CHAPTER 3

Our Fragile Inheritance

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The planetary oasis on which we live today continues to be strongly influenced by its own creation—by the way it was, immediately following its accretion out of the primitive solar nebula. Billions of years ago a star became unstable and exploded with an incredible release of energy. The 'accretion disc' of gas and dust that was probably created from this explosion was later the context for the Earth-formative events that began over 4.5 billion years ago. Within the disc-womb the dominant gases pulled together to form the Sun and to illuminate it by the hot nuclear fusion reaction in which hydrogen burns and produces helium.

As the sun formed, its gravitational field strongly guided the remaining material in the accretion disc. Most of the dust had begun to coagulate, and the swarm of objects within one zone of the accretion disc came to be dominated by planetesimals—little planets that

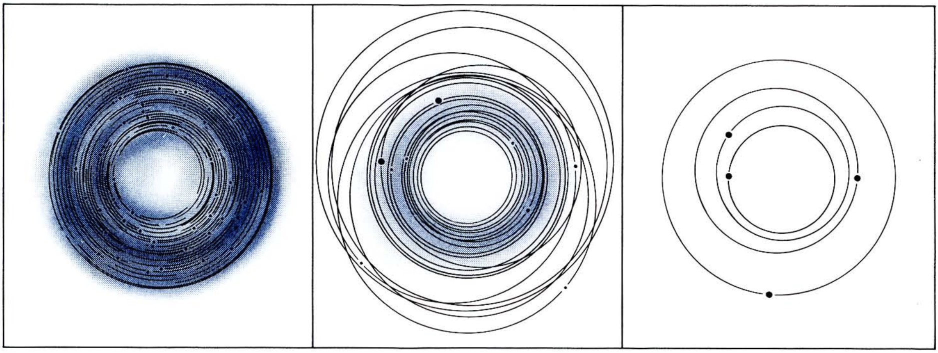


FIGURE 17. *Formation of the sun and planets. Following the explosion of an earlier star, the hot mass of the early Sun rotated around an axis, radiating heat and attracting gases and dust. This is a computer simulation of the accretion of the terrestrial planets Mercury, Venus, Earth, and Mars, beginning with a large number of planetesimal-sized objects. The process took about 100 million years—a small fraction of the Earth's age, approximately 4.6 billion years.*

we now believe must have evolved very quickly to produce the terrestrial planets themselves: Mercury, Venus, Earth, and Mars. They took up the distances they now occupy from the Sun. Further away, a residual gaseous component remained that would seed the formation of the giant planets of Jupiter and Saturn.

The best estimate of the time it took for the terrestrial planets to evolve is less than 100 million years, a small fraction of the Earth's age. Figure 17 shows a modern computer model of the way gravity brought the terrestrial planets together and formed them.

Since this final coming-together happened so relatively quickly, the Earth and other planets near it must have formed hot—in fact so hot that the initially homogeneous compositions of the individual planetesimals were completely differentiated. By the end of accretion, therefore, most of the heaviest element, iron, had sunk to the centre of the primitive planet Earth, leaving the remaining material, mostly iron-magnesium silicates, to form a thick mantle surrounding the molten iron core—the same planetary structure as exists today (Figure 18).

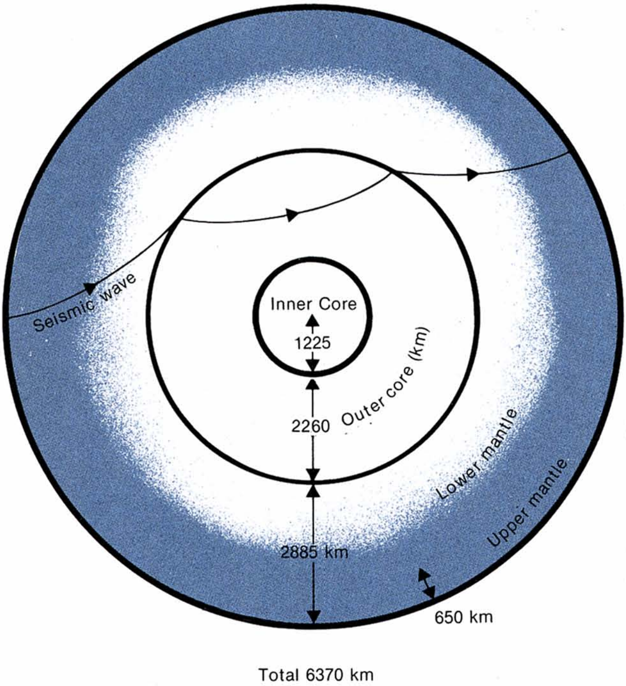


FIGURE 18. *The interior of the Earth. The curved lines traversing the structure represent the paths of travel of seismic energy released by earthquakes. The travel times of these packets of energy reveal the structure of the Earth.*

CONVECTION CURRENTS

The mantle convective circulation that dominates the outermost region of Earth (see Chapter 1) has influenced in a singular way Earth's evolution ever since it was born, and because of it the layer on which we stand is often in violent upheaval. The mantle of Earth is in continuous upheaval, since it is being constantly turned over by convection currents, causing the continental plates to shift about on the Earth's surface at the rate of a few to 10 centimetres a year. We cannot feel the steady, minuscule shift—called continental drift—under our feet, but the sophistication of modern astronomical measuring systems is so great that by watching the stars in relation to our own movement, we can actually observe the motion of the planet's surface plates.

