_2 concentration dissolved in ocean water in four regions of the world ocean.
NA = North Atlantic,
NP = North Pacific,
NI = North Indian Ocean,
AA = Antarctic (S. of 45° S).
TCO_2 (μmol/kg) = micro moles (or 10^{-6} moles) of CO_2 dissolved in one kg of seawater.

Isotopes of Water

Stable isotopes of water have long been used to study past climates because they have different masses, react at different rates, and are separated from one another during important hydrologic processes such as evaporation and condensation. Lamont studies of isotope ratios in ice cores, paleogroundwaters and tree rings have shown these ratios vary with climate, in particular during glaciations. By putting stable isotopes of water into the hydrologic cycle of the GISS General Circulation Model (GCM) we can learn how the GCM water cycle works both during glaciation and for modern conditions.

The stable isotopes of water commonly used in geochemistry are protonium (^1H), deuterium (D), oxygen-16 (^{16}O), and oxygen-18 (^{18}O), and the radioactive isotope of water tritium (T). Tritium is a very powerful tracer for studying the hydrology in a GCM. During the nuclear weapons tests in the 1950's and 1960's, enormous amounts of tritium were released to the atmosphere. This provided geochemists with a "spike" of the water cycle that could be followed in vapor, rain, groundwaters and the ocean. Tritium experiments can be conducted in the GISS GCM, and then followed as it moves about in the hydrologic cycle.

One remarkable discrepancy has already been uncovered using tritium. It is currently believed that three fourths of the tritium that entered the world's oceans did so by vapor exchange — i.e. via condensation on the ocean surface. The other fourth entered through precipitation, including continental runoff in rivers. However, the GISS GCM predicts that these pathways carried equal amounts of tritium to the ocean — an enormous difference. We have uncovered a flaw in either the GCM simulation of the water cycle or in our interpretation of the tritium observations.

Ocean Tracers

The ocean plays a major role in the global budgets of heat and carbon dioxide: CO_2 absorbs radiation emitted by the Earth, and as the CO_2 content of the atmosphere increases, the Earth's temperature increases. Heat is exchanged between the ocean and the atmosphere, and the ocean transports heat from one part of the Earth to another. The prediction of weather a few months ahead requires modeling of heat exchange between the ocean and atmosphere over the entire globe. To predict climate a few decades it is necessary to model both the heat exchange and also the CO_2 content of the atmosphere.

The heat exchange and oceanic heat transport is governed by ocean circulation and mixing. CO_2 also exchanges between the ocean and atmosphere. In some regions CO_2 is transported from the ocean to the atmosphere, and in other regions vice versa — the location of the exchange is controlled by ocean circulation and mixing. Today, the CO_2 content of the atmosphere is increasing, and more CO_2 is entering the ocean than leaving it. The rate at which this CO_2 is entering the ocean depends on ocean circulation and mixing, and the gas exchange rate.

Although general circulation patterns are known, especially in the upper ocean, little is known about current speeds and direction for most of the deep ocean. The magnitude of vertical and horizontal mixing is not well known for any region of the ocean, and it is not possible to predict how rapidly a substance introduced to the ocean surface will penetrate the interior regions of the ocean. It is known that the gas exchange rate increases as wind speed increases, but the functional dependence is not understood.

The Lamont ocean tracer program holds great promise for investigating and modeling ocean mixing and circulation, and gas exchange. There are steady-state tracers, naturally occurring radioactive substances whose distribution is not changing with time, and there are transient tracers, substances that have been introduced as a result of human activity only recently, and whose distribution in the oceans is changing with time.

The distribution of a steady-state tracer is maintained by a balance between supply, mixing and circulation, and destruction by radiodecay. Their decay rates are well known, and we know something of the supply of these tracers to the ocean. Therefore we can learn about mixing and circulation from their oceanwide distribution. Radon-22, with a half-life of 3.8 days, is used to estimate the gas exchange rate across the air-sea interface, and the rate of vertical mixing near the ocean floor. Argon-39 (269 years) and carbon-14 (5500 years) are used to investigate deep ocean mixing and circulation.

Transient tracers, have not yet been dispersed throughout the entire ocean. For some of them we know how rapidly their concentration in the atmosphere and in the surface ocean has changed with time. The rate at which they are dispersed in the ocean depends on circulation and mixing rates, and we can determine these rates by measuring the distribution of these substances in the ocean at various points in time. They also reveal the pathway that any compound dissolved in the surface ocean will follow to the deep ocean.

