Unpleasant surprises in the greenhouse?

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There is now clear evidence that changes in the Earth's climate may be sudden rather than gradual. It is time to put research into the build-up of carbon dioxide in the atmosphere on a better footing.

THE inhabitants of planet Earth are quietly conducting a gigantic environmental experiment. So vast and so sweeping will be the consequences that, were it brought before any responsible council for approval, it would be firmly rejected. Yet it goes on with little interference from any jurisdiction or nation. The experiment in question is the release of CO_2 and other so-called 'greenhouse gases' to the atmosphere. Because these releases are largely by-products of energy and food production, we have little choice but to let the experiment continue. We can perhaps slow its pace by eliminating frivolous production and by making more efficient use of energy from fossil fuels. But beyond this we can only prepare ourselves to cope with its effects.

The task of scientists is to predict the consequences of the build-up of CO_2 and othergases. To be useful these predictions must be reasonably detailed, but we are in no better a position to make them than are medical scientists when asked when and where cancer will strike a specific person. Understanding the operation of the joint hydrosphere — atmosphere — biosphere cryosphere system is every bit as difficult as understanding the factors that determine whether or not cancerous cells will get the upper hand. Because of our lack of basic knowledge, the range of possibility for the greenhouse effects remains large. It is for this reason that the experiment is a dangerous one. We play Russian roulette with climate, hoping that the future will hold no unpleasant surprises. No one knows what lies in the active chamber of the gun, but I am less optimistic about its contents than many.

My suspicion is that we have been lulled into complacency by model simulations that suggest a gradual warming over a period of about 100 years. If this seemingly logical response to a gradual build-up of greenhouse gases is correct, then one can imagine that man may be able to cope with the coming changes. While I do not have any complaints about how these modeling experiments were conducted — indeed they were done by brilliant scientists using the best computers available — the basic architecture of the models denies the possibility of key interactions that occur in the real system. The reason is that we do not yet know how to incorporate such interactions into models.

My impressions are more than educated hunches. They come from viewing the results of experiments nature has conducted on her own. The results of the most recent of them are well portrayed in polar ice, in ocean sediment and in bog mucks. What these records indicate is that Earth's climate does not respond to forcing in a smooth and gradual way. Rather, it responds in sharp jumps which involve large-scale reorganization of Earth's system. If this reading of the natural record is correct, then we must consider the possibility that the main responses of the system to our provocation ot the atmosphere will come in jumps whose timing and magnitude are unpredictable. Coping with this type of change is clearly a far more serious matter than coping with a gradual warming.

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For more than 100 years scientists have been aware that the Earth is in the midst of a series of cyclic glaciations. Oxygen isotope measurements made on microscopic shells from deep-sea sediments provide a continuous record of these events. They show that cycles averaging 100,000 years in length carried us from warm climates, comparable to today's, to the cold climates of full glacial time. Power spectra for these records point a finger at cycles in the Earth's orbital characteristics as the driving force[1,2]. Seasonality was at times stronger and at times weaker than it is today. Although most scientists now accept the orbital hypothesis, none of the mechanisms that have been proposed to explain the linkage between seasonality and climate is universally accepted. This matter is the subject of much research.

The $^{18}O/^{16}O$ record in deep-sea cores gives the impression that the response of the climatic system to orbital forcing is smooth and gradual (Fig. 1 — see over). Only recently have we begun to realize that this impression is a false one. One of the early clues came from studies of the ecology of the remains of planktonic organisms contained in deep-sea cores of rapidly accumulated sediment from the North Atlantic'. The ecological changes recorded in these cores probably reflect changes in surface-water temperature. This record does not show the gradual change scientists had become accustomed to. Instead it shows an abrupt end to glacial time and, even more interesting, a brief period of intense cold intemipting the warm period that followed (Fig. 1). Although the two records shown in Fig. 1 are quite different, they are not incompatible. Changes in $^{18}O/^{16}O$ in the shells of marine sediments are largely the result of the waxing and waning of the ^{18}O-deficient continental ice caps. As the response time of global ice caps is thousands of years, the ^{18}O record smooths out the rapid changes in climate.

