The natural causes that are most often invoked include major volcanic eruptions, which can partially block the Sun's incoming radiation, and variations in the Sun's radiation itself, caused by some unknown process or processes occurring in the surface layers or the deep interior of the Sun. Until quite recently, the constancy of the Sun's output of radiation went unquestioned, but several factors have combined to change this view. Measurements from spacecraft of the Sun's total energy output have shown that it varies slightly in association with sunspot activity, both on a day-to-day basis, which is too short to affect our climate, and also on the time scale of the 11-year sunspot cycle [*Willson and Hudson*, 1991]. While these variations are probably too small to have much of a climatic effect, attention is now focusing on a longer 80–100 year cycle that influences the amplitude of the 11-year cycle. Scientists in the United States and Denmark have presented evidence that the Earth's surface temperature has shown a striking correlation with this so-called Gleissberg cycle of solar activity since about 1850, when reliable temperature records began to be kept. The temperature record of the more distant past, determined from ice cores taken from the Greenland ice cap, has also shown a periodicity close to that of the Gleissberg cycle [*Johnsen et al.*, 1970].

This evidence, while circumstantial, bolsters earlier studies of a mysterious period in the late 17th and early 18th centuries when sunspots apparently disappeared from view. The existence of this period—known as the "Maunder Minimum" after its discoverer—was long questioned, but even in those early days the Sun was being observed regularly by telescope, and there is a great deal of supporting evidence for the absence of sunspots. The intriguing fact from the climatic point of view is that the Maunder Minimum coincided in Europe with the coldest part of the so-called Little Ice Age that affected the entire Earth in the late 16th century, and from which we may still be recovering. The Maunder Minimum may reflect a still longer periodicity in the Sun's activity, and evidence from radiocarbon studies has tended to support this view [*Stuiver and Braziunas*, 1989].

Climate models have been used to estimate the magnitude of the variation in the Sun's output that would be needed to cause the terrestrial temperature changes observed. The climate system is quite sensitive to small changes in solar radiation, and current estimates are that a few tenths of a percent, or about 1% at most, is all that would be needed [*Reid*, 1991]. Solar astronomers have not been able to identify a mechanism that could produce such variations, but studies of other stars in our galaxy of the same general size and type as our Sun have indeed shown evidence that brightness does vary at this level [*Baliunas and Jastrow*, 1990].

The mounting evidence for the Sun's control of our past climate should not be taken, however, as an indication that human activities are not important. The increasing atmospheric burden of greenhouse gases such as carbon dioxide must inevitably lead to further warming. The only question is one of timing, and it is of the utmost importance to try to determine when this anthropogenic warming will overcome the natural variability. Much current research activity focuses on attempts to answer this question.

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Deglaciation Triggered by the Resumption of North Atlantic Deep Water

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Changes in the distribution of solar radiation received on Earth, as a result of the planet's orbital variations, are well-established as the pacemaker of Pleistocene climate change [*Hays et al.*, 1976]. However, several hypotheses suggest that these radiation changes cannot account by themselves for the manner in which the ice ages wax and wane. New evidence clearly defines the role of deep ocean circulation during the last deglaciation and supports a stronger connection between deep ocean circulation changes and warming trends.

Considering only the effect of solar radiation, climate change such as the transition from the last ice age to the present should occur gradually over several thousand years and should be out of phase in the Northern and Southern hemispheres. However, the last deglaciation was composed of two distinct steps, each of which lasted less than 1 kyr [*Fairbanks*, 1989] and, apparently, was "felt" synchronously between the hemispheres. Hypotheses proposed to explain this most recent climate change focus either on changes in the level of greenhouse gases, such as CO_2, methane, and water vapor, or on large-scale ocean circulation, which delivers heat to high latitudes.