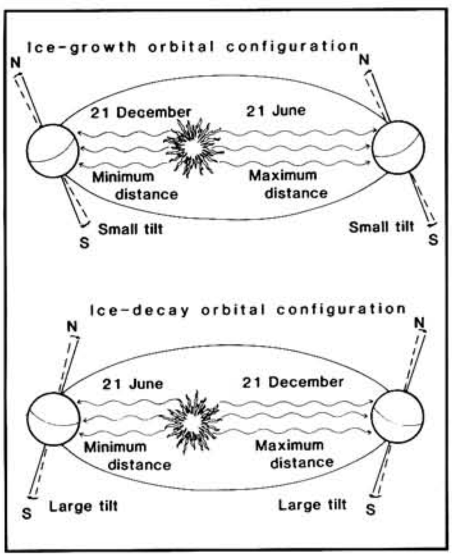
Climate Changes in the Past

Historical observations tell us of the El Niño events that have great impact on the climate of many regions. Records kept by trees allow us to assess the frequency with which damaging droughts beset us. Sediments from the floor of the sea and the bottom of lakes tell us not only how climate has changed on the 1,000 to 1,000,000-year time scale, but give us powerful clues about the causes of those changes. Lamont scientists are in the thick of the effort to reconstruct the changes, and together with scientists from GISS they seek to understand their implications for future climate changes that might stem from man's activities.

Orbital Changes and Climate

In 1941 the Yugoslav astronomer M.M. Milankovich hypothesized that ice ages begin when summer insolation at critical latitudes in the Northern Hemisphere (ca. 65°N) decreases to values low enough to cause the snow to descend and intersect regions of high terrain, so that large fractions of ice and snow survive from the preceding cold season. As the ice cover grows, increased reflectivity aids the glaciation process. Scientists at Lamont-Doherty have played a key role in confirming this hypothesis with their discovery that the waxing and waning of the ice has been periodic and is controlled by the Earth's orbital variations.

This orbit/climate link guides atmospheric scientists at GISS in using sophisticated numerical models to clarify specific mechanisms in the Earth's response to changes in the amount of energy reaching Earth from the Sun. It also ties together data on past changes in the ocean circulation system — previously considered unrelated. The basic discovery gives rise to many questions: Why does the Earth respond so severely to such a small forcing? How do these large changes affect smaller changes in climate? Can understanding this phenomenon elucidate the "greenhouse effect"? What areas of the Earth respond to changes in Earth's orbit most quickly, and do these areas introduce climate changes that cause further change elsewhere?



There is a relationship between the Earth's orbital elements (tilt, precession, eccentricity) and the presence or absence of ice ages in the past. The figure above shows the orbital configurations of the Earth and Sun during periods of rapid ice-growth and ice-retreat.

Predicting the El Niño Anomaly

There is a two-way interaction between atmosphere and ocean in the tropics: the distribution of Sea Surface Temperature (SST) influences both the atmospheric circulation and the distribution of tropical rainfall. The pattern of tropical rainfall heats the atmosphere and so influences the surface winds over the tropical ocean. These winds drive the current system in the upper layers of the tropical oceans, influencing the sea surface temperature. Along with this interactive loop there are important side effects: changes in tropical rainfall patterns cause changes in global weather. Changes in the ocean affect the upwelling of nutrients, with important consequences for the marine ecosystem.

There has been a growing realization that these interactions are implicated in the year-to-year variations in climate. Understanding this natural climate variability demands that the tropical ocean and atmosphere be considered together as a coupled system.

In the past decade computer models developed by oceanographers have reproduced the major variations of the tropical ocean when forced by specified surface winds. Meteorologists have modeled the changes in the atmosphere when SST distribution is prescribed. We are now only beginning to understand the behaviors that become possible when atmosphere and ocean are both free to respond to each other.

The most energetic and best defined pattern of interannual variability is the global set of climate anomalies referred to as ENSO, an acronym derived from its oceanographic component, El Niño, and its atmospheric component, the Southern Oscillation.