The mantle's convection circulation determines the rate at which the Earth cools, by controlling two factors: first the escape of primordial heat from the liquid core; and second the rate at which the heat generated by continuous decay of the long lived radioactive elements—thorium, potassium, and uranium—rises to the surface.

Figure 19 is a model of the main characteristics of the convective circulation as most earth-scientists envision it today. Hot material rises from the core mantle boundary to the Earth's surface, where its melting creates mid-oceanic ridges. Simultaneously cold material descends from the Earth's surface, and where it plunges down it forms deep ocean trenches. The rising hot material and sinking cold material constitute a closed thermal circulation that is manifest at the surface in the pattern of relative motions that drives continental drift.

Model of earth mantle convection currents

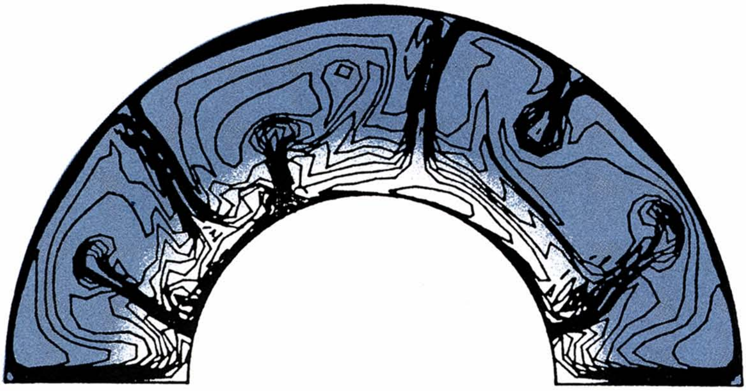


FIGURE 19. *A modern computer simulation of the mantle convection process responsible for continental drift and sea-floor spreading. Hot material rises from the core-mantle boundary to the Earth's surface, where it creates mid-oceanic ridges. Similarly cold material descends from the surface to the core-mantle boundary, inducing deep sea trenches at the surface.*

CONTINENTAL DRIFT

The radical theory that the relative positions of the continents are not fixed was first suggested in 1915 by the German scientist Alfred Wegener; but it was widely rejected until the 1960s. Scientists now accept that Earth's present continents were once part of a single super-continent they call Pangea. This mass began to break up about 200 million years ago, and the fragments slowly drifted to their present global positions. The discovery of the motion of the plates led to a revolution in the earth sciences that has been continuing ever since. Figure 20 is a recent model of this plate motion pattern, based on seismological and paleomagnetic data. It shows the estimated direction and velocity of the plates.

The earth's tectonic plates move slowly—at present approximately 5 centimetres per year on average. Even so, it is clear that over tens of millions of years or more there will be significant redistributions of the continents. It is because of these slight but continuous rearrangements

