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Man's Great Geophysical Experiment: Can We Model the Consequences?

by Kirk Bryan

Man's Great Geophysical Experiment:

Greenhouse gases in the atmosphere produced by modern man are changing the global radiation balance—Carbon Dioxide and Climate: A Scientific Assessment. Climate Research Board, National Academy of Sciences, 1979. *Resulting climate trends, however, depend on complex interactions between the ocean, atmosphere, and biosphere. Is it possible to harness existing knowledge of ocean and atmospheric circulation to build models accurate enough to forecast the climate consequences of a probable buildup of greenhouse gases continuing well on into the 21st century?*

by Kirk Bryan

Professor Roger R. Revelle, former director of the Scripps Institution of Oceanography and doyen of ocean scientists, calls the buildup of greenhouse gases* in the atmosphere "Man's greatest geophysical experiment." A greenhouse gas in the atmosphere absorbs the invisible, long-wave radiation to space that serves as the Earth's indispensable air-conditioning system. Hence, the greenhouse gases tend to trap heat within the atmosphere, and, in the absence of negative feedback, cause climate warming. The oceans are a very important component of the incredibly complex climate system. This is particularly true when climate is in the process of changing. Is it possible to synthesize existing knowledge of the oceans and atmosphere into mathematical models in order to provide a guide to future global changes in temperature and rainfall patterns? Providing such a forecast is the most intellectually challenging problem now confronting Earth scientists.

The most ubiquitous natural greenhouse gas of all is the natural blanket of water vapor in the Earth's atmosphere. Almost everyone has experienced the great difference in night-time cooling between a dry desert climate and a moist humid climate. Revelle's attention was first attracted to this problem through his pioneering work on the global carbon cycle.

Carbon dioxide is increasing, but it is still only a small constituent of the atmosphere. However, there is a limited band of wavelengths in which water vapor does not absorb outgoing long-wave radiation. This band from 7 to 20 microns, called the water vapor "window," is shown in Figure 1. Outside of this window, the transmission of thermal radiation in the lower atmosphere is effectively zero. It is within the window that carbon dioxide plays its important role.

Carbon dioxide has a high transmission over most wavelengths, but a very low transmission band within the water vapor window. The greenhouse

Roger R. Revelle, director emeritus of Scripps Institution of Oceanography, was awarded the 1986 Balzan Prize for oceanography and climatology from the International Balzan Foundation of Milano, Italy. Revelle pioneered research in oceanography and atmospheric conditions and was one of the first scientists to recognize changes in the atmosphere due to the "greenhouse effect."

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* Radiatively active gases in the atmosphere which are transparent to incoming solar radiation, but which absorb outgoing long-wave radiation, are called greenhouse gases. Carbon dioxide produced by the burning of fossil fuels is the most important man-made greenhouse gas.

Can We Model the Consequences?

