melt the Laurentide Ice Sheet, while keeping it in the far western Pacific will favor ice sheet growth.

Satellite-based cloud climatologies show a tendency toward less low cloud during warm events, when the tropical area covered by cold waters is at a minimum. Low cloud has a net cooling effect because it reflects solar radiation but has little net effect on outgoing longwave radiation. There is also some evidence for an increase in atmospheric water vapor during warm events (*16*). These changes are small amplitude, but they all line up in the right sense for El Niño–like states to favor interglacial conditions and La Niña–like states to favor glacial conditions. Only atmospheric CO_2, which decreases during El Niño events in the modern record, is out of line.

The scenario sketched out here does not address the crucial issue of how the rest of the world will feed back on the tropical Pacific (*17*). It is very far from a comprehensive attempt to fit the existing paleoclimate record to a tropical Pacific perspective. There is clearly much modeling work and observational analysis to be done with the data in hand. Most paleoclimate data come from higher latitudes, however, and the records of the tropics in general and the Pacific in particular badly need to be enhanced.

It is premature to grant the tropical Pacific the lead role in explaining the expanded repertory of paleoclimate cycles. The weaknesses in the hypothesis are too serious, although arguably no worse than other contenders. However, now that it has been clearly established that these cycles are global, our understanding of modern climate suggests that the tropical Pacific must at the least be a featured player. Even at this early stage, the perspective presented here points in a new direction for paleomodeling and observational studies, one signposted by ideas of modern climate variability (*18*).

References and Notes

1. See the report by the CLIMAP Project Members [*Science* **191**, 1131 (1976)].
2. These data were brought up to date at the recent Chapman Conference on "Mechanisms of Millennial-Scale Global Climate Change" in Snowbird, Utah.
3. T. Stocker, *Science* **282**, 61 (1998).
4. For example, W. B. Curry and D. W. Oppo [*Paleoceanography* **12**, 1 (1997)] for the Atlantic, F. Sirocco *et al.* [*Nature* **364**, 322 (1993)] for the Indian, and B. K. Lindsley [*Nature* **380**, 243 (1996)] for the Pacific. Land changes are indicated by methane variations [J. Chappellaz *et al.*, *Nature* **366**, 443 (1993)].
5. W. S. Broecker and G. H. Denton, *Geochim. Cosmochim. Acta* **53**, 2465 (1989).
6. This is true even among the strongest advocates of the North Atlantic; W. S. Broecker [*Science* **278**, 1582 (1997)] does not abandon the North Atlantic, but he points to something largely tropical, water vapor.
7. D. Rind *et al.*, *Clim. Dyn.* **1**, 3 (1986); S. Manabe and R. J. Stouffer, *J. Clim.* **1**, 841 (1988); S. Rahmstorf, *Nature* **372**, 82 (1994).
8. J. W. Hurrell, H. van Loon, *Clim. Change* **36**, 301 (1997).
9. M. P. Hoerling, M. Ting, A. Kumar, *J. Clim.* **7**, 745 (1994).
10. J. D. Neelin and H. A. Dijkstra, *ibid.* **8**,1325 (1995); A. Clement, R. Seager, M. A. Cane, S. E. Zebiak, *ibid.* **9**, 2190 (1996).
11. S. E. Zebiak and M. A. Cane, *Mon. Weather Rev.* **115**, 2262 (1987).
12. E. Tziperman, M. A. Cane, S. E. Zebiak, *J. Atmos. Sci.* **54**, 61 (1997).
13. A. Clement, R. Seager, M. A. Cane, in preparation.
14. K. C. Taylor *et al.*, *Nature* **361**, 432 (1993).
15. A. Clement and M. A. Cane, in *Mechanisms of Millenial-Scale Global Climate Change*, P. U. Clark and R. S. Webb, Eds. (American Geophysical Union, Washington, DC, in press).
16. K. Hamilton and R. R. Garcia, *Bull. Am. Meteorol. Soc.* **67**, 1354 (1986).
17. B. Soden, *J. Clim.* **10**, 1050 (1997).
18. A. B. G. Bush and S. G. H. Philander, *Science* **279**, 1341 (1998).
19. I am grateful to T. Stocker for his insightful comments. My thanks to all my colleagues at the Chapman Conference and to the organizers, P. Clark and R. Webb. This is Lamont-Doherty Earth Observatory Contribution 5859.