It took more than this, however, to make us take these abrupt changes seriously. The evidence that turned our heads came from holes drilled through the Greenland ice cap. As a foot or so of ice forms from each year's snowfall, the record captures changes in the ice-cap environment no matter how rapid they have been. These changes are recorded in the ratio of isotopically 'heavy' to isotopically 'light' water in the ice (a measure of air temperature)[4,5], in the content of particulate matter in the ice (a measure of the dustiness of the air over the ice cap)[6] and in the content of CO_2 and other greenhouse gases contained in the air trapped as bubbles in the ice (a measure of the atmosphere's greenhouse capacity)[7]. Like the ecological record in deep-sea muds from the North Atlantic, the ice core records from Greenland give a dramatically different impression of the manner in which climate changes than do the oxygen isotope records for marine shells. They show that during glacial time climate changed frequently and in great leaps. The typical leap involves a 6°C change in air temperature, a fivefold change in atmospheric dust content and a 20% change in the CO_2 content of air. In cold times the air was dustier and contained less CO_2.

While the record in Greenland's ice shows that climate can change in big leaps, we have to look further for a clue as to why these leaps occur. The last of the events seen in the Greenland record is well documented not only in Greenland ice and in North Atlantic sediment, but also in lake and bog sediments from throughout Western Europe and maritime Canada[8]. On land it is recorded by large shifts in the ecology of plants (as recorded by their pollen grains). During warm periods trees grew in these areas; during cold periods the trees were replaced by tundra shrubs. Although this last of the Greenland events is found in bog and lake sediments throughout northern Europe, it is not seen in similar records from the United States. This geographical distribution suggests the North Atlantic Ocean as the culprit. Based on this clue, we are beginning to see how devilish are the links between components of the climatic system.

Rather than responding smoothly to gradual forcing, the ocean-atmosphere system appears to respond by changing the way it works. India's climate provides an apt analogy. The winters in India are very dry because of the descent of cold air from the Tibetan plateau. Summer heating causes this atmospheric circulation pattern to reverse abruptly. Air rises from the Tibetan plateau, drawing oceanic air across the Indian subcontinent, and the dry conditions give way to monsoonal rains.

The Earth's climatic system currently works in a way beneficial to northern Europe. This region is warmed by heat released from the surface waters of the North Atlantic. The amount is a staggering 30% of that received by the North Atlantic from the Sun! This heat is steadily carried northward, as on a conveyor belt, by the ocean circulation system. In the vicinity of Iceland the warm water meets cold air. The air warms and ameliorates climate on the adjacent land. The water cools, sinks to the abyss and flows as a great river, down the full length of the Atlantic, around Africa, through the southern Indian Ocean and finally up the Pacific Ocean (Fig. 2). This current car- ries 20 times more water than the world's rivers combined.

In the North Pacific the ocean conveyor belt runs just the other way round. Deep waters move towards the north and rise to the surface and then flow towards the Equator in the upper ocean. So in today's world, the Atlantic conveyor belt carries tropical heat for delivery to the atmosphere at high northern latitudes, while the Pacific conveyor belt forces cold surface waters to move southward, pushing the invading warm waters back towards the Equator.

Why does our ocean operate in this fashion? Although we don't have the complete answer, we do have the first principle. The circulation system is governed by salt. Because of the difference in the circulation patterns, surface waters in the North Atlantic are on average warmer than those in the North Pacific. This allows more water to evaporate from the North Atlantic than from the North Pacific, and in turn gives rise to a net transport of water vapour through the atmosphere from the Atlantic to the Pacific. The North Atlantic is enriched in salt by this process (and the North Pacific waters cor- respondingly diluted). The enrichment of salt in the North Atlantic must somehow be compensated by a flow of salt through the sea from Atlantic to Pacific. The compensation in today's ocean is achieved by the flow of a deep current of salty water from the Atlantic to the Pacific and a matching flow of correspondingly less salty water around the other way in the upper ocean.