Ice cores indicate that atmospheric levels of pCO_2 were 80 ppm lower during the Last Glacial Maximum relative to the interglacial levels of the Holocene (10 k.a. to the present). The deep-sea record shows a clear relationship between deep-water circulation patterns and modes of climate; that is, high North Atlantic Deep Water (NADW) flux during interglacial intervals, and low flux during glacial intervals (for example, see *Boyle and Keigwin* [1982] or *Oppo and Fairbanks* [1987]). It is possible that either greenhouse gas changes or deep-ocean circulation reorganization could have contributed to the character of the last deglaciation, although existing geologic records do not allow us to determine if either was the key mechanism. The available deglacial intervals in ice cores are apparently plagued by dating uncertainties and possible summer melting, while the temporal resolution in deep-sea records is insufficient to resolve whether the renewed NADW production triggered deglaciation, or merely responded to it.

Recently, new evidence that clearly defines the role of deep ocean circulation in the last deglaciation was presented by *Charles and Fairbanks* [1992]. They evaluated the benthic (deep ocean) foraminiferal stable isotope record from a Southern Ocean core with a high sedimentation rate (25 cm/kyr). The Southern Ocean record constantly and vigorously mixes the deep water output from the Atlantic, Indian, and Pacific oceans, and therefore records only those NADW changes with global significance.

Several important relationships were defined by *Charles and Fairbanks* [1992]. They found that the NADW contribution to the global oceans was renewed almost instantaneously between 12.6–12.2 ka. This was synchronous with the first stage of ice sheet melting that was recorded in Barbados corals [*Fairbanks*, 1989]. NADW contribution increased again between 10–9 ka and correlates with the second stage of deglaciation. The mid-depth Atlantic also recorded large-scale changes that coincided with increased NADW between 12.6–12.2 ka. The dramatic geochemical changes recorded at this time in mid-depth regions of the Atlantic Ocean have been well-established, although the cause remains elusive. *Boyle and Keigwin* [1987] noted that the higher NADW production was one possible explanation, and the Charles and Fairbanks record strongly suggests that reorganization of deep-water circulation caused geochemical changes at mid-depths in the Atlantic. The return to warm European climates, indicated by pollen assemblages recovered from lake sediment

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cores, was also synchronous with the major NADW production increase.

The connection between NADW and climate change is becoming more apparent. *Broecker and Denton* [1989] reviewed several effects that NADW may have on the climate system. The production of NADW results in a significant release of heat from the ocean to the atmosphere in the North Atlantic, which has been coined the "Nordic heat pump." This gain of heat by the atmosphere is responsible for the warmer European climates and possibly for ice sheet melting. The upwelling of NADW is also important for the heat budget in the Southern Ocean, and therefore provides a mechanism for synchronous climate changes in the Northern and Southern hemispheres. As Charles and Fairbanks noted, coincidence alone does not constitute proof. However, the fact that the resumption of NADW and ice sheet melting occurred almost instantaneously, as well as simultaneously, provides a clear test by which all climate change hypotheses can be evaluated. The mechanism that triggered NADW production has yet to be determined. One possibility is that the ocean has an internal salt oscillator [*Broecker et al.*, 1990], which is at least partially consistent with the Charles and Fairbanks results.

The Charles and Fairbanks results do not exclude changes in greenhouse gases as a contributor to deglaciation or even a trigger for it. One might predict from their results that CO_2 changes recorded in the ice cores would be synchronous with changes in NADW [*Boyle and Keigwin*, 1987]. The rapidity of the climate and deep-water reorganizations underscores the need for high resolution ice-core records to assess the role of CO_2 in climate change.

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A New View of Mantle Structure

PAGES 24–25

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A specific and unique property of the solid state is its regular internal structure, which effectively acts as a memory to store information about its deformation history. Most of the Earth, except for the liquid outer core, is in the solid state and is composed of crystals. Of particular importance for processes in the Earth's crust, such as volcanic activity, earthquakes, and mountain building, is the deformation of the mantle. One of the goals of geophysical research is to understand this deformation and to model its evolution. Within the mantle, large cells of convection are induced by instabilities and driven by temperature gradients. This convective flow has been modeled by geophysicists since the early 1960s with increasing sophistication (see, for example, *Hager and O'Connell* [1981]). The models were generally based on the assumption that the material was a viscous liquid with neither internal structure nor directional properties.

