extinction, Sepkoski's work does not bear very directly on the human weal.

Looking back on the history of evolutionary biology as exemplified by this dozen or so biologists, Ruse sees a steady increase in the influence of epistemic factors from Erasmus Darwin to Jack Sepkoski and a corresponding diminution of cultural factors. Yet to make these extrapolations from his data, Ruse has to introduce another consideration—professional versus popular science. Present-day scientists exclude reference to the cultural from their professional publications, reserving it, if used at all, for their more popular writings. Most of the evolutionary biologists that Ruse discusses have published at least some popular works. Instead of being thankful for scientists like Steve Gould, Richard Dawkins, Paul Ehrlich, and Carl Sagan for taking so much time away from their professional pursuits to educate the general public, we "Saganize" them. Nor is Ruse himself immune. After all, *Mystery of Mysteries* is itself written for a wide audience.

Ruse can be sure that his fellow professionals, from the safety of their isolated areas of expertise, will not be kind. Some will claim that Ruse's attempt to evaluate the merits of the various sides of the science wars by recourse to data simply shows which side he is on. More reasonably, they may note a sampling of a dozen scientists over a 200-year period does not seem adequate to Ruse's task. Perhaps if he had included yeoman scientists in Darwin's day, he would have found a different pattern. Ruse acknowledges this potential criticism and responds by challenging others to do better. The readers of Ruse's spirited and ambitious book get to enjoy one more salvo in the science wars.

SCIENCE'S COMPASS • PERSPECTIVES

PERSPECTIVES: PALEOCLIMATE

Ice Age Temperatures and Geochemistry

Edouard Bard

How harsh was the last ice age? This issue is not merely a historical curiosity, because the climate during the last ice age is a test bench for general circulation models (GCMs), which are ultimately used to predict the forthcoming greenhouse warming. Indeed, the last glacial maximum (LGM) was quite different from modern conditions, and the drastic changes that occurred at that time in the complex atmosphere-ocean-biosphere system can no longer be considered simply as small departures from the present-day climate. Moreover, the LGM occurred around 21,000 years ago, which is recent enough to allow us to retrieve reliable climatic information from suitable records. For example, the composition of the atmosphere can be obtained from polar ice cores, and the chemistry of deep ocean waters can be derived from deep-sea sediments.

During the last few years, numerous high-resolution climate records have shown that the last ice age was far more variable than previously considered in the framework of the CLIMAP project during the 1970s and 1980s (*1*). In particular, the last period of maximum ice volume (in a strict sense, the definition of the LGM) does not always correspond to the coldest temperatures. This is clearly the case for the North Atlantic and surrounding continents, where temperature minima occurred during periods of massive surges and melting of icebergs (so-called Heinrich events or HE) originating mainly from the Laurentide Ice Sheet (*2*, *3*). In fact, the LGM took place in the period bracketed between HE1 and HE2, two prominent events that have been precisely radiocarbon dated with accelerator mass spectrometry. The abrupt start of HE1 and the end of HE2 are dated at 15,000 and 20,400 ^{14}C years ago, respectively, as compiled recently by Elliot *et al.* (*3*), which correspond to about 18,000 and 24,000 calendar years ago when using the newest ^{14}C calibration INTCAL98-CALIB4 (*4*). This 6000-year interval, centered on 21,000 calendar years ago, can be viewed as a working definition of the LGM that enables us to gather together and compile climatic data from various records with different time resolutions. Furthermore, 21,000 ± 3000 calendar years ago agrees rather well with an independent approach based on glacio-hydro-isostatic modeling that takes into account relative sea-level curves recorded throughout the world (*5*).

Documenting the LGM climate is evidently an indirect and a posteriori process, being inherently less precise than the use of modern instruments to characterize the present-day climate. For example, there is still some debate about the magnitude of cooling during the LGM, especially concerning sea-surface temperatures (SSTs) at low latitudes and the comparison between temperatures over continents and oceans. Several very recent studies have substantially improved our knowledge of the LGM, and a coherent picture is now beginning to emerge for the tropics. These recent advances are mainly based on climate modeling performed in the framework of the PMIP project (*6*–*8*) and on paleotemperature reconstructions based on new geochemical proxies such as noble gases in groundwaters [(*9*); see panel A of figure], trace element concentrations in corals (*10*) and foraminifera (*11*, *12*), and alkenone distribution patterns in deep-sea sediments (*13*, *14*) (see panel B of figure for a summary of open ocean SSTs based on published data). The new SST estimates based on magnesium in planktonic forams (*11*, *12*) show that CLIMAP SSTs were indeed overestimated in the tropics. Moreover, the observed cooling is on the order of 2°C, which agrees with most alkenone results for the tropical zone (*13*, *14*) as summarized in panel B of the figure [additional alkenone results may be found in Rosell-Melé *et al.* and associated web site (*14*)]. Although the spatial coverage of alkenone data could still be improved, it seems that the tropical cooling was more pronounced in the Atlantic than in the Indian and Pacific oceans (*13*, *14*). A similar conclusion was previously obtained by mapping the $\delta^{18}O$ changes measured in planktonic foraminifera (*15*). This may also explain why coral data for the LGM at Barbados suggest a very low SST based on strontium concentrations (*10*).