PERSPECTIVES: CLIMATE CHANGE

The Seesaw Effect

Thomas F. Stocker

Abrupt shifts in climatic conditions at high latitudes in the Northern Hemisphere have captured the attention of climate scientists and the public since their discovery in terrestrial and marine records (*1*). When evidence from Greenland ice cores (*2*) and ocean models (*3*) converged in the mid-1980s, it became clear that these events can happen within a few years to decades, with effects that are at least hemispheric in extent (*4*). Recent modeling studies have further indicated that the dynamic behavior of the distant past may repeat itself in the future (*5*), and it is, therefore, of paramount importance to find out what determines rapid and millennial-scale climatic change.

There were 24 abrupt climate shifts (called Dansgaard/Oeschger events) during the last glacial period (*6*). The 16 events between 25,000 and 60,000 years ago occurred on average every 2000 years. The recurrence time scales for these events are highly variable. On the other hand, one notices a striking similarity in the Greenland ice record between individual events: The warming is abrupt and completed within a few years to decades, whereas the cooling is slower and takes at least a few centuries (*7*). Any theory of millennial-scale events must quantitatively explain this apparent asymmetry.

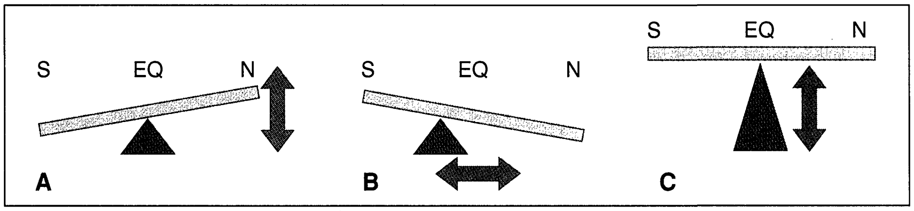
Paleoclimatic records are based on the analysis of ice cores from northern and southern polar ice sheets, marine and lacustrian sediments, pollen profiles, and tree rings. Indicators complementary to the paleorecords allow us to identify the underlying mechanisms. Such indicators include (i) geographical patterns of events and their phase relationship; (ii) biogeochemical signals, such as changes in atmospheric greenhouse gases CO_2 and CH_4 and signals in their isotopic composition, particularly ^{13}C and ^{14}C; (iii) concomitant changes in the ocean and the distribution of tracers; and (iv) amplitudes, rates, and patterns of millennial-scale change as simulated by coupled physical-biogeochemical models. One of the pressing questions is where the centers of activity responsible for these abrupt and millennial-scale climate changes are located. The region of the high northern latitudes, especially the North Atlantic, has been the classic focus of this research. However, it may be argued that the first institutions of paleoclimatic research have been located around the North Atlantic, and a certain bias cannot be excluded. More recently, the focus has moved away from the North Atlantic to consider the influence of other regions on global climatic change.

A simple mechanical analog suggests some possibilities of how the climate system operates during such climatic swings. The system could react like a seesaw (*8*) to perturbations occurring in the north. In consequence, signals in the Southern Hemisphere would be of opposite sign (see panel A of figure). Alternatively, as Cane describes in his accompanying Perspective on page 59, the forcing could be located in the equatorial region rather than at high latitudes (*9*). In our mechanical analogy, this would correspond to a shift of the support point of the seesaw (panel B of figure). By comparing paleoclimatic records from only the high latitudes, we would be unable to distinguish these two cases from each other. A third possibility exists in which the equatorial regions drive changes in both hemispheres synchronously (panel C of figure).