The interactions that sustain the ENSO cycle are an instance of the general scheme described above, acted out in the tropical Pacific. Fig. 1 shows the normal state of affairs: The Pacific is warmest in the west and coldest in the east. There is a tremendous center of tropical rainfall over the pool of very warm water in the far western Pacific. The easterly tradewinds blowing toward this atmospheric heating region drive warm surface waters to the west at the same time that they pull colder subsurface waters upward at the east. Thus the temperature contrast responsible for the atmospheric circulation is maintained by that circulation.

If, as in Fig. 2, the eastern ocean somehow becomes warmer, then the rainfall spreads eastward with the warm water, and the surface winds slacken. As a result, some of the warm western water moves eastward while less cold water is upwelled. Hence the east becomes still warmer and the interactions shown in Fig. 2 continue to operate. This is an El Niño event.

The interactions shown in Fig.1 and Fig. 2 were first hypothesized by the meteorologist Jacob Bjerknes two decades ago. Either phase seems self-sustaining, and Bjerknes could not explain why there were transitions from one phase to the other in an endless cycle. Lamont oceanographers and modelers have recently developed a theory for the swings of the ENSO cycle. The key idea requires going beyond the vertical plane along the Equator and considering the north-south circulation in the ocean. The equator *is* special and the ocean behaves differently there. At the peak of an El Niño event water moves not only from west to east, but also poleward, emptying the reservoir of warm water at the Equator (Fig. 3). After a time there is no longer enough warm water to sustain above-normal surface temperatures in the east and the El Niño begins to decay. The aftermath of this decay (Fig. 4) leaves the eastern Pacific colder than normal, and the easterlies stronger than normal — an enhanced version of the normal situation of Fig. 1. The transition to the El Niño state of Fig. 2 cannot take place until enough warm water flows back from the higher latitudes to refill the equatorial heat reservoir. Before that happens the easterlies may slacken, but there is not enough warm water available to sustain the "chain reaction" that generates an El Niño.

