Dust: A Diagnostic of the Hydrologic Cycle During the Last Glacial Maximum

Yuk L. Yung,* Typhoon Lee, Chung-Ho Wang, Ying-Tzung Shieh

Dust concentrations in ice of the last glacial maximum (LGM) are high in ice cores from Greenland and Antarctica. The magnitude of the enhancements can be explained if the strength of the hydrologic cycle during the LGM was about half of that at present. This notion is consistent with a large decrease (5°C) in ocean temperature during the LGM, as recently deduced from measurements of strontium and calcium in corals.

A major uncertainty in our ability to predict climate changes in the next century that are caused by anthropogenic activities is feedback due to the hydrologic cycle (*1*). The key variable that determines the partitioning of water into vapor, liquid, and ice is temperature, which itself depends strongly on the amount, distribution, and state of water (*2*). This coupled system is sufficiently complex that a fundamental understanding of it from first principles is difficult, though understanding can be gained from study of the dynamics of paleoclimates and modern climates (*3*). In this report, we focus on two apparently unrelated phenomena during the LGM. The first is a dramatic increase in dust as recorded in polar ice cores (*4*, *5*). The second is an apparent drop in ocean surface temperature in the tropics of about 5°C as suggested by recent measurements in corals (*6*). We argue that these two phenomena point to a profound change in the hydrologic cycle during the LGM.

The amount of continental dust in the LGM ice of polar ice cores from Antarctica and Greenland (*7*) is about 30 times greater than that in modern ice. Marine aerosols are enhanced by a factor of about 4 in the Antarctic core (*7*). Modeling studies of dust that make use of general circulation models (GCMs) of the atmosphere cannot account for the observed dust concentrations. Simulations by Genthon (*8*) of the amount of marine aerosols and desert dust deposited in snow in Antarctica at present and during the LGM predicted enhancements in eastern Antarctica (where dome C is located) of 1.3 and 2.2 for marine aerosols and desert dust, respectively. Simulations by Joussaume (*9*) of continental dust in Antarctica and Greenland at present and during the LGM predicted enhancements of about 1 for Antarctica and 4 for Greenland. It is conceivable but unlikely that this discrepancy could be resolved by an increase of an order of magnitude in the strength of the dust source (*10*).

There is another puzzle in the LGM record. The CLIMAP data (*11*) showed that the sea-surface temperature (SST) of the tropical oceans decreased by less than 2°C during the LGM, whereas temperatures at the poles decreased by 8° to 9°C. Thus, the temperature of the polar regions of the planet seems to have been much more sensitive to climate change than was the temperature at lower latitudes. However, the CLIMAP results at low latitudes conflict with several continental markers of climate change, such as snowlines (*12*), vegetation (*13*), and noble gas concentrations (*14*), and with recent data from corals on SSTs in tropical oceans (*6*). These data all suggest that the tropical temperature was about 5°C lower during the LGM. This, then, raises a difficult question: Can the much lower SST deduced from the corals be accounted for by the observed decrease in CO_2 and the associated reduction in greenhouse forcing (*3*)?

We suggest that the high dust enhancements in the polar regions show that the hydrologic cycle (as diagnosed by the washout rate of dust) must have been weaker during the LGM. We focused on the dust in Antarctica because its source in South America appears to be well defined (*15*). Using a two-dimensional (2D) model of the terrestrial atmosphere (*16*), we simulated the effect of the hydrologic cycle on the transport of dust from South America (45°S) to Antarctica (85°S). For current conditions, only a small fraction (<1%) of the midlatitude dust survived the trip over the oceans and reached Antarctica (curve a in Fig. 1). The reason was that although the mean transport time was on the order of several months, the washout lifetime of the dust particles was on the order of a week. This result obtained with our 2D model is in agreement with computations done in a 3D GCM (*17*). In contrast, a model in which the washout lifetime of the dust is reduced by half (curve b in Fig. 1) shows that rates of dust deposition are enhanced by more than a factor of 5. Thus, a much reduced hydrologic cycle (as diagnosed by a reduced wet deposition rate for dust) during the LGM could yield a solution to the dust problem.

Some geochemical evidence supports the above hypothesis of a reduced hydrologic cycle during the LGM. Using ^{10}Be as a marker of past accumulation rates, Jouzel *et al.* (*18*) inferred that the precipitation rate recorded in the Vostok (in Antarctica) ice core during the LGM was only half of the mean Holocene value. Because air masses producing polar precipitation originate at lower latitudes, this result reinforces our hypothesis of a globally weakened hydrologic cycle, although the change in the precipitation rate at Vostok may be a local phenomenon. Furthermore, as the rate of precipitation is reduced, the rate of dust deposition relative to ice increases proportionally. Combining this result with the enhancement factor of 5 (absolute increase) in the deposition rate deduced from Fig. 1, we conclude that this hypothesis of a reduction in the hydrologic cycle of one-half could account for an enhancement of dust in the polar ice of a factor of 10 (relative increase), which is within a factor of 3 of the observed enhancement factor in Antarctica (*7*).

