NMR. Given the role of oxygen vacancies in such diffusion (*1*) and the likelihood of such vacancies in the most common mineral in Earth's lower mantle (*11*), these mechanisms may also have key importance for understanding large-scale geophysical processes.

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PERSPECTIVES: CLIMATE

An Exceptionally Long Interglacial Ahead?

A. Berger and M. F. Loutre

When paleoclimatologists gathered in 1972 to discuss how and when the present warm period would end (*1*), a slide into the next glacial seemed imminent. But more recent studies point toward a different future: a long interglacial that may last another 50,000 years.

An interglacial is an uninterrupted warm interval during which global climate reaches at least the preindustrial level of warmth. Based on geological records available in 1972, the last two interglacials (including the Eemian, ~125,000 years ago) were believed to have lasted about 10,000 years. This is about the length of the current warm interval—the Holocene—to date. Assuming a similar duration for all interglacials, the scientists concluded that "it is likely that the present-day warm epoch will terminate relatively soon if man does not intervene" (*1*, p. 267).

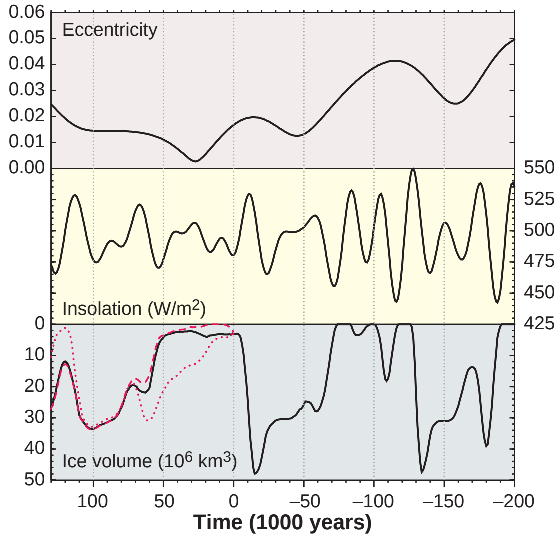
Some assumptions made 30 years ago have since been questioned. Past interglacials may have been longer than originally assumed (*2*). Some, including marine isotope stage 11 (MIS-11, 400,000 years ago), may have been warmer than at present (*3*). We are also increasingly aware of the intensification of the greenhouse effect by human activities (*4*). But even without human perturbation, future climate may not develop as in past interglacials (*5*) because the forcings and mechanisms that produced these earlier warm periods may have been quite different from today's.

Most early attempts to predict future climate at the geological time scale (*6*, *7*) prolonged the cooling that started at the peak of the Holocene some 6000 years ago, predicting a cold interval in about 25,000 years and a glaciation in about 55,000 years. These projections were based on statistical rules or simple models that did not include any CO_2 forcing. They thus implicitly assumed a value equal to the average of the last glacial-interglacial cycles [~225 parts per million by volume (ppmv) (*8*)].

But some studies disagreed with these projections. With a simple ice-sheet model, Oerlemans and Van der Veen (*9*) predicted a long interglacial lasting another 50,000 years, followed by a first glacial maximum in about 65,000 years. Ledley also stated that an ice age is unlikely to begin in the next 70,000 years (*10*), based on the relation between the observed rate of change of ice volume and the summer solstice radiation.

Other studies were more oriented toward modeling, including the possible effects of anthropogenic CO_2 emissions on the dynamics of the ice-age cycles. For example, according to Saltzman *et al.* (*11*) an increase in atmospheric CO_2, if maintained over a long period of time, could trigger the climatic system into a stable regime with small ice sheets, if any, in the Northern Hemisphere. Loutre (*12*) also showed that a CO_2 concentration of 710 ppmv, returning to a present-day value within 5000 years, could lead to a collapse of the Greenland Ice Sheet in a few thousand years.

On a geological time scale, climate cycles are believed to be driven by changes in insolation (solar radiation received at the top of the atmosphere) as a result of variations in Earth's orbit around the Sun. Over the next 100,000 years, the amplitude of insolation variations will be small (see the figure), much smaller than during the Eemian. For example, at 65°N in June, insolation will vary by less than 25 Wm^{-2} over the next 25,000 years, compared with 110 Wm^{-2} between 125,000 and 115,000 years ago. From the standpoint of insolation, the Eemian can hardly be taken as an analog for the next millennia, as is often assumed.



Orbiting the Sun. Long-term variations of eccentricity (**top**), June insolation at 65°N (**middle**), and simulated Northern Hemisphere ice volume (increasing downward) (**bottom**) for 200,000 years before the present to 130,000 from now. Time is negative in the past and positive in the future. For the future, three CO_2 scenarios were used: last glacial-interglacial values (solid line), a human-induced concentration of 750 ppmv (dashed line), and a constant concentration of 210 ppmv (dotted line). Simulation results from (*13*, *15*); eccentricity and insolation from (*19*).

The small amplitude of future insolation variations is exceptional. One of the few past analogs (*13*) occurred at about 400,000 years before the present, overlapping part of MIS-11. Then and now, very low eccentricity values coincided with the minima of the 400,000-year eccentricity cycle. Eccentricity will reach almost zero within the next 25,000 years, damping the variations of precession considerably.