The distinction of in-phase versus antiphase in the context of millennial cli-

---

The author is in the Department of Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland. E-mail: stocker@climate.unibe.ch



The ups and downs of climate. Simple mechanical analogs of three different types of behavior of the climate system as a response to perturbations (blue arrows). **(A)** Perturbations in the northern high latitudes (such as meltwater from the continental ice sheets) trigger transitions between different states of the thermohaline circulation in the North Atlantic. Through the effect of the meridional heat flux in the Atlantic, the amplitudes of climate signals are large in the region around the North Atlantic and are weak and of opposite sign (the other end of the seesaw) in the south. This is the typical interhemispheric seesaw forced in the northern North Atlantic region. **(B)** Perturbations in the tropical region (such as the hydrological cycle feeding into the Hadley cell) cause transitions between different states of the thermohaline circulation in the North Atlantic with effects identical to (A). This is analogous to a seesaw, whose motion is forced by changes of the position of the fulcrum. **(C)** Perturbations in the tropical region lead to parallel changes in Northern and Southern Hemispheres. Here, the seesaw is locked and changes are synchronous and in phase everywhere, as if the height of the fulcrum point were changing.

mate change is a challenging task and requires that the common time scale of paleoclimatic records be known with a resolution better than 500 years or less, irrespective of whether the time scale is absolute or relative. Nevertheless, present paleoclimatic evidence makes the third scenario (panel C of figure) unlikely. First, it is hard to come up with a mechanism that would induce globally synchronous changes on such short time scales. Second, recent synchronizations of temperature records, derived from ice cores from Greenland and Antarctica, clearly exclude in-phase changes for the most prominent of the Dansgaard/Oeschger events (*10*). This is also supported by a recent analysis of a pollen record from New Zealand (*11*). Surprisingly, as Steig *et al.* report on page 92 of this issue, the Taylor Dome ice core from the outer area of Antarctica (*12*) shows an abrupt warming during the deglaciation that may be synchronous with the well-documented abrupt warming 14,500 years ago in the Northern Hemisphere. High-resolution analyses of $\delta\Delta$, $\delta^{18}O$, and CH_4 during the glacial part of the Taylor Dome ice core and comparison with results from other Antarctic ice cores (*10*) are required to obtain a clearer picture of possible regional expressions of abrupt climate change in Antarctica.

Numerous modeling studies (*13*) have shown that changes in the meridional heat transport in the Atlantic Ocean, caused by sudden changes of the Atlantic's thermohaline circulation, are resulting in antiphase behavior of north and south. A sudden increase of the northward meridional heat flux draws more heat from the south and leads to a warming in the north that is synchronous with a cooling in the south (*14*). It has been shown that the stability of this circulation is limited (*5*) and that changes in the surface salinity can trigger major reorganizations of this circulation. More importantly, simulations demonstrate that the amplitudes and rapidity of events compare well with the paleoclimatic record (*15*).

Some models show thermohaline circulation oscillations on time scales of several thousand years, but they occur mainly in highly idealized models, in diffusion-dominated regimes and under particular surface boundary conditions. Their amplitudes are much larger than any paleoclimatic evidence indicates so far (*16*). This suggests that a natural, self-sustained oscillation of the ocean-atmosphere system is unlikely on the millennial time scale and calls for triggers in the climate system instead. One such trigger would be discharges of meltwater from the Northern Hemisphere ice sheets during the last glacial.

For each of the Dansgaard/Oeschger events, layers of ice-rafted debris can be found in marine sediment cores of the northern North Atlantic. Geochemical analyses suggest that they derive from various sources around the North Atlantic (*17*). However, some of these events stand out, in that they are followed by a longer interstadial (warm) phase. They are also associated with a distinct climatic signal in the Antarctic ice cores (*10*), indicating an antiphase relationship between north and south. This supports the hypothesis that these changes are associated with shut-downs of the Atlantic thermohaline circulation.

However, major questions remain to be solved, which will lead to revisions of the relatively simple picture of a global seesaw. The chicken-and-egg problem is still unresolved: Are ice sheet margins inherently unstable, and do episodic meltwater discharges trigger reorganizations in the deep circulation? Or are changes in the ocean circulation modifying the supply of heat and moisture to the ice sheets such that increased melting is initiated? Although climate models couple ocean, atmosphere, and sea ice, fluxes between these components, as well as crucial processes such as deep water formation, are still represented rather crudely in these models. Another limitation confronting modelers is that the location, timing, and amplitude of meltwater events are still poorly known, despite their importance for the response of the ocean circulation and, hence, the climate recorded in the high latitudes.