It is more difficult to account for the remaining factor of 3. One plausible cause is the increased area for dust sources, which could be the result of exposure of continental shelves as a consequence of lowered sea levels (*19*). Another plausible cause is that atmospheric winds were stronger during the LGM (*4*). Not only is the total number of dust particles greater in LGM ice, but the mean radii of particles are also greater (for instance, particles as large as 5 μm in radius are present in LGM but not in Holocene ice). Stronger winds would increase the efficiency of transport of dust particles and shorten their transit time to the poles; larger wind stress near the ground would loft more dust into the atmosphere (*4*). The nearly fourfold enhancement in salt particles (derived from nearby seas) is further evidence of stronger winds in the LGM (*7*).

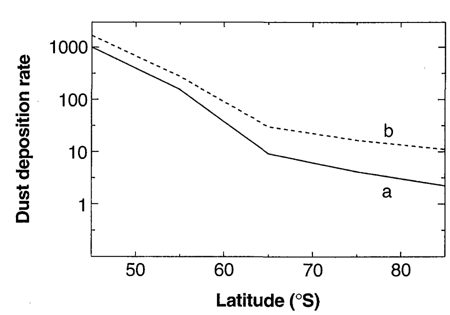

Fig. 1. Modeling of the deposition of dust and aerosols in Antarctica with the 2D model described in (*16*). Curve a is for the present atmosphere and curve b is for the LGM atmosphere. Dust deposition rate is in arbitrary units.

Y. L. Yung, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA.
T. Lee, C.-H. Wang, Y.-T. Shieh, Institute of Earth Sciences, Academia Sinica, 128 Yen Chiu Yuan Road, Nankang Taipei Taiwan, Republic of China 115.

*To whom correspondence should be addressed.

These data seem to be sufficient to explain the dust data in Antarctica. To explain the Greenland data (enhancement by a factor of 100), we need to account for a further factor of about 3. During the LGM, the Northern Hemisphere had more deserts (*20*) and large areas of land that were covered by ice sheets. The denudation of boreal forests and the formation of loess (*21*) could have contributed additional sources of continental dust.

It remains a challenge to atmospheric modeling to explain why the hydrologic cycle during the LGM (as revealed in the dust washout lifetime) was so greatly weakened (*22*). One interesting possibility is that the enhanced amount of dust might have played an active role in modifying the climate of the LGM (*23*). In this case, dust may be more than an indicator of climate change; dust itself could be an agent of climate change, as it is on our sister planet Mars (*24*).

