no strange attractors were deduced from experimental data. Anke Brandstäter and Swinney at Texas have now done this for Couette flow.

Attractors are the general name for the steady-state trajectory of a dynamical system. In the case of a fluid, the trajectory at each point in time is described by the values of the components of the velocity field at each point in space, a very large number of variables. For Taylor vortex flow, the attractor is a single point in this multidimensional space because the flow is time-independent. For wavy modes, the attractor is a closed loop formed as the velocity oscillates between the maximum and minimum values during the passage of a wave. For a type of flow with two frequencies similar to modulated wavy modes (quasi-periodic flow), the attractor is a torus. One frequency corresponds to motion around the major axis of the torus, and the other corresponds to motion around the minor axis. Motion on a strange attractor, which has a complex shape, is unpredictable, giving a noisy Fourier spectrum in the turbulent regime.

It is clearly impractical to construct a trajectory for a real fluid. But theorists have shown that an equivalent can be made much more simply by measuring the velocity, at a single location in the fluid. A point in the trajectory at time t is defined by the velocity at this location at times t, $t + \tau$, $t + 2\tau$, $t + 3\tau$, and so on. A practical limit to the number of multiples of τ needed is reached when the form of the trajectory fails to change with the addition of more terms.

With the aid of extremely accurate laser-Doppler velocimetry measurements, the Texas researchers were able to construct trajectories at different values of the cylinder speed. The trajectories had an important feature that branded them as belonging to a strange attractor. Trajectories starting from almost identical but slightly different initial points diverge exponentially on a strange attractor. This behavior is measured by a parameter called a Lyapunov exponent, whose value must be positive. From the experimental data, Alan Wolf and Jack Swift of Texas, calculated a positive Lyapunov exponent whose value increased as the cylinder speed rose.

Another important characteristic of strange attractors is that their dimension need not have an integer value. Swinney told the workshop that Doyne Farmer and Erica Jen of the Los Alamos National Laboratory have used the Texas data to calculate the dimension of the strange attractor. They found it to be small in accordance with chaos models and to vary continuously from 2 to 4 over the range of cylinder speeds studied.

There is as yet no specific chaos model that applies to Couette flow, but theorists are said to be working on one. Moreover, at a NATO advanced research workshop at Haverford College in early June, Pierre Bergé and Monique DuBois of the French Nuclear Studies Center in Saclay and George Buzyna and Richard Pfeffer of Florida State University presented evidence for strange attractors in other fluid systems.†

All in all, if the transition to turbulence remains a murky topic for the moment, fluids researchers seem to have more promising leads than they have had in quite a while.—**Arthur L. Robinson**

†NATO Advanced Research Workshop on Testing Nonlinear Dynamics, Haverford College, Haverford, Pennsylvania, 6 to 9 June 1983.

An Early Glacial Two-Step?

The most recent ice age seems to have exited in two steps, the earlier one perhaps coming sooner than had been thought possible

When the end of the last ice age came more than 10,000 years ago, it came quickly. After 100,000 years of gradual accumulation from winter snows, ice piled as high as 3000 meters over Canada, Greenland, and northern Europe wasted away to nearly nothing in only a few thousand years. This suddenness has been an awkward problem for geologists, a problem complicated by the recent detection of an apparent pause in the disintegration of the great ice sheets. But new evidence suggests that the first step of deglaciation, the one before the pause, may have been driven largely by forces other than the gradual warming of the climate.