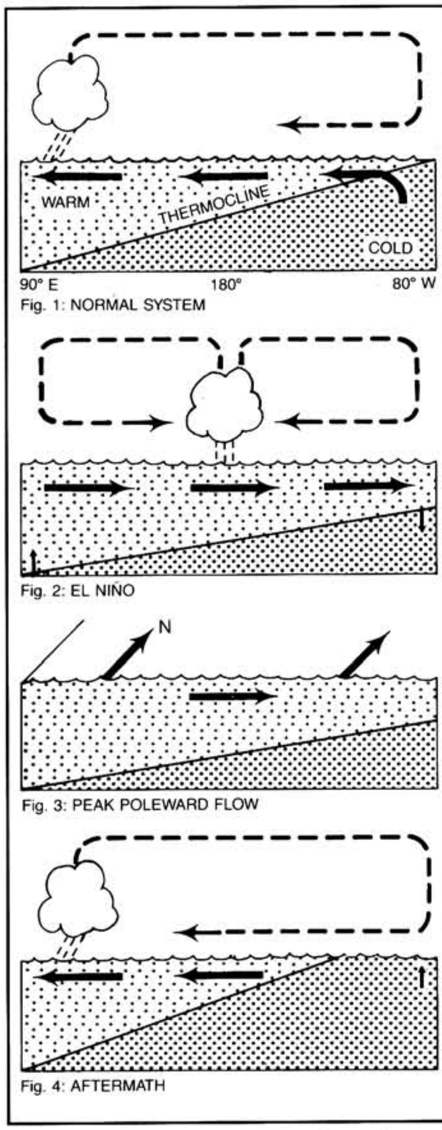


Fig. 1: NORMAL SYSTEM

Fig. 2: EL NIÑO

Fig. 3: PEAK POLEWARD FLOW

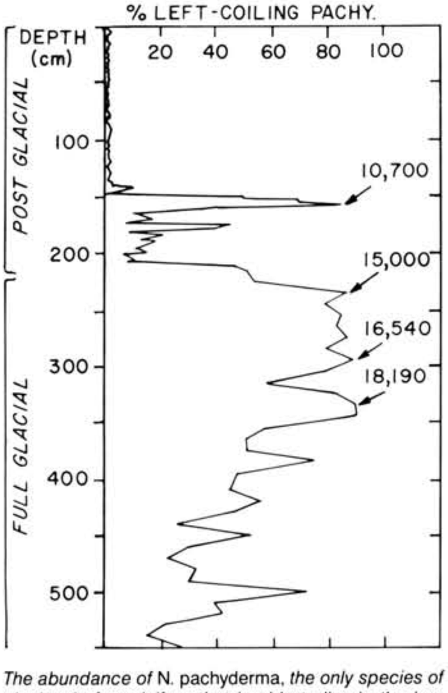
Fig. 4: AFTERMATH

Abrupt Climate Change

Abrupt climate changes, unlike the major glacial and interglacial cycles of the last two million years, appear too rapid to be directly related to the Earth's orbital variations. The origin of these rapid (i.e. decades to centuries) large-scale climatic events must lie in some feedback of the ocean-atmosphere-cryosphere system or in an external cause such as volcanic eruptions or solar events. Possibly they represent a seesawing from one stable climate system to another as a result of changes in the circulation of the deep ocean. Understanding the rapidity, magnitude, and distribution (both spatial and temporal) of such events will permit us to better assess the likelihood and implications of such oscillations in the future.

The Earth's paleoclimatic record reveals such abrupt changes most clearly in variations in oxygen isotopes in ice cores from Greenland and Antarctica, carbonate isotope stratigraphy in lakes, faunal and floral remains in ocean sediments, and micro and macrofossils from lakes and bogs. Abrupt species change about 11,000 years ago indicate that dramatic changes took place in the position of the polar front in the N. Atlantic Ocean. Similar surface water changes are being investigated through accelerator radiocarbon dating of foraminiferal shells 25-40,000 years old.

Studies of the sensitivity of the paleoclimate system to abrupt paleoclimate change are possible through the 3-dimensional global climate model (GCM) at GISS. Thus when colder ocean surface temperatures are introduced to the North Atlantic, the model produces large changes in air temperature over northwestern Europe. This suggests, for instance, that the "Little Ice Age" might have been caused by a cooling of the North Atlantic water.

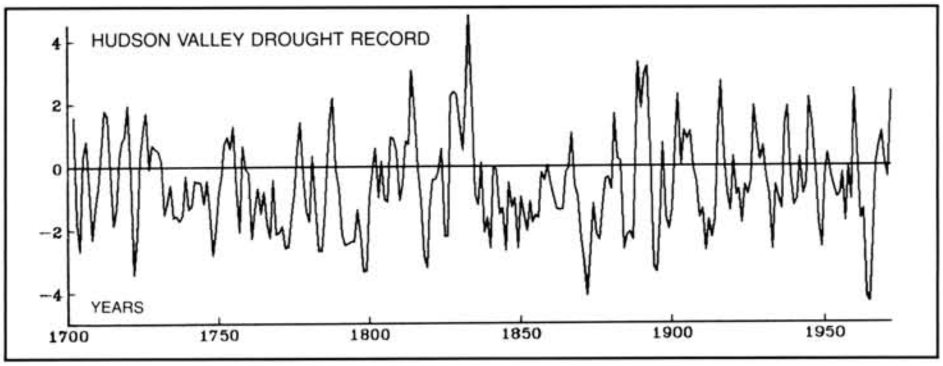


The abundance of N. pachyderma, *the only species of planktonic foraminifera that is able to live in the ice-filled waters of the East Greenland current, traced as a function of depth in a sediment core taken off England. The sharp peak in the abundance of this species 10,700 years ago (as determined by accelerator radio-carbon dating) marks a brief time of intense cold in the northern Atlantic region.*

Tree Rings and Droughts

Dendroclimatology—the reconstruction of past climates from tree rings—was originated over 70 years ago, in the arid Southwest. The open-canopy trees of that region are relatively free from competition from other trees for light and moisture, which made it easier to achieve the absolute year-by-year dating of tree-rings, the standardization of raw data from the measurement of such growth rings, and the application of these data to reconstruction of rainfall, streamflow and other climatically dependent phenomena in that region. Scientists at Lamont's Tree Ring Laboratory have pioneered new methods required for quantitative dendroclimatology in close-canopy semi-humid environments of the Northeast. They have become sophisticated in selecting the sites and species that render the truest chronologies, and skillful at analytical computer techniques that remove non-climatic effects and idiosyncratic tree responses from the record.