Movement of continental plates

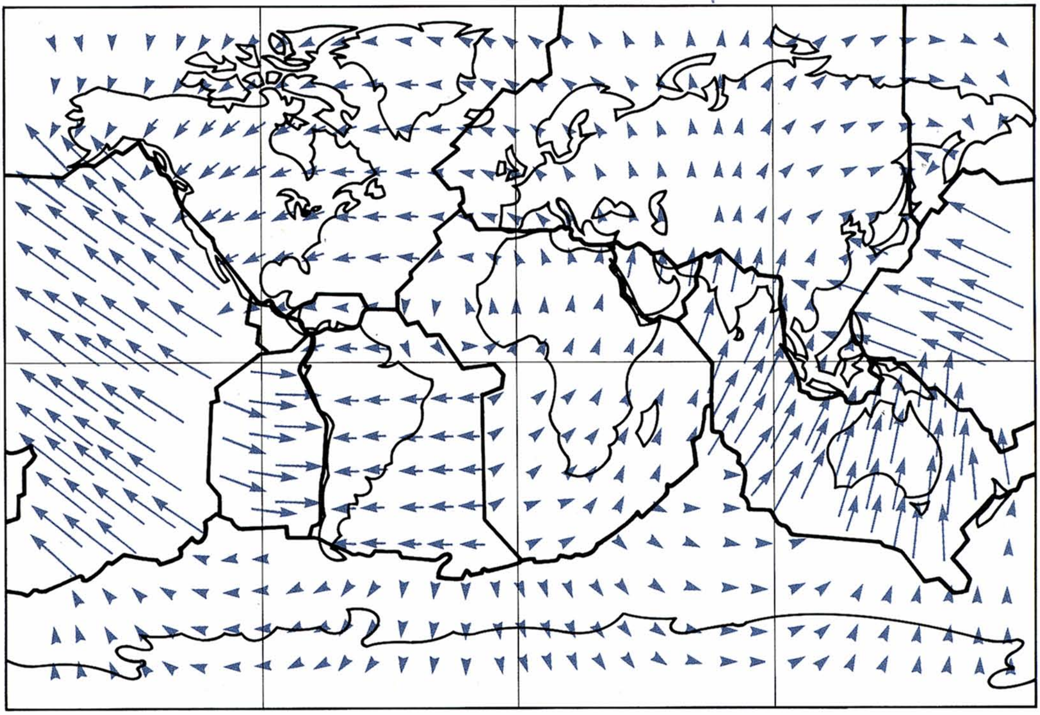


FIGURE 20. *The speed and direction of travel of the continental plates today, according to a current model of the process of plate tectonics and continental drift. The length of the shaft of the arrows indicates the speed of travel.*

that the mantle convection process exerts such profound control on the physical climate system over long periods.

The first 4.5 billion years of the planet's life very clearly reveals the nature and influence of the mantle convection process that has governed the chemical and dynamic evolution of the planet since it first formed (see Chapter 1). By controlling the drift of the continents over the planet's surface, and by regulating the opening and closing of ocean basins, this process has always determined the nature of the 'field' on which the physical and biological components of the Earth's ecosystem play out their complementary roles.

More than two million years ago the continental masses had been arranged into more-or-less their present positions. At about this same time the ascent of the human species—so beautifully recorded in the fossils of the Olduvai Gorge in East Africa—had clearly begun, and another dominant natural process, glaciation, was underway. By that time Greenland was similarly ice-covered. In the Southern hemisphere, Antarctica was covered by an ice sheet about four kilometres thick, and had been for approximately 40 million years.

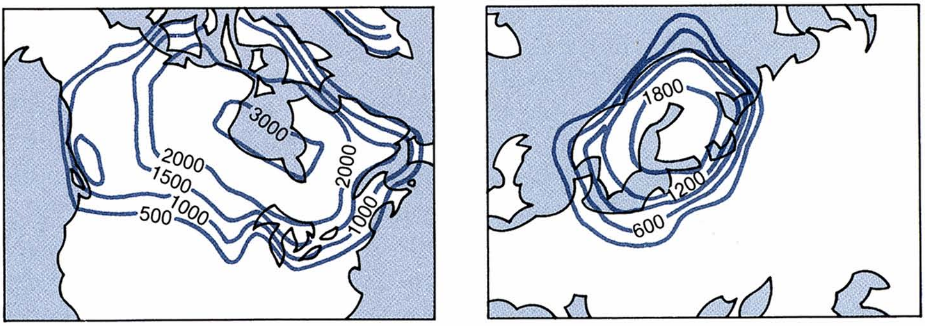
In thinking of the Earth as a system, it is useful to see it as composed of many spheres of action, or domains—among them the air, the oceans, and ice. These spheres all operate with different characteristic time-scales: changes in the atmosphere occur most quickly, taking a few years; in the oceans the characteristic time for mixing is a hundred years or so; and in ice, thousands of years. The different spheres of relativity, which together constitute the 'Earth System', fit together in a delicate and interlocking way. If we can grasp the delicacy of this balance, and the nature of the connections between the various planetary changes that involve these spheres, and if we can discern the natural variability of these changes, we may begin to come to grips with global change, or at least make a start in understanding it. If, furthermore, we can filter out the effects of the natural dynamics of the Earth, we may be able to recognize a residual, human-initiated effect. This portion we perhaps have some hope of controlling. This is why we are led to develop more and more sophisticated models of the influences on our planet, trying to see how they interrelate, so that we may better identify the influence of the human component.

GLACIATION

The story of one of these spheres—ice—of how and why it appears, is remarkable. We have been theorizing about it for over a century, and the quality of our observations improved enormously when we recovered the first sedimentary cores from the deep sea. These observations have revolutionized our thought, and because of the new data we are beginning to discern clearly the way the sphere of ice is controlled by the Sun. The unravelling of this story demonstrates just how precariously the environmental spheres are balanced, one with the other.

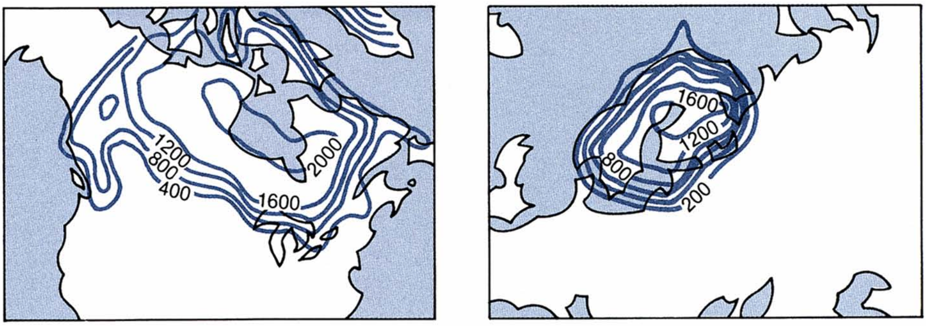
To remind us of the most recent history of ice on this planet over the last few tens of thousands of years—just an instant in the age of the