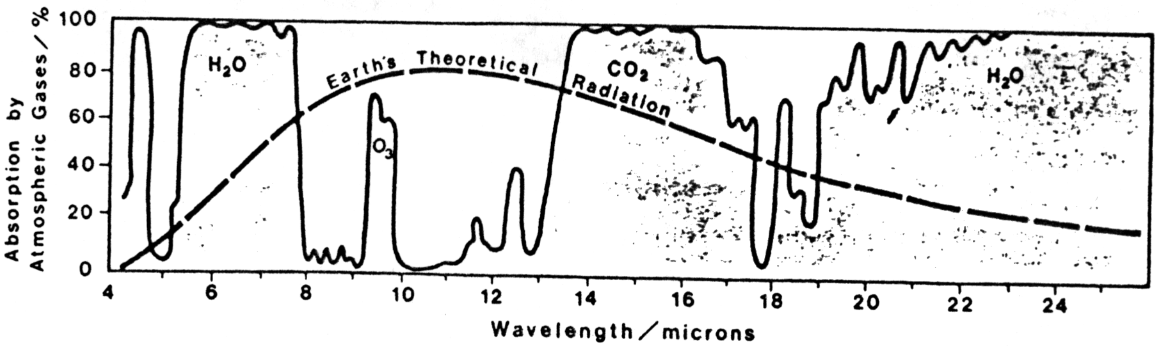


Figure 1. Wavelengths radiated by the Earth (dashed line) with percent absorption by atmospheric gases (solid line). The majority of radiation emitted from the Earth's surface lies in the wavelengths ranging from 4 to 80 microns, the infrared or heat portion of the electromagnetic spectrum. Although radiation of some wavelengths, notably those between 8 and 12 microns, is able to pass directly to space unless intercepted by cloud (clear area on graph), most of the outgoing radiation is absorbed by the atmosphere—principally by water vapor, and, in the "water vapor window," at least partially by carbon dioxide. (After K. L. Coulson, 1975. Solar and Terrestrial Radiation, *Academic Press)*

effect of carbon dioxide is particularly important because it absorbs long-wave energy in this window, blocking the escape of long-wave energy to space, and making the Earth's natural air conditioning system less effective. Recently it has become evident that other greenhouse gases, such as the chlorofluorocarbons (freons to the layperson), are also rapidly increasing in the atmosphere. The effect of these different gases is thought to be additive. Thus, the combined contribution of these other gases taken together could soon be comparable to the greenhouse effect of carbon dioxide alone.

Supercomputers and Modeling

The climate response to greenhouse gases depends on the interplay of many processes. For example, any warming of the atmosphere allows an increase of water vapor that in turn increases the greenhouse effect. Likewise, the melting of snow and ice decreases the reflectivity of the earth's surface and enhances climate warming. Many of these effects can be studied in the context of models of the atmosphere alone.

Extremely detailed mathematical models of the atmosphere have been developed and are now being used routinely in medium-range (4 to 10 days) forecasting by the U.S. Weather Bureau and the European Center for Medium-Range Weather Forecasting, located near Reading in England. Some components of these models, such as the radiation balance and the equations of motion for large-scale atmospheric flow, are developed from basic physical principles and can be verified in detail. Others, such as the formulation of clouds and precipitation, are more empirical, and are still in the process of development. A key factor in recent progress in atmospheric models has been the great increase in the power of supercomputers. One of the most detailed models of the atmosphere now in existence is being used at the European Center for Medium-Range Forecasting, where European countries have pooled resources and scientific manpower in a remarkably successful venture. As the power of computers keeps growing, it will become feasible to use these very detailed models as one of a variety of tools for testing climate sensitivity to greenhouse gases.

The ocean plays two very important roles in a greenhouse gas-induced climate change. First, the ocean absorbs carbon dioxide. In fact, a 1983 National Academy of Science report estimated that about half of the carbon dioxide produced by fossil fuel burning has already been taken up by the ocean. The growing importance of other greenhouse gases, which are not absorbed to the same extent by the ocean, make the carbon dioxide uptake by the ocean less crucial than previously thought.

The second role of the ocean, however, remains extremely important. This is related to the ocean's enormous ability to store heat. The thermal inertia of the ocean is very important in the transition from one climate regime to another. A complete adjustment of the ocean to a new climate requires thousands of years. Indeed, the deep ocean is

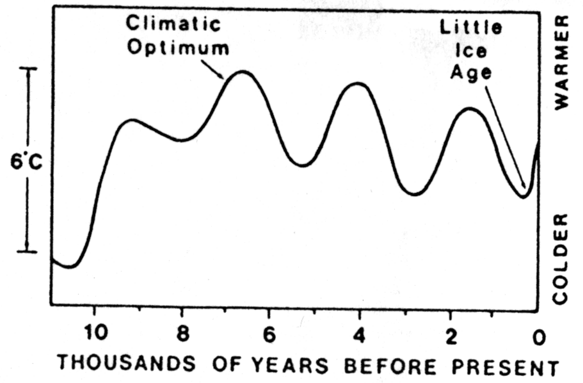
The Little Ice Age

"Our years are turned upside down; our summers are no summers, our harvests are no harvests," declared John King, an Elizabethan preacher in 1595. This bad weather was part of the Little Ice Age, when, although the land was not covered by ice sheets as in past geological ice ages, for a few hundred years the weather in Europe and America was considerably worse than today. Thus, although we tend to think of climate as stable, in fact, it can and does change—as the Little Ice Age attests to.