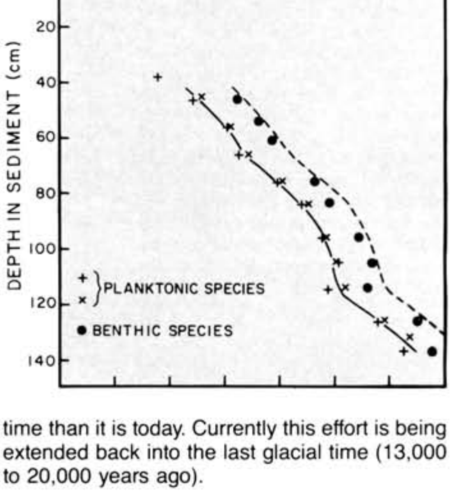
The extraordinary drought of the 1960's in the Northeast led to legislation requiring evaluation of water supply and demand, and vulnerability to future droughts. The Tree Ring Laboratory is now embarked on a program of climatic reconstructions of specific areas and variables. They have established a drought chronology of the Hudson Valley going back to 1702, a reconstruction of Potomac River Basin streamflow, going back to 1730, and a regional assessment of drought in the Middle-Atlantic states going back to 1700. So far these longer records indicate that except for that of the 1960's the Northeast has been relatively free of serious drought in this century, a period that coincides with the greatest population expansion, industrial growth and water-supply development. But the longer perspective indicates that extended and sometimes severe droughts occurred more often prior to 1900, and seem to be occurring more frequently since 1960. This increased precipitation variability is set against a static or even decreasing supply system, coupled with increasing demand. Thus the likelihood is for more frequent and more critical water supply shortages in the near future.



Index of moisture surplus or deficit in the Hudson Valley. Negative numbers indicate drier than average conditions. An index value of —2 represents a moderate drought; —4 extreme drought.

Paleoocean Circulation Rates

While climatologists are convinced that the ocean has played an important role in past climate changes, little is known about changes in the operation of this great system. The advent of accelerator mass spectrometry has opened a way to get into this difficult subject. It allows radiocarbon age determinations to be made on one-milligram carbon samples (as opposed to 1,000 milligrams by the decay counting method). This permits the dating of hand-picked foraminifera samples from deep sea sediment cores. By comparing ages obtained on benthic (bottom dwelling) foraminifera and planktonic (surface dwelling) foraminifera from slices from deep sea cores it is possile to compare the ^{14}C age of deep waters over the last 20,000 years with those for today's ocean. Working cooperatively with scientists in Switzerland geochemists at Lamont have made the first application of this new technology. The results as shown in the figure suggest that the rate of ventilation of the deep Pacific Oean was the same or perhaps slightly faster during Holocene time than it is today. Currently this effort is being extended back into the last glacial time (13,000 to 20,000 years ago).



Climates of the Future

The better our understanding of climate the better our ability to predict coming changes. The build-up of CO_2 and other "greenhouse" gases is at the front of most planners' minds. While most scientists agree that our planet is in for a warming, the signals are far from clear. Despite a 30% increase in CO_2, a doubling of methane and the appearance of manmade greenhouse gases such as freon in our atmosphere, no clear evidence for warming can be seen. Scientists interpret this disparity as an indication that the greenhouse warming is being temporarily masked by natural cooling or manmade cooling. Changes in the atmosphere's dustiness is a prime suspect in this regard. This must be clarified before we can confidently predict the consequences of our industrial activity.

Modeling CO_2 Climate Effects

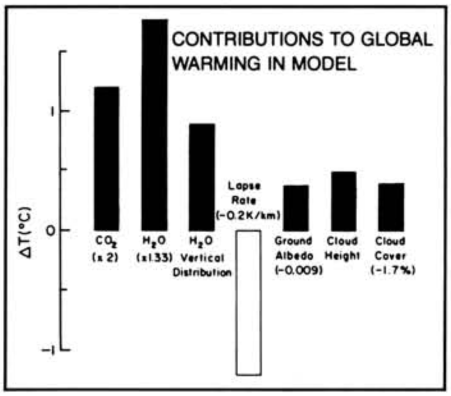
It is known that the composition of the Earth's atmosphere is changing, at an increasing rate, due to anthropogenic activities such as burning of fossil fuels. Man is adding not only carbon dioxide, but also methane, nitrous oxide, chlorofluorocarbons ("freons") and other gases to the atmosphere. These gases all absorb thermal radiation emitted by the Earth's surface, and thus tend to warm the lower atmosphere and ground in what is called the "greenhouse effect."