The phenomenon that maintains this situation is, I suspect, a potentially dangerous one. The circulation pattern is self-reinforcing and hence self-stabilizing. The deep current is driven by the extra density supplied to the waters of the North Atlantic by the enrichment of salt.
The enrichment of salt is driven by the heat carried by the warm water which flows northward in the upper Atlantic to supply the deep current. A classic chicken and egg situation! Excess evaporation causes the deep current; the deep current causes excess evaporation.

What are the consequences of perturbation of this system? Palaeoclimatic evidence points to a shutdown of the North Atlantic conveyor belt during glacial periods. Such a shutdown would cool the North Atlantic and its adjacent lands by 6-8°C. This is turn would cause the boreal forests in these areas to give way to tundra shrubs.

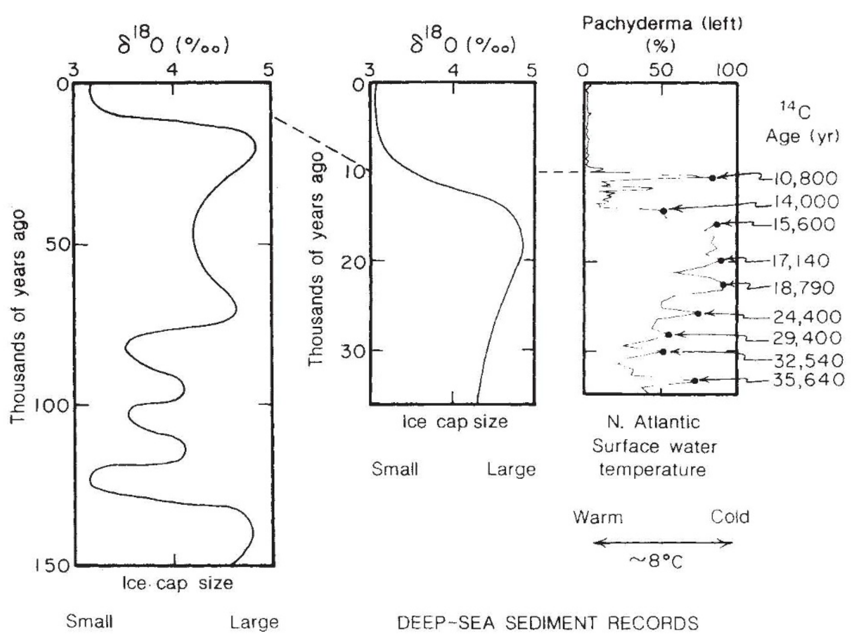

Fig. 1 The ratio of heavy oxygen (^{18}O) to light oxygen (^{16}O) in foraminifera shells preserved in deep-sea sediments provides our best record as to how the great continental ice sheets of the Northern Hemisphere waxed and waned. The reason is that the snow that builds ice caps is depleted in the heavy oxygen isotope. Therefore as ice caps grow, the ocean is correspondingly enriched in heavy oxygen. So also is the oxygen in the calcium carbonate of shells living in these waters.

The oxygen isotope record on the left covers just over one major climate cycle. There have been eight such cycles in the past million years. The diagram in the middle is an enlargement of that on the left, designed to emphasize that these oxygen isotope records indicate a gradual and smooth transition from full glacial to full interglacial conditions. Recent findings demonstrate that this view of natural climate change is misleading. The sluggish retreat of the ice and blurring of the record by burrowing worms combine to give what proves to be the wrong impression.

On the right is the record from a deep-sea sediment obtained west of the British Isles. This record is based on the abundance of the shells of the planktonic herbivore Pachyderma (left coiling) which lives in waters adjacent to Greenland. It is the only species of planktonic foraminifera found in these icy waters. During cold periods this species dominated the entire North Atlantic, providing up to 90% of the shells found in the sediments off Britain.