Ice Sheets



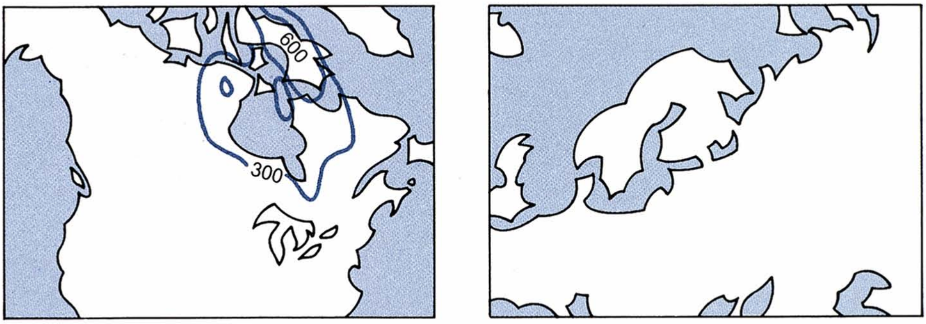
(A) 18,000 years ago

(B) 18,000 years ago



(C) 12,000 years ago

(D) 12,000 years ago



(E) 8,000 years ago

(F) 8,000 years ago

FIGURE 21. *A computer model of ice sheets over northern North America and northern Europe at 18,000, 12,000, and 8,000 years before the present, showing ice thickness in metres.*

Earth—if you had been flying over North America 20,000 years ago and looked down over the North Pole, you would have seen almost all of Canada covered by a huge ice sheet, as in Figure 21. Even 14,000 years ago, this picture wouldn't have been much different. The ice sheet was thick—about three to four kilometres deep, centred geographically over Hudson Bay, and so large that in order to grow it, the sea level had to fall 60 to 65 metres. This phenomenon was therefore no minor event! The ice sheet itself was both an effect and, as it grew, a major cause of climatic change.

The global extent of ice coverage 20,000 years ago involved much more than the huge ice sheet that sat on Canada. Greenland was also more heavily glaciated, as was Antarctica, as was a vast region of northwestern Europe, over the Barents and Kara Seas, the Gulf of Bothnia, Scandinavia—a region so large that it required an additional fall in sea level of about 65 metres to generate the ice coverage.

These ice sheets began to melt about 18,000 years ago, and by 6,000 years ago had almost entirely disappeared, causing the sea level to rise by the same amount that it fell as the ice sheet complexes grew. By that time the Earth's surface had acquired nearly the same distribution of continental ice as at present. From 18,000 years ago until today the sea level has risen close to 130 metres average over the entire global ocean.

ISOSTATIC REBOUND

Great as that increase in sea level was, there was another modifying process going on at the same time. As the ice on the land melted and the melt water ran off into the sea, the land was released of an enormous load. In response the unloaded regions rebounded and rose. In all the regions that were once ice-covered—Canada, northwestern Europe, western Antarctica, Greenland—much of the land today is well above sea level, forced up by the release of the ice. We call this process isostatic rebound, or isostatic adjustment, and the physics of it is very simple. Over the tens of thousands of years that the ice sheets pressed down on the earth's surface, the 'solid' earth beneath them was eventually depressed as the underlying mantle flowed from beneath it like a viscous fluid. The material under the ice was squeezed out by the weight of the load and flowed horizontally from under it. When the ice melted, the material slowly oozed in the reverse direction and land once covered by ice rose out of the sea. Even today this process continues, thousands of years after deglaciation was complete.

This process has left an indelible record on the global landscape, particularly that of Canada, which had been covered by the greatest

Ancient beaches in the Richmond Gulf of Hudson Bay. Radiocarbon dating of materials from the different levels shows the local history of relative sea level change.

Raised beaches on a small island off the Melville Peninsula, NWT. Each of the concentric shoreline rings has been produced as the land has slowly emerged from the sea in the process of isostatic rebound. The oldest shorelines are in the centre and highest part of the island, as they were the ones that first emerged. (Photo Alan Morgan.)

load of ice. In Richmond Gulf on Hudson Bay, for example, the hillside is cut by a series of beaches that from the air look like giant staircases. They were created as the ice began to melt roughly 18,000 years ago; the land began rising higher and higher out of the sea through the process of isostatic adjustment. Each stair is an ancient sea level, a place where the sea used to intersect with the land. Sea level histories like this have been collected from many places on the Earth's surface.

Today we can walk these beaches, collecting the shells of the dead animals that were either stranded out of the sea (if local sea level was falling) or submerged into the sea (if it was rising). The shells of these familiar clams and related species continue to reflect the chemical characteristics of their environment while they were alive. Carbon 14 radioactive dating reveals their ages, so that we may reconstruct a local history of relative sea level change.