Finally, the role of the low latitudes and tropics is still unclear (*9*). Their importance is highlighted by the fact that the atmospheric concentration of CH4 exhibits changes with each of the Dansgaard/Oeschger events (*18*). Methane is primarily influenced by low-latitude wetlands during the glacial, indicating that the hydrological cycle is key to a better understanding of the climate system. A combination of the wealth of knowledge on the tropics and the high latitudes, together with more high-resolution paleoclimatic archives, will be required in the next years to make more progress toward a unified view of the climate system.

References and Notes

1. J. Mangerud, S. T. Andersen, B. E. Berglund, J. J. Donner, *Boreas* **3**, 109 (1974); W. F. Ruddiman and A. McIntyre, *Quat. Res.* **16**, 125 (1981).
2. W. Dansgaard *et al.*, in *Climate Processes and Climate Sensitivity, Geophys. Monogr. Ser.*, vol. 29, J. E. Hansen and T. Takahashi, Eds. (American Geophysical Union, Washington DC, 1984), pp. 288–298; H. Oeschger *et al.*, in *ibid.*, pp. 299–306.
3. F. Bryan, *Nature* **323**, 301 (1986).
4. W. S. Broecker, D. Peteet, D. Rind, *ibid.* **315**, 21 (1985).
5. S. Manabe and R. J. Stouffer, *ibid.* **364**, 215 (1993); T. F. Stocker and A. Schmittner, *ibid.* **388**, 862 (1997).
6. W. Dansgaard *et al.*, *ibid.* **364**, 218 (1993).
7. K. C. Taylor, *ibid.* **361**, 432 (1993).
8. W. S. Broecker, *Paleoceanography* **13**, 119 (1998).
9. M. Cane, *Science* **282**, 59 (1998).
10. T. Blunier *et al.*, *Geophys. Res. Lett.* **24**, 2683 (1997); T. Blunier *et al.*, *Nature* **394**, 739 (1998).
11. C. Singer, J. Shulmeister, B. McLea, *Science* **281**, 812 (1998).
12. E. J. Steig *et al.*, *ibid.* **282**, 92 (1998).
13. For example, see T. J. Crowley, *Paleoceanography* **7**, 489 (1992); T. F. Stocker, D. G. Wright, L. A. Mysak, *J. Clim.* **5**, 773 (1992); A. Schiller, U. Mikolajewicz, R. Voss, *Clim. Dyn.* **13**, 325 (1997).
14. A very crude estimate of the thermal inertia of the Southern Ocean (55°S to 70°S, 4-km depth) is 5×10^{23} J/K. The meridional heat transport into the Atlantic is estimated at 0.25×10^{15} W [S. J. Rintoul, *J. Geophys. Res.* **96**, 2675 (1991)]. If that heat export stopped, with all else unchanged, the Southern Ocean would heat up by about 1.6°C per century.
15. U. Mikolajewicz, T. J. Crowley, A. Schiller, R. Voss, *Nature* **387**, 384 (1997).
16. For example, see A. J. Weaver and E. S. Sarachik, *J. Phys. Oceanogr.* **21**, 1470 (1991); M. Winton and E. S. Sarachik, *ibid.* **23**, 1389 (1993).
17. R. H. Gwiazda, S. R. Hemming, W. S. Broecker, *Paleoceanography* **11**, 371 (1996); H. Snoeckx, F. E. Grousset, M. Revel, A. Boelaert, *Mar. Geol.*, in press.
18. B. Stauffer *et al.*, *Nature* **392**, 59, (1998).
19. Supported by the Swiss National Science Foundation. I thank P. Clark and the organizers of the American Geophysical Union Chapman Conference "Mechanisms of Millennial-Scale Global Climate Change".