As can be seen, this record tells a different story. The North Atlantic warmed abruptly about 15,000 years ago, and has so remained (except for two brief cold relapses) until the present. It is the abruptness of the warming and of the two brief and intense epochs of renewed cold that are of great interest. The second of these cold epochs was first recognized from study of the pollen records in bogs created in northern Europe during the retreat of the last great ice sheet. These records show that the forests which repopulated this area after ice departed were destroyed by a brief and intensely cold interval of several hundred years' duration. They were replaced by the shrubs of glacial time.

The sparsity of vegetation would permit far more dust to be lifted into the atmosphere. Finally, the only feasible mechanisms scientists have come up with to explain rapid changes in the atmosphere's CO_2 content involve modifications in the ocean's circulation pattern and intensity. Thus we surmise that the reorganization of ocean circulation that accompanied the shutdown of deep-water production in the North Atlantic produced all of the environmental changes recorded in ice cores. The many leaps in climate seen in the glacial part of the Greenland ice core records probably represent flips of the system back and forth between two self-stabilizing modes of operation.

It must be emphasized that tire leaps in climate seen in the ice and sediment records for the North Atlantic region were confincd to the cotd parts of the climatic cycle. Following the transition from cold to warm conditions 10,000 years ago, the climate in this region has remained remarkably constant. Apparently Earth's climatic system has remained firmly locked in its present mode of operation. If so, what is the likelihood that increases in CO_2 and other greenhouse gases will jolt the ocean—atmosphere system out of its current mode into one more suitable to the coming conditions?

Unfortunately, we have little basis for answering this critical question. Nature provides us with no recent analogy to the super-interglacial conditions we are about to generate. The climate of the past 10,000 years is representative of the warmest part of the last several glacial cycles. Hence nature has not explored the superinterglacial climatic regime (at least not in sufficiently recent times that our geological records give an adequate picture of Earth's environment to be useful for future prediction). Further, as we have only recently become aware of the complexity of the linkages which tie together ocean, atmosphere, ice and terrestrial vegetation, we have not even begun to formulate means by which these linkages might be modelled. Indeed, reliable modelling may never be possible.

If we are to get into a position to cope with the effects not only of the greenhouse gases, but also of the various poisons being released to the environment, we must greatly expand our efforts to understand the individual parts of the Earth's great surface system and the interactions among them. The task, however, is every bit as complex as that of preventing cancer.

I see no hope of getting much done in the United States without a fundamental reorganization of our approach to environmental research. I believe that most scientists would agree that the handling of research on greenhouse effects by the Department of Energy and on acid rain by the Environmental Protection Agency has been ineffective. The problem lies partly in the perception by the managers of these programmes that their mandate is to obtain quick fixes, and partly in their inability to grasp the subtleties of the problems placed under their jurisdiction. The result is that these managers avoid long-term strategies designed to build up our base of knowledge. Rather, they are strongly attracted by proposals to re-work existing information even though most scientists agree that it has been squeezed nearly dry. Thus, while the existing programmes serve to keep management informed, they do little to further our ability to predict the consequences of our actions. It is as if the efforts to prevent cancer were based largely on epidemiological information with no biochemical or cellular research. If we are to get out of this rut, the responsibility for basic research on environmental systems must be wrested from these mission-orientated agencies and given instead to an organization which is dedicated to basic research and is isolated from immediate political pressures.