These data play an extremely important role, not only in understanding past climatic change, but also in constructing geophysical models of the mantle convection process. It is the best information we have to measure the viscosity of the planetary mantle that limits the strength of the convection process and therefore the rate of continental drift. Isostatic rebound dominates the 'natural' variability of sea level in regions that were ice-covered, and must be taken into account everywhere when we try to measure possible sea-level changes due to human activities.

At sites that were once ice-covered, like the Richmond Gulf, sea level has continued to fall at a progressively decreasing rate since deglaciation. Models show that maximum rates of change at present are nearly one centimetre a year. In ring-shaped areas around the centres of postglacial rebound, however, the sea level is steadily rising today at a maximum rate of 2 millimetres a year. At sites like Boston and Halifax, located near the ancient margin of the Canadian ice mass, the record of sea-level change shows both rise and fall. Further still from the main centres of glaciation, throughout the major ocean basins, the sea level, with local variations, in general falls at a rate of nearly .5 millimetres a year, due solely to the process of glacial isostatic adjustment.

GLOBAL SEA-LEVEL RISE AND THE GREENHOUSE EFFECT

It's not surprising that the expected increase of mean-surface temperature due to the release of carbon dioxide and other greenhouse gases is likely to cause rising sea levels (see Chapter 2)—for two reasons. First, increasing atmospheric temperatures will inevitably be passed on to the oceans, which will expand, raising the sea level. We are not

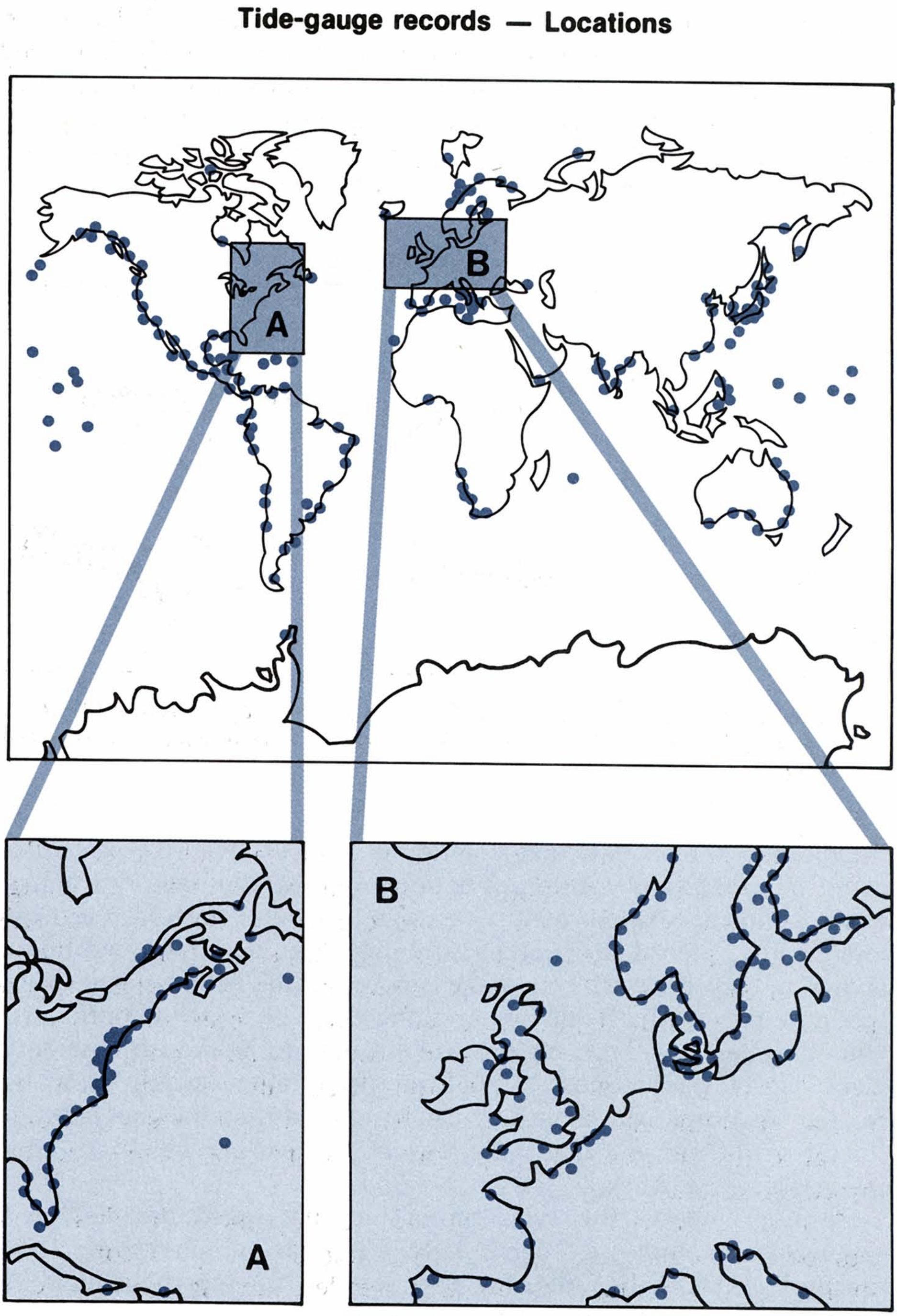


FIGURE 22. *Locations around the world from which relative sea level histories are available.*

at all certain how rapidly this will happen (see Chapter 6). However, probably more important is a second influence, namely increased ocean volume caused by the melting of continental ice. Since most land ice is located in high latitudes, and since the impact of greenhouse warming will likely be most pronounced near the poles, this cause of rising sea levels will probably dominate.