Temperature maps for the LGM have been used extensively as boundary conditions for GCMs or as an independent data set to be compared with GCM outputs. Since the first modeling work (*16*) based on CLIMAP reconstructions (*1*), much progress has been made in improving the numerical models and in testing the simulations against paleodata. As part of PMIP (*6*–*8*), tropical temperatures were

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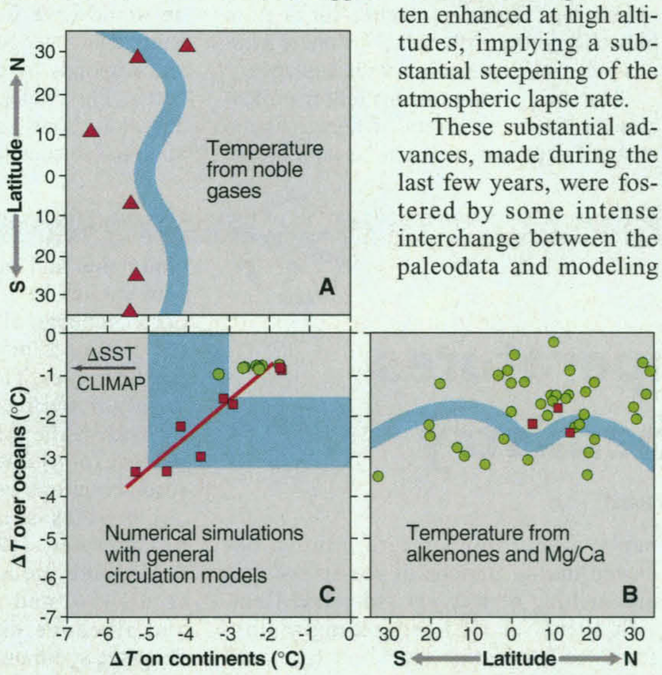
compared over continents and oceans with 16 different GCMs to strengthen the overall conclusions. One of the strong points of PMIP is that all different GCMs are forced by the same boundary conditions, such as insolation, sea-level elevation, atmospheric CO_2 concentration, albedo, sea ice cover, continental ice sheets, SST, and so forth, thus ensuring that the results are truly comparable. For the tropical belt, the main outcome of the comparison with PMIP is that CLIMAP SSTs are, again, probably too warm but that the LGM cooling is clearly more pronounced on land than on the oceans (*6–8*). This enhanced cooling on continents is a key result that appears both in atmospheric GCMs forced by the CLIMAP SSTs (green dots in panel C of figure) and in GCMs able to provide temperatures of the ocean's mixed layer (red squares). In these latter cases, tropical cooling over continents varies between 1.8° and 5.5°C according to the model, which shows that GCMs could be further improved. As emphasized by Pinot *et al.* (*8*), there is a clear relation between the temperature decreases on land and on oceans, with a slope of about 1.3, corresponding to a substantial "amplification factor" on the continents [panel C after the work by Pinot *et al.* (*8*)]. The results of the PMIP comparison are also in broad agreement with those obtained from an idealized and fully coupled ocean-atmosphere model (*17*) in which the average tropical cooling is on the order of 2.4°C on oceans but 4.6°C on continents (thick shaded lines in panels A and B). The cooling over the tropical Atlantic (3.3°C) predicted by this efficient coupled model is again greater than that for the Indo-Pacific province (2.1°C), a result that is in agreement with paleodata.



Cool data. (**A**) Red triangles: LGM cooling obtained from noble gases in groundwaters, distributed over different latitudes (*9, 20*). These temperatures are often at the cold end of the compilation by Farrera *et al.* (*20*). (**B**) LGM SST decreases measured in deep-sea sediments with new methods based on alkenones [green dots; published data from (*13, 14*)] and Mg/Ca ratios [red squares; data from Hastings *et al.* (*11*)]. Some scatter is due to coherent longitudinal patterns (for instance, the Atlantic is usually colder than the Indo-Pacific Ocean). The thick shaded curves on (A) and (B) show the simulation results obtained with a coupled ocean-atmosphere model (*17*). (**C**) LGM cooling over tropical oceans versus the cooling on tropical lands (*6–8*). Models with prescribed CLIMAP SSTs are shown by green dots and models with computed SSTs with red squares. True ΔT's are probably bracketed in the blue area.

Another long-standing LGM problem has been to reconcile the tropical cooling at sea level with other data obtained from high-elevation records such as the depression of snowlines (*18*) and $\delta^{18}O$ in ice cores from mountain glaciers at low latitudes (*19*). However, both the recent modeling work by Pinot *et al.* (*8*) and the comprehensive data compilation by Farrera *et al.* (*20*) suggest that LGM cooling was often enhanced at high altitudes, implying a substantial steepening of the atmospheric lapse rate.