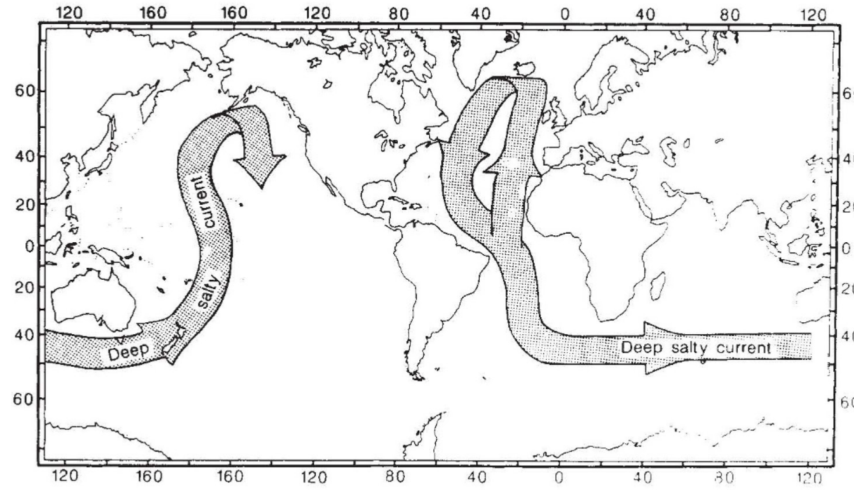

Fig. 2 A large-scale salt transport system operates in today's ocean to compensate for the transport of water (as vapour) through the atmosphere from the Atlantic to the Pacific Ocean. Salty, deep water formed in the North Atlantic flows down the length of the Atlantic, around Africa, through the southern Indian Ocean and finally northward in the deep Pacific Ocean. Some of this water upwells in the North Pacific, bringing with it the salt left behind in the Atlantic due to vapour transport. This atmospheric water vapour and ocean salt transport system is self-stabilizing. Records from ice and sediment tell us that this great conveyor system was somehow disrupted during glacial time and replaced by an alternative mode of operation.

As it now stands, a healthy component of basic research is being carried out only in those areas where there is a strong tradition of federal sponsorship (that is, the atmospheric and ocean sciences). Research on the continental parts of the environmental system (vegetation, soils and waters) remains in the Dark Ages. It's a Catch-22 situation managers at the National Science Foundation (NSF) feel that basic research in these areas should be sponsored by the appropriate mission-orientated agency, but such agencies shun basic research.

Unique opportunities to expand our knowledge of environmental systems slip by without being fully exploited. A prime example is the invasion of man-made tracers (that is, nuclear-testing tritium and radiocarbon, reactor radiokrypton and industrial freons) into the sea. A detailed knowledge of the patterns and rates of movement of these substance through the sea will prove a tremendous boon to the validation of general circulation models for the atmosphere-ocean system. Although the atmospheric side of such models is fully developed, the oceanic side is still in a primitive state. Further development is hampered by our lack of knowledge of the physics of key processes occurring in the sea. Because of this, ocean models of adequate sophistication are decades away. Despite the obvious value of tracer data, the efforts to map the passage of these substances through the sea's interior are sparse. NSF is concerned that surveying brings too little immediate scientific yield, while the mission-orientated agencies fail to appreciate the fact that if we are to understand the Earth's system we must adopt long-term strategies. With the exception of the French, who have developed a remarkably good tracer programme in the Indian Ocean, other industrial countries have shown no greater interest in ocean tracers than had the United States. Hence future ocean modellers will rue the deficiencies in the documentation of man's great ocean-tracer experiment.

I am not suggesting that things could be altered simply by increasing NSF's budget NSF is not set up to put strings on the use of its funds. Nor should it be. But to do the kind of research that will be required if we are to deal effectively with long-term environmental problems, there must be some strings.

In this time of budget deficits it may be unrealistic to call for new government entities, but I am convinced that the only way to straighten out the mess in environmeinal research is to create a new national institute. This institute would have two objectives. First, it would sponsor environmental research; second, it would advise thc government on a broad range of environmental questions.