Sea Level Trends

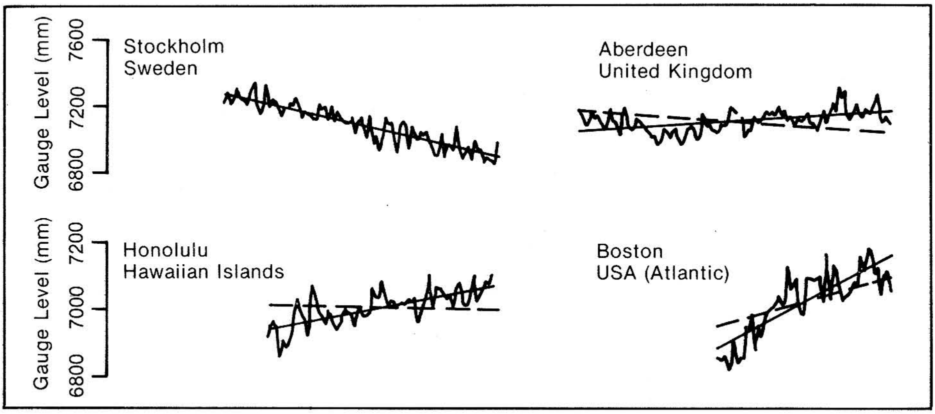


FIGURE 23. *Some long tide-gauge records (solid curves). Where the rate of sea level change would be different if glacial isostatic adjustment alone were the cause, a broken line shows the theoretical rate.*

Do observations show that a component of sea level rise exists that could be due to the melting of continental ice? We have tide-gauge observations of relative sea-level change from sites for which records longer than a decade exist at an extremely large number of locations, shown in Figure 22. (The coverage is not uniform, as most gauges are located either in the Baltic Sea or along the east coast of continental United States, and both regions are strongly influenced by ongoing glacial isostatic adjustment.) Data from these stations clearly show the isostatic rebound experienced by each area. But that does not account for all of the present-day variations of relative sea level. Another process is also at work.

Figure 23 shows the variation of monthly mean heights for a number of examples of particularly long tide-gauge records. The broken lines show the rates of relative sea level change that should be observed, if glacial isostatic adjustment alone were active. The global pattern of this isostatic adjustment signal is shown in Figure 24. It does seem that, except at the Baltic Sea sites, other factors are contributing to the observed changes. Careful analysis of 50-year-long records indeed shows that this residual signal is probably caused by the melting of continental ice and could therefore be due to greenhouse warming. If global sea level rise should accelerate, as is expected, it could have a devastating impact on the very large number of people who live in areas that would be innundated. We may in fact already be observing its beginnings.