The Little Ice Age began near the end of the European Medieval period. The earliest known advances of mountain glaciers that heralded the Little Ice Age date to the 12th and 13th centuries. An early phase of cold climate lasted until the end of the 15th century, when a minor climate reversal occurred. The main phase of the Little Ice Age came when, in the early 17th century, many glaciers reached their greatest extent since the last glacial age. For some glaciers, the maximum was reached even later, in the early 19th century. About 1850, a general warming trend began and caused glaciers to recede dramatically, with minor halts or reversals occurring in the 1880 and 1890s, and again in the 1920s.

During the cold centuries of the Little Ice Age, the sea ice spread southwards. The ice edge at one time extended beyond Iceland to the Faeroes Islands, which lie 200 miles northwest of the Shetland Islands, and reportedly even allowed a polar bear to land there from the ice pack. As might be expected, ice played a large part in the change of climate during this period; but, whether this is cause or effect remains unclear until research into climate change reveals more about the mechanisms behind the large- and small-scale weather variations.

This climate change not only varied considerably from decade to decade, but also affected various parts of the world differently.



Climate of the past 10,000 years. The general trends in global temperature have been estimated from geological records of mountain glaciers and fossil plants. During the Climatic Optimum, temperatures were about 2 degrees warmer than at present. About 300 years ago, during a climatic episode known as the Little Ice Age, temperatures were cooler than at present. (After Imbrie and Imbrie, 1979, *Ice Ages*, Enslow Publ.)

Winters in China and Japan were actually milder during the Little Ice Age, because weaker winds from the west allowed them to benefit more from the warm Pacific air. The American Midwest was cooler and wetter than before or after the Little Ice Age, because the wet Pacific winds traveled further south across the country.

For the latter part of the Little Ice Age, deductions from old archives are paralleled by evidence from a worldwide network of meteorological observing stations, which have produced up to 300 years of continuous records of barometric pressure, wind speed, temperature, and rainfall. By reconstructing maps of typical air pressures over the North Atlantic and Europe, and then studying patterns of high and low pressure that produce these winds and weather, Hubert Lamb, chairman of

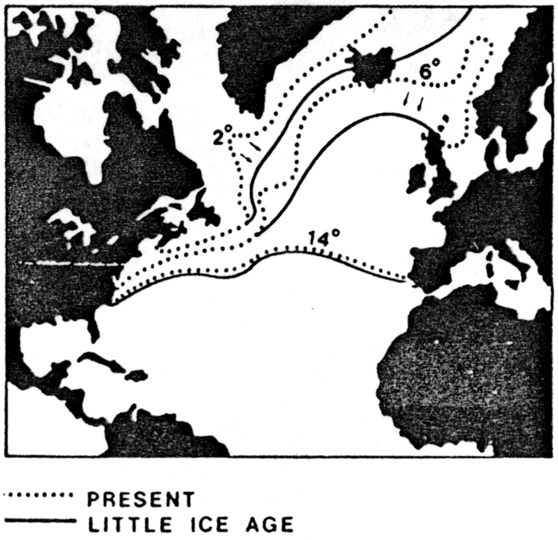
probably still adjusting to the present climate from the colder climate that prevailed during "the Little Ice Age" in the 17th and 18th centuries. Unfortunately, we have little quantitative data to guide us on how the ocean responds to long time-scale changes in climate forcing. This lack of data makes it difficult to verify the behavior of ocean models designed to estimate the thermal inertia of the ocean. Many experts feel that the possible role of the ocean in delaying the onset of climate change is one of the most uncertain factors in the entire question of the effect of greenhouse gases on climate.