The International Committee of Scientific Unions has recently given its blessing to a new initiative in environmental science, the International Geosphere—Biosphere Program (IGBP). The aim is to further our understanding of the operation of the individual elements of the environmental system and of the linkages between them. The mission-orientated agencies in the United States are already planning how to capture their share of this new pie. Judging by past performance, it would be a mistake to let them have any of it. Instead, the US monies to be spent on IGBP should be funnelled through a new entity, The National Institute for the Environment. The primary responsibility of this institute would be to develop integrated programmes dedicatedto furthering our knowledge of environmental systems. In particular. the Institute would focus on those areas that most need attention. namely, the continental components of the climatic system. The programmes would be planncd by the most capable scientists in the country and conducted in the most appropriate laboratories (university, industry and government). The institute would be overseen by a board of trustees, consisting of eminent scientists. Its director, chosen by this board, would be a highly capable scientist, skilled in management. While the institute would have its own in-house scientific staff, most of its resources would go towards the funding of external activities. There are isolated success stories. For example, two NASA managers, Shelby Tilford and Bob Watson, are running a programme designed to determine the sources of atmospheric methane and how the strengths of thesc sources have changed with time. This programme is a beautiful example of how environmental research should be conducted. It was designcd oy the nation's most knowledgeable scientists and is being carried out by highly capable groups throughout the country. The cost is modest, about two million dollars a year, and the payoff will be large. It works because Watson and Tilford are themselves outstanding scientists who know what the traceable problems are and where the intellectual resources to tackle them reside.

Most of the research of the new institute should be housed in universities. It is in such settings that excellent research is generated for a minimum cost. By placing graduate education and research under one roof, an optimum environment for both is created. With a few exceptions, environmental research in large laboratories operated by government agencies has, in my opinion, proved to be unproductive and wasteful.

There are, however, two tasks that clearly require facilities not available to universities. One involves satellite obser- vations,

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which will be the cornerstone of the effort to monitor the climatic system. Such platforms are best operated by NASA. The other is large-scale climate modelling, which is now the basis for all climate prediction. These facilities require large research staffs and immense computer power. Fortunately, a successful format has already been found which involves cooperation between universities and government departments. The National Oceanic and Atmospheric Administration has its primary effort on Princeton's campus. NASA bases such an effort on Columbia's campus. NSF opcrates such an effort at its National Center for Atmospheric Research in Boulder , Colorado. Because of the great importance of the so-called 'general circulation models' to climate prediction. these existing laboratories should be strengthened. Also, similar efforts must be launched in other university settings.

Five specific areas in which research must be greatly expanded can be singled out for special attention: (1) the largescale circulation of the ocean; (2) the processes regulating soil moisture ; (3) the processes responsible for cloud formation; (4) the role of biogeochemical processes on the atmosphere's composition ; (5) the processes regulating sea ice.

Of course, there are already research programmes in these areas, but in my estimation they will not come up with answers quickly enough. In each area we need major new observational programmes to supply the key data that are necessary to develop a better physical understanding. In each area we need a cadrc of young scientists with the appropriate training.

We also have to intensify our study of the climatic changes that have taken place over the past 100,000 years. As discussed abeve, nature herself has conducted large-scale climatic experiments. The response of the system to these natural experiments is recorded in sediments and in ice. By study of these records, we will be able to learn valuable lessons about the interactions that link the various elements of Earth's system together. I should stress once again that it is changes in these linkages which are likely to carry the greatest threats.

Although we don't know nearly enough about the operation of the Earth's climate to make reliable predictions of the consequences of the build-up of greenhouse gases, we do know enough to say that the effects are potentially quite serious. Whatever happens, it seems to me that the Earth's remaining wildlife will be dealt a serious blow. If, as the climatic record in ice and sediment suggests, changes in climate come in leaps rather than gradually, then the greenhouse build-up may threaten our food supply. To date, we have dealt with this problem as if its effects would come in the distant future and so gradually that we could easily cope with them. This is certainly a possibility, but I believe that there is an equal possibility that they will arrive suddenly and dramatically.

To prepare ourselves, we must take the problem of climatic change as seriously as we take those of cancer and nuclear defence. There are no easy solutions, and we must gear up for the long, hard job of working out how Earth's climate operates. To do this will require not only more financial and human resources, but also the administration appropriate to the task. Not only do our current managers lack a proper intellectual grasp of the problem, but they are obsessed with legislatively imposed 'five-year reports', and give little attention to developing a long- term strategy to build the needed base of knowledge. Even with a great intensifica- tion of effort, I fear that the effects of the rise in concentration of the greenhouse gases will come largely as surprises. But the greater our knowledge, the greater the wisdom that will be brought to bear if surprises do come.

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