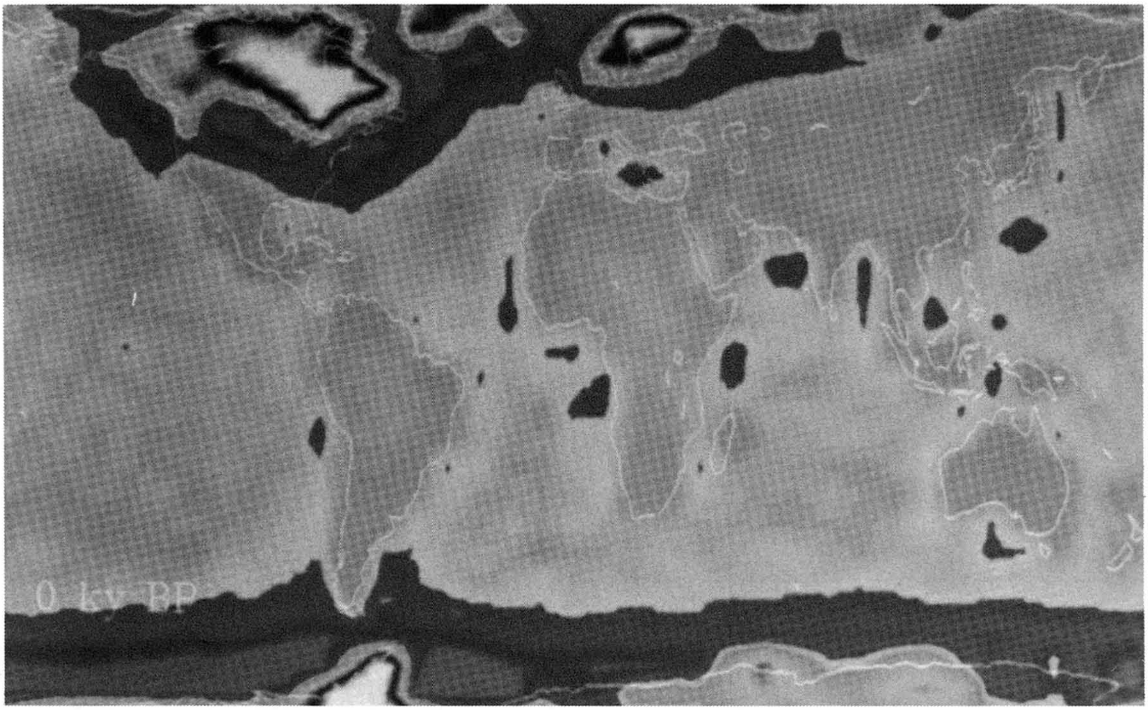


FIGURE 24. *Model of the present rate of global sea level rise or fall, using the long tide-gauge records.*

CAUSES OF CLIMATE CHANGE

Where did the ice sheets come from in the first place? How often has the planet been glaciated in the past? How likely is this to happen again? It is only in the past two decades that we have begun to answer these questions. The introduction of computerized modelling, along with the analysis of the contents of cores drilled from the major ocean basins, have helped us answer some of them. The sediments in these very long cores, some more than several hundred metres long, provide information about the volume of ice that existed on the continents in the past, and why the ice sheets appeared and disappeared. This story is one of the most exciting in modern Earth science.

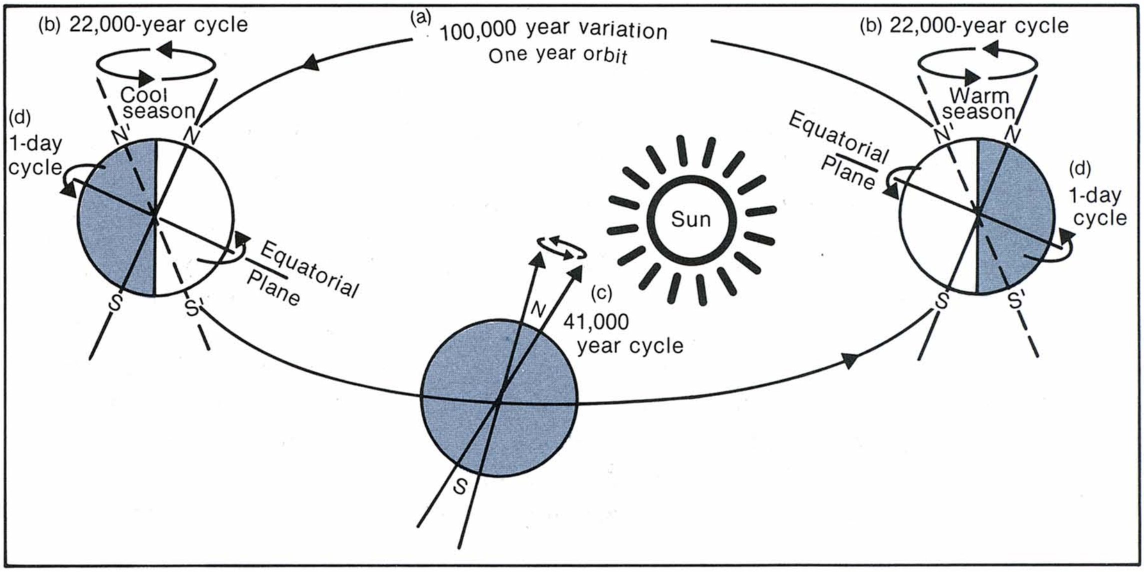
Ice sheets are made from snow accumulated and compressed over hundreds or thousands of years, and the water that makes the snow is produced by evaporation off the surface of the sea. However, the water vapour that is precipitated as snow in the construction of an ice sheet is anomalously rich in the lighter isotope of oxygen (the water contains more $H_2{}^{16}O$ than average), leaving the water in the ocean isotopically heavier than average (containing more $H_2{}^{18}O$), and this signature is recorded indelibly in the shells of micro-organisms called Foraminifera living in the water. When these animals die, their shells sink to the sea bottom. The proportion of different oxygen isotopes in the accumulated shells in the sedimentary column therefore tells when glacial periods occurred and how much ice existed on the continents through time.

In the record of oxygen isotopic variations in a core from an ocean-drilling project site in the Panama Basin, certain patterns emerge. The record displays a history of about two million years, with a marked transition in character near the mid-point. The earliest half of the record reveals relatively small fluctuations in the proportions of heavy and light oxygen isotopes. But in the last million years the record shows large changes, indicating times of large ice volume on land. The time between minimum and maximum volume is about 100,000 years during this most recent period.