Simulations with a two-dimensional climate model (*14*), forced with insolation and CO_2 variations over the next 100,000 years, provide an insight into the possible consequences of this rare phenomenon. Most CO_2 scenarios (*15*) led to an exceptionally long interglacial from 5000 years before the present to 50,000 years from now (see the bottom panel of the figure), with the next glacial maximum

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in 100,000 years. Only for CO_2 concentrations less than 220 ppmv was an early entrance into glaciation simulated (*15*).

Such a long interglacial appears to have occurred only once in the last 500,000 years, at MIS-11 (*2*, *3*, *16*). At this time, astronomical insolation and some proxy climate indicators were similar to those of today. The CO_2 concentration was at an interglacial level [slightly above 280 ppmv (*8*)]. Simulations with these values (*16*) also show a particularly long interglacial, illustrating the importance of CO_2 concentrations during periods when the amplitude of insolation variation is too small to drive the climate system.

The present-day CO_2 concentration of 370 ppmv is already well above typical interglacial values of ~290 ppmv. Taking into account anthropogenic perturbations, we have studied further in which the CO_2 concentration increases to up to 750 ppmv over the next 200 years, returning to natural levels by 1000 years from now (*13*, *15*). The results suggest that, under very small insolation variations, there is a threshold value of CO_2 above which the Greenland Ice Sheet disappears (see the bottom panel of the figure). The climate system may take 50,000 years to assimilate the impacts of human activities during the early third millennium.

In this case, an "irreversible greenhouse effect" could become the most likely future climate. If the Greenland and west Antarctic Ice Sheets disappear completely, then today's "Anthropocene" (*17*) may only be a transition between the Quaternary and the next geological period. J. Murray Mitchell Jr. already predicted in 1972 that "The net impact of human activities on the climate of the future decades and centuries is quite likely to be one of warming and therefore favorable to the perpetuation of the present interglacial" [(*1*), p. 436].

This scenario will have to be confirmed with models that better simulate ice sheets and ocean circulation. Recent results by Peltier and Vettoretti (*18*) are encouraging. With the Canadian climate general circulation model, they showed that under the present-day insolation regime and preindustrial CO_2 concentration, no glacial inception is possible. In contrast, the model is able to simulate a glacial transition at the end of the Eemian.

Most model studies to date confirm that the pattern and range of global climatic conditions likely to be experienced in the future will be close to those during the warmest phases of the last few tens of millions of years. We must use the reconstructed record of these past climates to test our understanding of the behavior of the climate system and as a guide to future conditions.

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PERSPECTIVES: THERMODYNAMICS

Water and Ice

Alan K. Soper

To the nonspecialist, it must come as a bit of a surprise to discover how much scientific attention is paid to the apparently simple water molecule, H_2O. Almost every week, new results on water and ice appear in high-profile journals, while lesser molecules like hydrogen fluoride or ammonia seem to get little or no coverage.

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The apparent simplicity of the water molecule belies the enormous complexity of its interactions with other molecules, including other water molecules. In common with all other molecules, it experiences repulsive overlap and attractive van der Waals forces, but added to this is the strongly directional force of hydrogen bonding. A satisfactory description of this force still eludes scientists. In water, the strength and directionality of the hydrogen bond combine with molecular geometry in a way that sets this molecule apart from almost any other, giving water its complex and still poorly understood phase diagram (see the figure).

A well-known aspect of this phase diagram is the fact that at ambient pressure and 0°C (273 K), ice is less dense than water, and that the liquid is less dense at 0°C than at +4°C. In fact, if you supercool the liquid below 0°C at ambient pressure, it continues to become less dense (*1*). But this process does not continue indefinitely. At about –40°C (233 K), the liquid will spontaneously crystallize, no matter how pure it is (*2*). This temperature, known as the homogeneous nucleation temperature (HNT), is the cause of much controversy that remains unresolved.

But the plot gets even thicker. As water is supercooled, its diffusion constant diminishes, and appears by extrapolation to go to zero just below the HNT. This observation has led to the conjecture that there is a "stability limit" to the supercooled liquid (*3*). For water, however, this limit is not the usual glass transition temperature, as it would be for many other liquids. Instead, it represents the start of a region where disordered water apparently cannot exist. The glass transition temperature for water is in fact much lower, probably around 136 K.

One simple method of circumventing this "no man's land" in the water phase diagram is to take hexagonal ice at 77 K and pressurize it to about 2 GPa (*4*). This process leads to a dense form of amorphous ice, called high-density amorphous ice (HDA), which remains dense if kept below ~100 K. But if HDA is warmed to ~115 K, it suddenly expands to another form of amorphous ice called low-density amorphous ice (LDA). LDA appears to be similar in structure to the amorphous ice produced by vapor deposition and hyperquenching of the liquid.

The suddenness of the HDA-LDA transition was one of several factors leading to the conjecture that water exhibits a liquid-liquid critical point below which two different forms of liquid water coexist (*5*). This tantalizing suggestion, which was based on a computer simulation, went a long way toward explaining, at least qualitatively, many of the anomalous properties of water. It was, however, controversial, because the proposed location of the second critical point at 200 K was in the middle of the region where, according to the stability limit conjecture, bulk water can only exist in crystalline form.

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