Also in the 1960s, seismologists noticed that seismic waves travel over oceanic ridges with different velocities in different directions. Waves perpendicular to the ridges travel about 5% faster than those parallel to the ridges. *Hess* [1964] interpreted this as a result of a preferential alignment of crystals with directional properties, proposing that this alignment was attained during the convection process. The main constituent of the upper mantle is the magnesium silicate olivine, which exhibits about a 25% difference between velocities in the slowest and fastest crystal directions. In an aggregate with preferred orientation of component crystals, it would seem plausible to expect a directional dependence of seismic wave propagation (anisotropy). Geologists have indeed observed a strong preferred alignment of olivine crystals in rocks that have been brought up from the mantle. While the general concept of preferred orientation was accepted, it was never incorporated into macroscopic convection models, mainly because of the great complexities it entails.

On a microscopic scale, olivine is deformed in the upper mantle by intracrystalline processes, slip of dislocations in the crystal lattice, and accompanying recrystallization. In a crystal aggregate, the interplay of deforming single crystals also needs to be considered. In general, there is a tendency to minimize a mismatch in grain shapes (strain compatibility) and stresses across grain boundaries (stress equilibrium). Metallurgists have developed various theories of polycrystal plasticity that allow us to predict—quantitatively—the macroscopic flow pattern, the development of preferred orientation, and the anisotropy of properties for a given deformation path, based on assumptions about microscopic processes. In successful collaborations between Earth and materials scientists, metallurgical theories have been applied to model deformation of rocks composed of minerals such as halite, quartz, calcite, and olivine. Calculated crystal-orientation patterns agree with those produced in the laboratory under corresponding conditions and those observed in nature. Surprisingly, the brittle minerals deform in a fashion similar to metals, because slow geological strain rates and high pressures compensate for the much higher ductility and diffusivity in cubic metals.

So far these calculations have been done for very simple strain histories such as the compression of a rod along its axis. In a mantle convection cell, the strain is very heterogeneous and changes as deformation proceeds, as illustrated along a flow line in Figure 1a. At each point, the next deformation increment is controlled by the accumulated previous states and the strength of the preferred orientation may either increase or decrease. In other words, to correctly predict the flow behavior at any point in the mantle, we need to consider the microscopic deformation processes in all single crystals over the whole deformation history—obviously a formidable task. Yet such problems have recently been solved by mechanicians at Cornell University who needed to predict anisotropy changes during the rolling of a steel sheet. The deforming volume is divided into cells and a two-dimensional, finite-element computer code is used to update the structure and crystal orientation distribution in each cell for each increment of the deformation process.

In a project between mechanicians at Cornell and geologists at the University of California-Berkeley, this approach has been applied to the mantle (Y. B. Chastel, P. R. Dawson, H.-R. Wenk, and K. Bennett, An anisotropic convection model for the upper mantle, submitted to *J. Geophys. Res.*, 1992). The model predicts development of strong preferred orientation during upwelling, as illustrated in Figure 1b in crystal-orientation diagrams of a-axes. The preferred orientation stabilizes during spreading and attenuates during subduction. The orientation patterns—represented as pole figures of a particular crystal direction (a-axis) in stereographic projection—are asymmetric, contrary to Hess' intuitive assumption that they should align with flow lines. Knowing the orientation of crystallites in a convection cell and the physical properties of single crystals, one can then average over the mantle to get seismic velocities in different directions. The model predicts an anisotropy of 6%, just about what is actually observed. Through interdisciplinary collaboration, the qualitative Hess intuition has now been recast into a

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