These substantial advances, made during the last few years, were fostered by some intense interchange between the paleodata and modeling research communities. Indeed, new paleothermometers are still being investigated, and the spatial coverage and reliability of existing proxy data are being improved continuously. For example, the European Community research project known as TEMPUS is aimed at reconstructing and mapping SSTs during the LGM by means of alkenones (*13, 14*). Simulating past climates has also been useful in forcing theoretical workers to improve their numerical models and to take more long-term processes into account (such as ocean-atmosphere interactions and vegetation changes). The best example of this type of fruitful collaboration has been the discovery that the abrupt climatic changes documented in recent geological history could be equivalent to switches (modelers call them bifurcations) between different stable modes of coupled models (*21*). The interchange between these two scientific communities will be the central topic of the first EPILOG workshop under the auspices of the HANSE Wissenschaftskolleg, International Marine Global Change Study, and Past Global Changes, a core project of the International Geosphere-Biosphere Program (*22*).

References and Notes

1. CLIMAP stands for Climate/Long-Range Investigation, Mapping and Prediction. CLIMAP Project Members, *Science* **191**, 1131 (1976); *Geol. Soc. Am. Map Chart Ser. MC-36* (1981).
2. G. Bond *et al.*, *Nature* **360**, 245 (1992); G. Bond *et al.*, *ibid.* **365**, 143 (1993); G. Bond and R. Lotti, *Science* **267**, 1005 (1995); L. Vidal *et al.*, *Earth Planet. Sci. Lett.* **146**, 13 (1997).
3. M. Elliot *et al.*, *Paleoceanography* **13**, 433 (1998).
4. M. Stuiver *et al.*, *Radiocarbon* **40**, 1041 (1998); E. Bard *et al.*, *ibid.*, p. 1085.
5. K. Fleming *et al.*, *Earth Planet. Sci. Lett.* **163**, 327 (1998).
6. PMIP stands for Paleoclimate Modeling Intercomparison Project; see http://www-pcmdi.llnl.gov/pmip/home.html.
7. S. Joussaume *et al.*, *Geophys. Res. Lett.*, **26**, 859 (1999).
8. S. Pinot *et al.*, *Clim. Dyn.*, in press.
9. T. H. E. Heaton, A. S. Talma, J. C. Vogel, *Quat. Res.* **25**, 79 (1986); M. Stute, P. Schlosser, J. F. Clark, W. S. Broecker, *Science* **256**, 1000 (1992); M. Stute *et al.*, *ibid.* **269**, 379 (1995); J. F. Clark *et al.*, *Water Resour. Res.* **33**, 281 (1997); W. M. Edmunds *et al.*, in *Isotope Techniques in Studying Past and Current Environmental Changes in the Hydrosphere* (IAEA, Vienna, 1998), pp. 693–707; M. Stute and A. S. Talma, in *ibid.*, pp. 307–318.
10. T. P. Guilderson, R. G. Fairbanks, J. L. Rubenstone, *Science* **263**, 663 (1994).
11. D. W. Hastings, A. D. Russell, S. R. Emerson, *Paleoceanography* **13**, 161 (1998).
12. The Hastings *et al.* study has been confirmed recently by other groups working on Mg/Ca of planktonic foraminifera: H. Elderfield, G. Ganssen, N. J. Shackleton, S. J. Brown, *Miner. Mag.* **62A**, 424 (1998); D. W. Lea, D. K. Pak, A. Davé, H. J. Spero, *Eos* **79**, F471 (1998); D. Nuernberg, A. Mueller, R. Schneider, *Terra Abstr.* **4**, 198 (1999).
13. R. Schneider, P. J. Müller, G. Ruhland, *Paleoceanography* **10**, 197 (1995); E. Bard, F. Rostek, C. Sonzogni, *Nature* **385**, 707 (1997); C. Sonzogni, E. Bard, F. Rostek, *Quat. Sci. Rev.* **17**, 1185 (1998).
14. A. Rosell-Melé *et al.*, *Eos* **79**, 393 (1998); associated TEMPUS project web site at http://nrg.ncl.ac.uk:8080/climate/Tempus.htm.
15. W. S. Broecker, *Quat. Res.* **26**, 121 (1986).
16. W. Gates, *Science* **191**, 1138 (1976).
17. A. Ganopolski, S. Rahmstorf, V. Petoukhov, M. Claussen, *Nature* **391**, 351 (1998).
18. P. Webster and N. Streten, *Quat. Res.* **10**, 279 (1978).
19. L. G. Thompson *et al.*, *Science* **269**, 46 (1995); L. G. Thompson *et al.*, *ibid.* **276**, 1821 (1997); L. G. Thompson *et al.*, *ibid.* **282**, 1858 (1998).
20. I. Farrera *et al.*, *Clim. Dyn.*, in press.
21. S. Manabe and R. J. Stouffer, *J. Clim.* **1**, 841 (1988); T. F. Stocker and D. F. Wright, *Nature* **351**, 729 (1991); S. Rahmstorf, *ibid.* **372**, 82 (1994); S. Rahmstorf, *ibid.* **378**, 145 (1995).
22. 3 to 6 May 1999 in Delmenhorst, Germany and organized by R. Schneider, E. Bard, and A. Mix. See http://www.allgeo.uni-bremen.de/sfb261/html/body/english.html.
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