Increase of CO_2 and other gases is expected to be the dominant force for climate change during the foreseeable future. Important climate effects may begin during the next few decades, with the potential impact including an increased frequency of summer heat waves, changed rainfall patterns, changes in the frequency and geographical distribution of hurricanes, increased melting of glaciers and ice sheets and modifications of the extent and vigor of vegetation types. Since the climate system has large inertia, once such changes are begun they will be difficult to reverse. Thus it is important to develop accurate predictions of the future climate changes before mankind has gone too far down the path of atmospheric modification.

For this purpose, global models are being developed which can numerically simulate climate on the time scale of decades to a century. Such three-dimensional models now include a broad range of weather and climate phenomena such as tropical thunderstorms, mid-latitude high and low pressure systems and the high reflectivity of polar ice sheets. But the world's climate is so complex that models still must make great simplifications, and many important processes are omitted or oversimplified. Thus, although the models can be used now for some interesting climate sensitivity experiments, reliable prediction of future climate depends on further model development as well as testing and verification of the models.

Much of this work is now going on at the NASA Goddard Institute for Space Studies in cooperation with scientists at Lamont-Doherty. A prinicipal example is the use of reconstructions of past ice ages and climate cycles, developed at Lamont, to test the realism and sensitivity of the global climate models. The models can also be tested by using them to simulate climates on other planets, the climate changes in the past century and the seasonal pattern of today's climate. It is hoped that this work will lead to models sufficiently realistic for reliable climate predictions, and thus provide a tool which can be used by decision makers on issues of gas emissions and future climate.

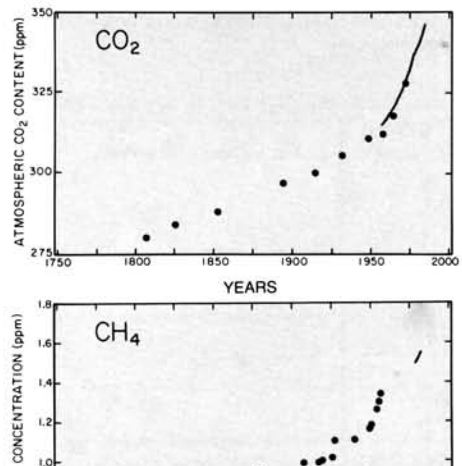
The GISS computer-based simulations of the effects of a CO_2 doubling reveal a number of feedback processes which either amplify or compensate for the primary "greenhouse" effect.



CO_2 and CH_4

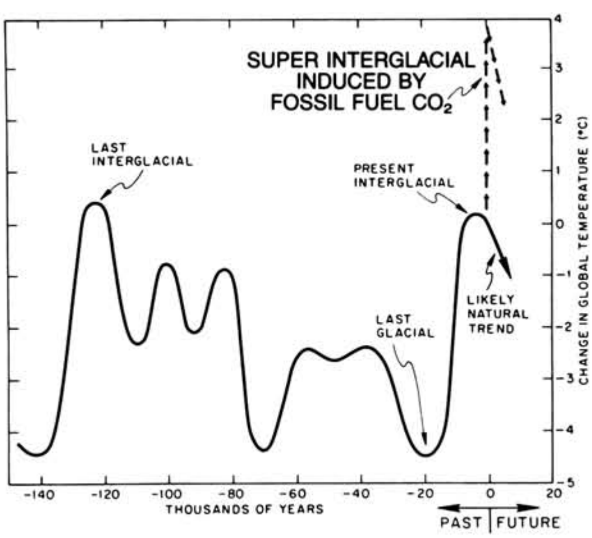
Measurements made on air trapped in bubbles in polar ice allow the instrumental records of the CO_2 and CH_4 content of the atmosphere to be extended back over the last several hundred years (see figure). In order to predict future changes in the atmospheric contents of these two important greenhouse gases it is necessary to understand their sources and sinks. For CO_2 the main source is the burning of fossil fuels. This contribution can be well documented. Secondary sources are forest cutting and soil tilling. The magnitude of these contributions is the subject of much controversy. The major sink for CO_2 is the ocean. A major effort is under way at Lamont to gather data and construct models which will allow our estimates of the extent to which the ocean has and will take up the excess CO_2 from the atmosphere.