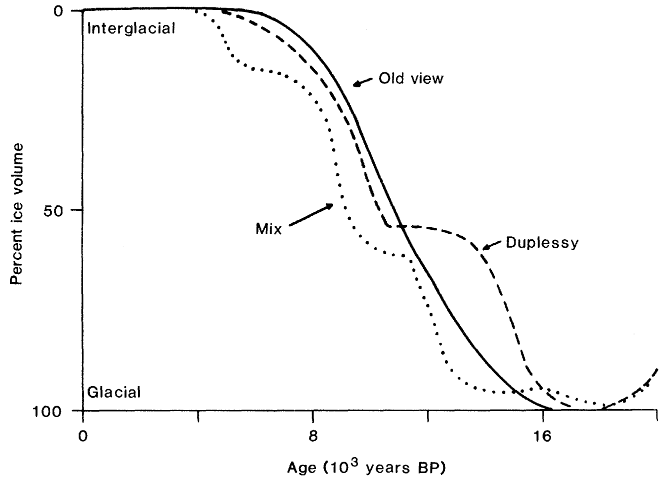
Scientists generally agree that the ultimate cause of the end of the last ice age was changes in the orbit and the axial tilt of Earth, the Milankovitch or orbital variations that seem to pace the comings and goings of the ice ages (*Science*, 21 January, p. 272). Orbital variations produced a smooth increase in the solar energy or insolation falling during the summer on the Northern Hemisphere, where most of the ice to be melted was located, so that by 17,000 years ago solar insolation conditions resembled those of today. By 11,000 years ago, summer insolation on Northern Hemisphere ice sheets peaked at a level no more than 9 percent higher than today's. The timing of that peak nicely fit geological evidence from the continents and isotopic evidence from the deep sea for the occurrence of the maximum rate of ice sheet disintegration at about 11,000 years ago. The strongest sunshine melted the ice the fastest, or so it seemed.

Nothing is that tidy anymore. Jean-Claude Duplessy of the National Center for Scientific Research, Gif-sur-Yvette, France, and colleagues there and at the University of Bordeaux have concluded from their oxygen-isotope study of deep-sea sediments from the Bay of Biscay, south of the English Channel, that at least one-third of the ice melted between 16,000 and 13,000 years ago. That was long before increasing insolation could have melted much ice. Further complicating matters, melting of the ice sheets appeared to pause between 13,000 and 10,000 years ago, just when the fastest melting had been deduced from earlier studies. A second episode of melting apparently led to the present volume of ice by about 6000 years ago. A similar study of equatorial Atlantic sediments presented at a recent meeting* in Airlie, Virginia, by Alan Mix and William Ruddiman of the Lamont-Doherty Geological Observatory also found two steps in the deglaciation. The second step (10,000 to 8,000 years ago) coincided with Duplessy's, but the first came between 13,000 and 11,000 years ago. Despite their disagreement on timing, these two studies convinced most of those at the Airlie meeting that something slowed or stopped the disintegration of the ice sheets at the least likely time.

*Conference on the Timing and Mechanism of the Last Deglaciation, held at Airlie House, Virginia, 2 to 6 May; William Ruddiman, Lamont-Doherty Geological Observation, and Jean-Claude Duplessy, CNRS, Gif-sur-Yvette, France, cochairmen.

The deglaciation

In the past, the loss of glacial ice (solid line) seemed to follow the smoothly increasing curve of sunlight falling on the Northern Hemisphere during the summer. New studies (Mix's and Duplessy's) suggest that deglaciation paused in the middle of the transition from the most recent ice age to the present interglacial period. [*Source: A. Mix—LDGO*]



Evidence from both the North Atlantic Ocean and the European continent supports this two-step deglaciation. In the same sediment samples used in their isotopic study, Duplessy and his group estimated past sea surface temperatures by determining the abundance of certain microfossils. They found that temperatures rose at least 6 degrees (Celsius) after 13,000 years ago but fell to near-glacial levels again during the period 11,000 to 10,000 years ago before warming for good. Ruddiman and Andrew McIntyre of Lamont found the same pattern across the entire North Atlantic north of 45°N. Apparently, cold polar waters retreated to the north and east only to push south again almost as far as they ever did under glacial conditions.

The European continent did not escape the effects of the renewed chilling of the Atlantic. European glaciologists have long divided the most recent transition from glacial to nonglacial conditions into short intervals of oscillating climate. Indicators as diverse as ice edge positions and the changing populations of plants, beetles, and mussels show that the strongest climate oscillation was a cold period called the Younger Dryas that fell between 11,000 and 10,000 years ago. Pollen in Duplessy's sediments links this continental cooling to the resurgence of polar waters in the Atlantic, but strong climatic effects do not seem to extend much beyond the regions surrounding the Atlantic.