A detailed analysis of this time-series record reveals a number of very well-defined characteristic periods, representing dominant cycles of increase and decrease in heavy-oxygen isotopes, and therefore heavy glaciation. In the last million years a major cycle of cold and warm periods occurred every 100,000 years, the very time-period over which we think the Laurentide Ice Sheet of Canada appeared and disappeared. From this record we can extrapolate that Canada was heavily glaciated roughly ten times over the past million years. There are four subsidiary cycles at about 41,000- , 23,000- , 21,000- , and 19,000-year periods. For the earlier million years of record, all of the four subsidiary peaks are present, but the 100,000-year component does not show.

These characteristic time-periods, and this history of ice-building, were postulated forty years ago by a Serbian physicist called Milutin Milankovitch, who proposed, following earlier suggestions of the German climatologist Vladimir Köppen, that ice ages occurred in response to very small changes, over time in the amount of radiation received by the Earth. These changes were caused in turn by variations in the geometry of the planet's orbit around the Sun (Figure 25). The reason: the geometric properties of the Earth's orbit vary in time, and affect the amount of sunlight reaching the planet. While the average over the year of the net radiance was the same, some summers were a little hotter than usual, and some were less hot or even cool. Although his theory was ridiculed for decades, Milankovitch continued to believe that ice sheets were extremely sensitive to summer temperatures. The winters were always cold enough to sustain an ice sheet if it was already there, but if summers got so warm that the ice sheets melted back, the succeeding winters may not have been cold enough to allow the ice to recover its full volume.

Using an extraordinarily complex formula, long before computers, Milankovitch determined all the tiny changes in the effective sunlight intensity of the summer and winter seasons over hundreds of thousands of years of the Earth's most recent history. Finally, he firmly demonstrated that every one of the recently observed glacial periods—100,000, 41,000, 23,000, 21,000 and 19,000 years (with the possible exception of the longest)—is a characteristic period expected in the ice-volume record due to the variation of one of the Earth's orbital parameters.



Orbit of Earth Around the Sun

FIGURE 25. *The geometry of the Earth's orbit around the Sun, showing the principal sources of variability.*

What are the varying orbital parameters that control the amount of sunlight reaching us? We all know that the Earth's orbit is roughly elliptical—almost circular. The elliptical shape of the orbit itself, under the same multiple gravitational attractions, also varies, with a dominant characteristic period of 100,000 years.

As the Earth moves in this elliptical orbit around the Sun, its 24-hour rotation gives rise to night and day. At the same time as the

Earth spins around its axis, the axis itself remains tilted at an angle of approximately 23½ degrees to the plane of the Earth's orbit around the Sun. If the Earth and the Sun were alone in the solar system, all the geometric properties of the orbit would be rigidly fixed. Because they share the system with other planets, tiny variations occur. The tilt in the spin-axis in particular is dominated by a characteristic period of 41,000 years. As the non-spherical Earth spins around the Sun—pulled by the gravitational force of not only the Sun but the moon, Jupiter, Mercury, Venus, and Mars—the direction towards which the spin-axis points with respect to the fixed stars also executes a conical motion in space. It slowly wobbles, like a top, completing a cycle in about 22,000 years. In consequence the seasons precess, or come a little earlier over the years, and therefore correspond to successively different positions in the orbital ellipse (Figure 25).

Of course the climate is not directly altered by these small changes in the Earth's orbit around the Sun; climate is sensitive rather to variations in the distribution, and the effective intensity, of the solar radiation received. It's a relatively straightforward matter to reconstruct the history of small fluctuations in the Earth's orbital geometry. In doing this we must include the influence of all the planets in the solar system on each other. With this reconstruction we can compute the history of variations in solar radiation and come to grips with the cause of fluctuations in continental ice-volume.

Some important issues remain to be resolved concerning what has come to be called 'the astronomical theory' of ice ages. Foremost among these is the reason for the 100,000-year cycle seen in the analysis of the last million years of oxygen isotope variability, and not in the earlier million years. Nevertheless we cannot now deny the fact that the climate system does respond dramatically to the extremely small fluctuations of sunlight caused by variations in the Earth's orbit around the sun. The climate system must therefore be a highly non-linear system, perhaps often responding dramatically to small external and internal stimuli.

A physical model that has been used most successfully to describe the link between variations of incoming solar radiation and ice-volume change involves an interaction between several elements of the global Earth system. In this model the characteristic 100,000-year variation that has dominated the last million years of earth history is shown to depend upon:

—the solid earth;
—the ice sheets;
—the oceans and their role in the carbon cycle;
—the interaction between these three elements and astronomical changes in the radiation field.

The complexity of this interaction is a striking example of the way the intricacy and non-lineality of the climate system can produce subtleties and surprises. In response to very tiny changes in the Earth's orbit, altering the heat of summertime seasonal solar energy by only a few percentages, huge ice sheets are created, to grow and decay. What could be more eloquent proof of the extraordinary fragility of the planetary environment?

The recognition that humanity has become an active player in driving the evolution of the ecosphere encourages us in our efforts to understand further the way in which the physical, chemical, and biological components of the Earth system mutually interact. It is only through such improved understanding that we can hope to evaluate the influence of human beings on a global scale, and thus be able to take remedial action where needed.