Oceanographers have far less data for guidance in building models than meteorologists. Nevertheless, a remarkable increase in information has resulted from programs such as the Mid Ocean Dynamics Experiment (MODE), Geochemical Ocean Sections Study (GEOSECS), and Transient Tracers in the Oceans (TTO). The new data provided by these *the World Meteorological Organization, has shown that during the winters around 1800 the winds coming into western Europe from the Atlantic were weaker than those of the first 40 years of the 20th century. A weaker flow of air from the ocean would have made western Europe more vulnerable, in winter, to cold air from Scandinavia and northern Russia.*

The lack of vigor in the warm Atlantic winds also may help explain the weaker behavior of the Gulf Stream and the extent of the sea ice that spread from the Arctic. Temperatures of the North and South Atlantic sea surface, as measured by British and American ships from 1780 onward, show that, during the Little Ice Age, the warm current of the Gulf Stream took a more southerly course across the Atlantic and swung further south than it does now as it approached the coast of Europe. It was as if the countries of western Europe had moved 300 miles to the north, or, more precisely, the pattern of global winds, including the jet stream, had shifted south.

The weather pattern also shifted eastwards or westwards. For example, around the 1740s, Britain had relatively dry summers while Moscow was repeatedly wet; three decades later, the situation was reversed. The wavy motion of the jet stream, blowing from west to east over the stormy zone, but also zigzagging north to south, helps determine the wet and dry areas around the world. These areas are a compromise between the attempts of the jet stream to keep to a consistent wavy pattern right around the world, and the mountains, plains, oceans, and ice packs that impose their own pattern.

During the Little Ice Age, four such zigzags were probably common, as opposed to this century's pattern of three, because the jet stream was weaker and traveling further south. If so, the area of warm southerly winds would have been pulled westwards into the Atlantic, while Europe suffered wintry blasts from the Arctic. Such patterns of east-west variation, linked to the jet stream, also explain why the worst winters as recorded in Moscow and London seldom coincided.



The southward shift of the warm Atlantic water during the Little Ice Age. The Gulf Stream, which sweeps across the Atlantic and delivers warm water to Europe, was less effective.

Although the Little Ice Age was 'little' in severity—yearly average temperatures for that period were 8.8 degrees Celsius as compared to 9.4 degrees Celsius for the first 50 years of this century—and relatively brief in duration, studying its climatic changes could help us forecast what may occur in the future. However, this cooling trend with its enormous variety of weather, serves notice of the manifest complexities involved in predicting the next 300 years of climate.

—Eleanore D. Scavotto

programs are particularly important for showing us the similarities and differences between the dynamics of the ocean and the atmosphere. These insights are in turn important in deciding which features of atmospheric numerical models can be adapted for the ocean. The data base for modeling will be vastly improved with the measurements planned for the World Ocean Circulation Experiment (WOCE), an international program to take place from 1987–1995 (page 25).

Coupled Models

Climate variability on longer time scales can not be understood without taking into account the interaction of the ocean and atmosphere. This has motivated the building of a hierarchy of coupled models, ranging from the very simple, and somewhat abstract, to the increasingly detailed and complex. The more complex models of atmospheric and ocean circulation are similar to those used in numerical forecasting models, but as yet are far less