The mid-transition cooling seems to be real, at least around the North Atlantic where the major ice sheets were clustered, but there is no agreement about why the transition did not go more smoothly. The possible explanations range from the inherent instability of climate in transition, as exhibited in computer models, to cyclic variations in the output of the sun. One of the more appealing explanations, offered by John Mercer of Ohio State University, is that huge numbers of icebergs flooded into the North Atlantic from the ice shelves of the Arctic and Norwegian seas, chilling the surface water and ultimately the European continent. What link there might be between such a mechanism for the cooling of the Atlantic and Europe and the apparent pause in global deglaciation is not clear yet.

Although the slowing of deglaciation in mid stride is enjoying growing acceptance, the idea that the disintegration of the ice sheets could have accelerated ahead of that expected from increasing insolation is still controversial. The isotopic evidence of Duplessy's group did indicate that at least one-third of the ice had melted by 13,000 years ago. From entirely different observations, Ruddiman and McIntyre also found that significant amounts of ice were gone by then. They found an apparent disappearance of microscopic organisms called foraminifera in the surface waters of the far North Atlantic between 16,000 and 13,000 years ago. The foraminifera were wiped out, Ruddiman and McIntyre suggest, when a torrent of ice sheet meltwater and icebergs spilled into the Atlantic and formed a cold, freshwater lid on the ocean, cutting off nutrients essential to the phytoplankton that foraminifera consume. The freshwater needed to do that could require the melting of perhaps half the ice sheets. But at that time, the insolation increase was still weak and the air near the ice was relatively cold. And besides, argue some glacial geologists, the ice sheets had shrunk by only 20 to 25 percent, not 50 percent.

Ruddiman and McIntyre believe that ice sheet disintegration can accelerate beyond that expected from direct heating because the initial meltwater would tend to cut off the supply of moisture that feeds snow to the ice sheets. This negative feedback would operate through several effects of the cold, freshwater lid on the North Atlantic, according to their proposal. Because the Atlantic was colder, less water would evaporate from the ocean and end up as snow on the ice sheets. Because it was fresher, more of it would freeze in winter, cutting off much moisture in the crucial winter months. And the thin, stable surface layer would store less summer heat that could be used to evaporate water in the winter.

Ruddiman and McIntyre's negative feedbacks also include the destabilization and removal of ice shelves by rising sea level. That would accelerate the calving of icebergs, which in turn would further cool and freshen the surface waters of the Atlantic. George Denton and Terence Hughes of the University of Maine have argued that rising sea level could also lead to the creation of relatively high-speed streams of ice flowing from the central ice sheets to the sea, as seen in Antarctica. That would rapidly thin the ice sheets without causing rapid retreats of their edges—collapsing them like a cooling soufflé—as required by the geological evidence. Ice streams would also carry much ice into the sea, where the ice could melt more rapidly. Taken together, these marine feedbacks could help explain why modest changes in insolation distributions cause rapid terminations of ice ages every 100,000 years (*Science*, 21 January, p. 272).

Although this all fits together nicely, there are some major hitches. One is Mix's age of 13,000 to 11,000 years, rather than 16,000 to 13,000 years, for the first step of deglaciation. At this later time, melting the ice sheets in place is not a great problem. Special marine feedback mechanisms would not necessarily be required, although melting would need to be quite rapid. Some glacial geologists also point to evidence that Denton and Hughes's ice streams could not have been flowing where and when they say they were. At the Airlie meeting, glacial geologist John Andrews did concede that if marine researchers could agree on an early date for the first step of deglaciation, then perhaps the transition could have been complex enough to accommodate ice streams within the constraints of the present evidence. Thus, it seems that the details of how and why the last ice age ended the way it did lie in the ocean.—**Richard A. Kerr**

Additional Reading

1. G. H. Denton and T. Hughes, *The Last Great Ice Sheets* (Wiley-Interscience, New York, 1981).
2. J. C. Duplessy *et al.*, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **35**, 121 (1981).
3. W. F. Ruddiman and A. McIntyre, *Quat. Res. (N.Y.)* **16**, 125 (1981).