For methane the major anthropogenic sources appear to be rice paddies, cows and other ruminants, and forest fires. The magnitudes of these sources remain uncertain. A project is under way at Lamont to use the isotopic composition of methane ($^{13}C/^{12}C$, D/H, $^{14}C/^{12}C$) to further constrain the importance of these sources.



Reconstruction of the atmospheric contents of two "greenhouse" gases, carbon dioxide and methane, over the last two hundred years. The solid circles are based on measurements on gases extracted from Antarctic ice samples (by scientists in Bern, Switzerland). The solid lines are instrumental records.

***Undoubtedly, the most significant** new parameter in the complex role played by the atmosphere governing the earth's temperature is the addition of carbon dioxide and other gases by man. The effects of these gases on the way man inhabits the earth may be truly profound. If the global warming predicted by the climatic models at NASA's Goddard Institute for Space Studies in New York (GISS) should take place, the increase will be comparable to that experienced between the coldest glacial and the warmest interglacial periods of the past million years.*



CO_2 Effects on Polar Ice

Because of the "greenhouse effect," increasing CO_2 can lead to increasing atmospheric temperature. Some scientists are evaluating the potential benefits of this impact, which might include increased agricultural productivity. But there are problems as well, such as the question of increased glacial melting leading to a potential 10- 20-foot rise in sea level. Studies indicate that atmospheric warming of several degrees will not, but itself, accomplish much surface melting of either the Greenland or Antarctic ice sheets, since most surface temperatures there would still remain below the freezing point year-round. The ocean water, which is at least periodically above the freezing point, has contact with about half of the Antarctic glacial ice perimeter and with the base of 10-15% of the ice cap that is floating in the ocean as ice shelves.

Lamont scientists have shown, from measurement of temperature, salinity, currents and various geochemical tracers that ocean-induced glacial melting is likely to be a significant factor in Antarctica's ice budget. Evidences of this glacial meltwater, and of anthropogenic inputs such as tritium and freon, have been identified throughout the shelf water and in the deep and bottom water near the Antarctic continental margin, where the deep ocean is ventilated. Warm water has been traced from the deep ocean to the base of the glacial ice, and it has been postulated that variable ice thicknesses may be related to the position and temperature of these inflows. How the ocean effect might be altered with a CO_2-induced global warming is a very important research question which must be answered to fully assess the CO_2 effect on sea level.

It might be of only academic interest if just the floating glaciers and glacial ice shelves were to melt away over the next several decades. After all, a floating ice cube displaces the same volume as its meltwater. However, some glaciologists believe that the flow of ice off the Antarctic continent may be retarded by the ice shelves, without which the outflow would be so rapid as to constitute a "collapse" of the West Antarctic ice sheet.

As sea level rises in response to thermal expansion and to the input of meltwater from continental ice, then the ice shelves will rise along with it, eventually lifting off grounding points which have retarded their flow. More rapid movement to the north could expose their northern edges to greater melting or calving, and allow a faster draw-down of the interior ice sheet. In short, the interactions are complex, the measurements must be made in extreme environments, and the effort must be carefully coordinated among several disciplines. These needs nicely coincide with relevant Lamont experience, and with its tradition of close collaboration between oceanographers, geologists and geochemists.

As the significance of the ice to large-scale climate patterns and variability becomes more apparent, there will be more ambitious attempts to gather the data necessary to resolve the relevant processes and develop effective polar inputs to climate models. Lamont oceanographers are particularly active in this quest.

Future Climate: Hot or Cold?

Several research teams at Lamont and GISS are involved in one of the major challenges of our time: to find out how manmade atmospheric pollution will change future climate.

The increased burning of oil and coal and the cutting down of forests has led to a recent rapid increase in the concentration of atmospheric carbon dioxide (CO_2). It is feared that this will lead to an unprecedented worldwide change of climate. A major international effort, led by the U.S. Department of Energy, is attempting to determine the seriousness of the CO_2 threat and what action can be taken to alleviate the potentially dire consequences.

The problem however, is complicated. CO_2 is not the only changing variable in the climate system. Ash and sulphur compounds released from burning fuels have a cooling impact. On longer time scales the Earth is gradually shifting into an orbital configuration which favors glaciation. Ocean currents are suspected of changing on the time scale of decades and centuries. The amount of energy emitted by the sun which drives the Earth's climate is known to fluctuate as well. We are still far from having the answers to the interaction of all these processes.