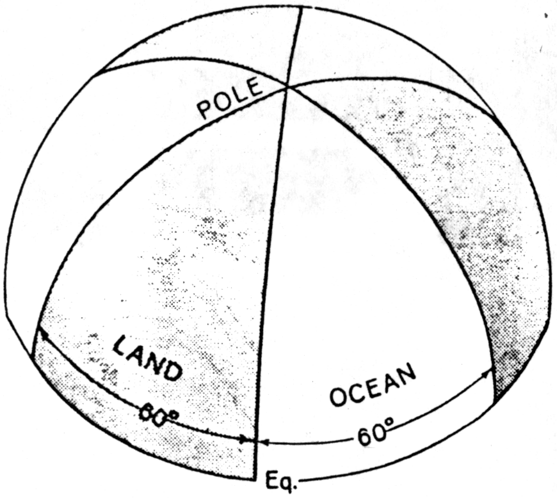


Figure 2. Effective modeling requires that complex systems be simplified. The numerical model of climate developed at the Geophysical Fluid Dynamics Laboratory, while it takes into account both the circulation of the ocean and atmosphere, is based on a highly idealized geography of the Earth. The atmospheric circulation is forced to be alike over each pair of ocean and land sectors, and the ocean circulation is alike in each ocean sector, with mirror symmetry across the equator. The atmospheric component includes individual cyclones and anticyclones, as well as a specification of rain and snowfall, and a detailed treatment of radiation. The ocean component simulates the separate contributions of wind action and of heat and salinity sources to the ocean circulation. (After Spelman and Manabe, J. Geophys. Res. 89, 1984).

detailed than the most advanced atmospheric models, such as those at the European Center. The simplified geometry of a coupled model developed with my colleague, Syukuro Manabe, at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, is shown in Figure 2. Similar coupled models also have been developed at Oregon State University and the National Center for Atmospheric Research, Boulder, Colorado. In the idealized geography of the Princeton model, each hemisphere is divided in six sectors which are alternately land and ocean. It is assumed that the circulation has a mirror symmetry across the equator and that it is the same in each of the three 120-degree longitude sectors around the hemisphere. This simplification reduces the calculation to only ⅙ of that required for an entire globe.

The atmospheric component of the coupled model predicts the flow of momentum, heat, and precipitated water into the ocean, as well as the loss of surface water as a result of evaporation. The atmospheric model has been used without coupling it to an ocean model by Manabe in many studies testing the sensitivity of climate to changes of carbon dioxide in the atmosphere. In coupling it to an ocean model, even the effect of river runoff on the salt balance of the ocean is taken into account in a simplified way. Where the model predicts temperatures below the freezing point of seawater, the numerical ocean model forms a thin layer of sea ice which tends to impede further heat exchange between the ocean and atmosphere.

The numerical representation is somewhat coarse (400 by 400 kilometers). The atmospheric component resolves individual storms, but the ocean model cannot resolve individual eddies, like the meanders in the Gulf Stream. Nevertheless, it does provide a simple representation of the thermohaline (density-driven) and wind-driven components of the ocean circulation.

Numerical Experiment

A numerical experiment is shown in Figure 3. The ordinate is the average sea-surface temperature. The lower horizontal dashed line represents the average sea-surface temperature for an equilibrium climate with normal atmospheric carbon dioxide content. The upper horizontal dashed line represents the average sea-surface temperature for a model climate with four times greater carbon dioxide.

The first stage of the calculation involves finding these two equilibrium climates by adjusting the ocean and atmospheric components of the model until a steady heat balance is achieved. It has been possible to find simulated climates in which the net drift of the ocean model was the equivalent of a flow of heat through the ocean surface of less than 1 watt per square meter. This is equivalent to a change of deep ocean temperature of 2 degrees centigrade per thousand years.

The second stage of the calculation is represented by the solid line in Figure 3. Starting with the steady climate for normal carbon dioxide, a numerical integration of the coupled model simulates the climate response when the carbon dioxide is suddenly increased by a factor of 4. The inertia of the ocean's heat capacity prevents an abrupt warming after the sudden increase of

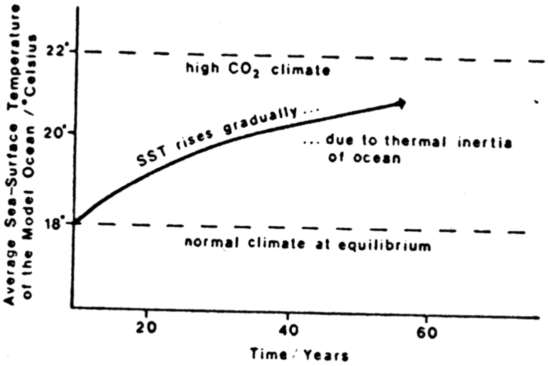


Figure 3. A numerical experiment to test the response of the Earth's climate to a rapid rise of atmospheric carbon dioxide. The ordinate is the average sea-surface temperature of the model ocean. The abcissa is a measure of time after a sudden increase of atmospheric carbon dioxide. The main factor in slowing the response is the thermal inertia of the ocean.

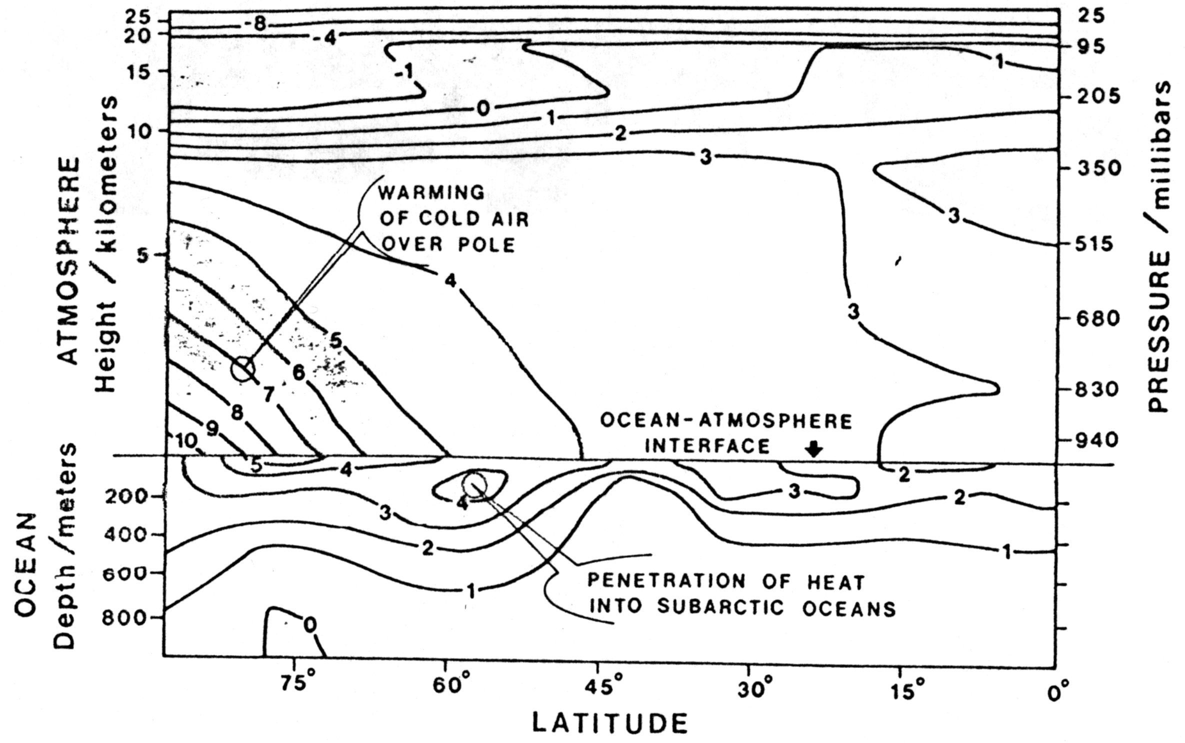


Figure 4. The zonally averaged excess temperature in the atmosphere and ocean in degrees Celsius predicted by the model one decade after the sudden increase of atmospheric carbon dioxide. Note the deep penetration of the excess heat into the ocean between 50 and 60 degrees North latitude. (From Spelman and Manabe, J. Geophys. Res. 89, 1984)

atmospheric carbon dioxide. The speed at which warming near the ocean surface takes place depends on the rate of penetration of excess heat into the ocean.