Computer models of climate, such as the one at GISS, are used to predict changes of the global mean surface temperature due to the increased concentrations of CO_2. It is not known whether the long-term trend in the global mean temperature will be toward warming as expected from the CO_2 rise or toward cooling. This is principally because it is not known how the natural climate would be changing if unaffected by man over the next several decades.

Models are still unable to predict regional changes of temperature or precipitation. For example, how will precipitation change in the cornbelt? Will sea level rise, flooding coastal cities like Miami? Will the winters grow longer or shorter in Vermont?

One of the efforts now underway is to evaluate records of temperature, precipitation, wind velocity and direction to see weather trends attributable to the CO_2 increase which has already occurred can be identified. Surprisingly, no clear signal can be discerned. The reason for this is not clear. Scientists at both Lamont and GISS are involved in these studies.

S. SAVAGE

Over 100 scientists attended *an International Symposium on Milankovitch and Climate at Lamont-Doherty in December, 1983. The meeting was focused on the orbital theory of ice-age climates proposed in the 1930's by the Yugoslav mathematician Mulutin Milankovitch (see p. 4). The Symposium considered the accumulated geological evidence for the theory for past glaciations, and then focused on a review and an evaluation of the progress made in understanding and modeling the physical mechanisms by which the climate system responds to the calculated changes in the patterns of incoming solar radiation.*

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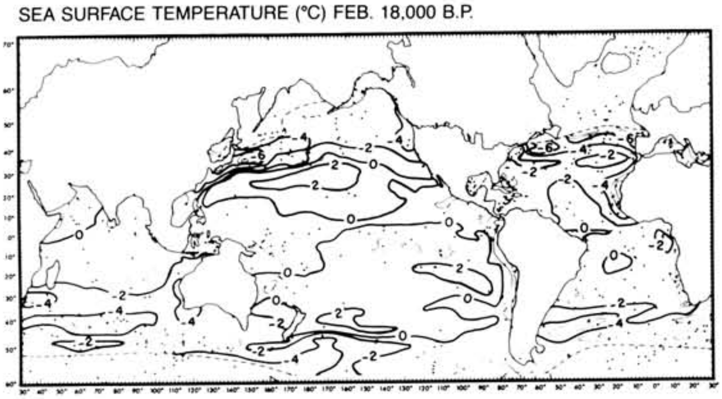
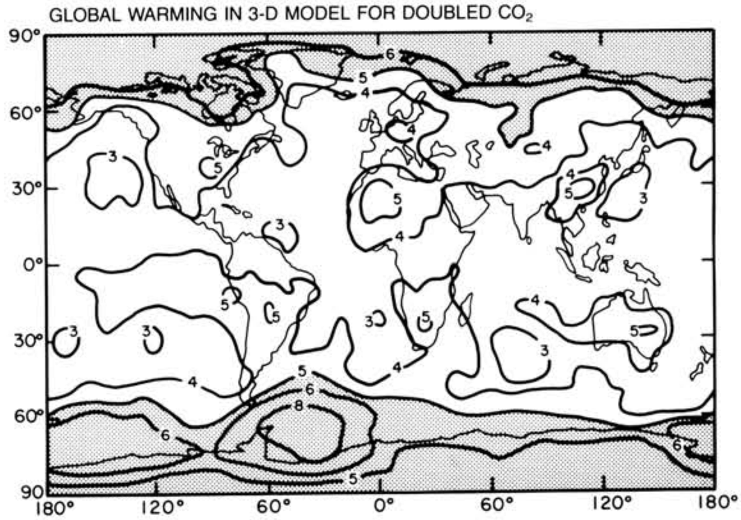
SEA SURFACE TEMPERATURE (°C) FEB. 18,000 B.P.



GLOBAL WARMING IN 3-D MODEL FOR DOUBLED CO_2



At left, map based on work of members of Project CLIMAP, centered at Lamont-Doherty, showing the difference in ocean-surface temperature, reconstructed from marine sediments for the peak of the last glacial period. At right, map calculated by using the GISS General Climate Model shows the difference in ground-level temperature assuming a doubled atmospheric CO_2 content.