At present, the vertical pathways by which surface influences find their way downward into the main thermocline* are a matter of intense interest to physical and chemical oceanographers. A picture of penetration in the model 10 years after the sudden carbon dioxide increase is shown in Figure 4. In the upper part of the panel, the temperature changes that have taken place in the atmospheric model can be seen. Note that the largest change takes place in the lower atmosphere in polar regions. This is associated with a warming of a very cold dome of air over the pole. This "polar amplification" takes place primarily in winter. Even though the model predicts rather spectacular temperature increases, the actual impact is uncertain, and may in fact be rather minimal. This is because, while the ice pack may be somewhat reduced, temperatures will remain quite cold, and the ocean effects may be little changed. The greater effects will likely be in the subarctic regions.

It is in subarctic latitudes where the stratification of the ocean is weakest, and penetration of excess heat down into the ocean is the greatest. In other areas, the penetration of excess heat is reduced by greater stratification of the water column. In the vicinity of the pole, for example, fresh water lowers the density of surface waters. In the tropics, very warm water at the surface also makes the water column stratified, and stable.

The model's results support an earlier estimate (1979) by the National Academy of Sciences that the full impact of the present increase of greenhouse gases will be delayed several decades by the thermal inertia of the oceans. In the late 1950s and early 1960s bomb tests released a large amount of radioactive material in the atmosphere that eventually fell out on the ocean. The penetration of these radioactive, transient tracers appears to provide a source of empirical data with which we can judge the realism of the penetration of excess heat in our coupled climate model.

It had been suggested that transient tracers would provide an overestimate of the penetration of excess heat because a warmer climate would make surface waters less dense and retard downward mixing. To check this idea, a passive tracer was introduced into the coupled model equivalent to the transient radioactive tracers caused by the bomb tests. The net penetration of this tracer into the

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* The layer containing the strong vertical temperature gradient.

ocean model was thus compared to the penetration of the excess heat.

In numerical experiments, like any other experiments, one has to be prepared for the unexpected! The thermal anomaly actually penetrated faster than a passive tracer introduced at the surface. The explanation turns out to be relatively simple. Climate warming in the model does not seriously modify the normal downward ventilation of heat into the main thermocline, but it does impede the upward pathways which normally bring heat to the surface in subarctic latitudes. Convection, which brings heat upward, is particularly sensitive to surface warming, and a weakening of convection and the thermohaline circulation therefore enhances the ability of the model ocean to absorb excess heat.

"In the Hands of the Builders"

The implications are interesting. If climate warming causes convection in subarctic latitudes to weaken and traps more heat below the surface than normal, the total uptake of heat by the ocean is enhanced. The delaying effect of the ocean will be greater. Consequently, the onset of a climate change in the atmosphere because of increasing carbon dioxide will be later than predicted.

A healthy skepticism must always be maintained toward all idealizations of reality, and coupled ocean/atmosphere models are no exception. These climate models can best be thought of as a collection of models. A necessary condition for the quality of the overall model is that each component has been carefully designed and tested before inclusion.

In general, atmospheric models like the one used in the coupled model at the Geophysical Fluid Dynamics Laboratory have been extensively tested against climate data for the atmosphere. Less verification and testing have been carried out for numerical models of ocean circulation.

Lewis F. Richardson, a distinguished English mathematician and meteorologist, anticipated most of the elements of a coupled ocean-atmosphere climate model in a remarkable monograph (*Weather Prediction by Numerical Process*, 1922, Cambridge University Press, 236 pp.) written more than 60 years ago. In regard to model making in the absence of complete information, he writes of the necessity to ". . . .carry on business on premises which are, so to speak, in the hands of the builders." These words hold true today, and we must be prepared to revamp our models as new data become available. A very comprehensive test of the assumptions of current ocean models will be provided by the data sets to be collected by the World Ocean Circulation Experiment (WOCE).

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