REFERENCES AND NOTES

1. Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment* (Cambridge Univ. Press, Cambridge, 1990); *Climate Change 1992: Supplement to the IPCC Scientific Assessment* (Cambridge Univ. Press, Cambridge, 1992); C. A. Senior and J. F. B. Mitchell, *J. Climate* **6**, 393 (1993); B. C. Weare, *ibid.* **7**, 248 (1994); R. D. Cess *et al.*, *J. Geophys. Res.* **95**, 16601 (1990).
2. R. S. Lindzen, *Bull. Am. Meteor. Soc.* **71**, 288 (1990); *ibid.*, p. 1465.
3. D. Rind and D. Peteet, *Quat. Res.* **24**, 1 (1985); T. J. Crowley and G. R. North, *Paleoclimatology* (Oxford Univ. Press, Oxford, 1991); J. E. Hansen *et al.*, in *Climate Processes and Climate Sensitivity*, J. E. Hansen and T. Takahashi, Eds. (Geophysical Monograph 29, American Geophysical Union, Washington, DC, 1984), pp. 130–163.
4. J.-R. Petit *et al.*, *Nature* **293**, 391 (1981).
5. C. U. Hammer *et al.*, in *Greenland Ice Core: Geophysics, Geochemistry, and the Environment*, C. C. Langway, H. Oeschger, W. Dansgaard, Eds. (Geophysical Monograph 33, American Geophysical Union, Washington, DC, 1985), pp. 90–94.
6. T. P. Guilderson, R. G. Fairbanks, J. L. Rubenstone, *Science* **263**, 663 (1994).
7. From (*4, 5*) we obtained the following: The enhancement factor for dust particles (radius > 0.4 μm) at dome C in Antarctica is 9 to 14; the enhancement factors for the elements Al, Na, and Cl are 34, 4.9, and 3.8, respectively; and the enhancement factor for dust particles in Greenland is 100.
8. C. Genthon, *Tellus* **44B**, 371 (1992).
9. S. Joussaume, *J. Geophys. Res.* **98** (D2), 2767 (1993).
10. There is no ice core data for low latitudes at sea level. However, ice cores taken from mountain glaciers show that dust contents are enhanced in the LGM layer [L. G. Thompson *et al.*, *Science* **246**, 474 (1989); L. G. Thompson *et al.*, *ibid.* **269**, 46 (1995)]. It is difficult to interpret the dust deposition rates in the high mountains because of possible changes in local meteorology during the LGM. The beauty of the polar data is that the poles are remote regions of the globe and any enhancement must be related to changes on a global scale (global change).
11. CLIMAP Project Members, *Geol. Soc. Am. Map Chart Ser.* **MC-36** (1981).
12. W. S. Broecker and G. H. Denton, *Geochim. Cosmochim. Acta* **53**, 2465 (1989).
13. V. M. Bryant Jr. and R. G. Holloway, in *Pollen Records of Late Quaternary North American Sediments*, V. M. Bryant and R. G. Holloway, Eds. (American Association of Stratigraphic Palynologists, Calgary, Ontario, 1985), pp. 39–70.
14. M. Stute, P. Schlosser, J. F. Clark, W. S. Broecker, *Science* **256**, 1000 (1992); M. Stute *et al.*, *ibid.* **269**, 379 (1995).
15. F. E. Grousset *et al.*, *Earth Planet. Sci. Lett.* **111**, 175 (1992).
16. The 2D model has four components: the photochemical module, the solar-radiative module, the infrared-radiative module, and the transport module. The model has 18 latitudes, from pole to pole. There are 40 layers, from 0 to 80 km in log pressure coordinates. Time-stepping is 1 to 4 steps per day. We usually used model times of 10 to 20 years to obtain convergence. The monthly averaged transport coefficients were computed by the method of H. Yang *et al.* [*J. Atmos. Sci.* **48**, 442 (1991)]. The details are described in R. L. Shia *et al.* [*J. Geophys. Res.* **94**, 18467 (1989)]. We adopted in the 2D model washout lifetimes computed with a 3D model by Y. J. Balkanski *et al.* [*ibid.* **98**, 20573 (1993)].
17. Our result should be compared with figure 23 in (*9*).
18. J. Jouzel *et al.*, *Quat. Res.* **31**, 135 (1989).
19. R. W. Fairbridge, *Phys. Chem. Earth* **4**, 99 (1961).
20. Recent work has shown that the total area of deserts during the LGM was about twice that in the Holocene [J. A. Chappellaz *et al.*, *Tellus* **45B**, 228 (1993); P. Friedlingstein *et al.*, *J. Geophys. Res.* **100**, 7203 (1995)].
21. G. Kukla *et al.*, *Geology* **16**, 811 (1988).
22. The saturated vapor pressure of water decreases by 34% from 30° to 25°C; thus, a change of 5°C in SST alone is not sufficient to cause a difference of a factor of 2 in the water vapor content of the atmosphere.
23. L. D. D. Harvey, *Nature* **334**, 333 (1988). We wish to speculate on the effect of atmospheric dust on the tropical "warm pool." Today a major source of moisture is the warm pool (with SSTs often >29°C) in the tropical western Pacific Ocean around Indonesia and New Guinea. If the combination of a lower ocean level (by 150 m), stronger winds, and atmospheric dust opacity were to reduce the SST of the warm pool by 10°C, this would decrease the source of moisture by half. The reduced moisture would greatly reduce the greenhouse effect caused by water vapor, thereby contributing to the cooling of the tropics.
24. The martian atmosphere is characterized by extreme aridity and dustiness, and dust plays a fundamental role in regulating the climate of Mars [J. R. Murphy *et al.*, *J. Geophys. Res.* **98**, 3197 (1993); M. Santee and D. Crisp, *ibid.*, p. 3261.

25. Supported in part by NASA grant NAGW 2204 to the California Institute of Technology and by NSC 84-2111-M-001-027GP from the National Science Council of the Republic of China. Y.L.Y. thanks the Institute of Earth Sciences and Academia Sinica for their hospitality during his sabbatical year and A. Ingersoll, L. Jaegle, C. Leovy, D. Rind, and I. Tegen for helpful discussions.

17 August 1995; accepted 1 November 1995

From Topographies to Dynamics on Multidimensional Potential Energy Surfaces of Atomic Clusters

Keith D. Ball, R. Stephen Berry,* Ralph E. Kunz,† Feng-Yin Li, Ana Proykova, David J. Wales

Multidimensional potential energy surfaces for systems larger than about 15 atoms are so complex that interpreting their topographies and the consequent dynamics requires statistical analyses of their minima and saddles. Sequences of minimum-saddle-minimum points provide a characterization of such surfaces. Two examples, Ar_{19} and $(KCl)_{32}$, illustrate how topographies govern tendencies to form glasses or "focused" structures, for example, crystals or folded proteins. Master equations relate topographies to dynamics. The balance between glass-forming and structure-seeking characters of a potential energy surface seems governed by sawtooth versus staircase topography and the associated collectivity of the growth process after nucleation.

Computational methods, particularly molecular dynamics (*1*), quenching (*2–4*), conjugate gradient minimization (*5*), and eigenvector-following (*6–11*) are now efficient enough to locate all the minima and all the important saddles on a given potential energy surface for a system consisting of as many as 10, and perhaps even 15, atoms.

However, the number of geometrically distinct minima grows at least exponentially with *N*, the number of particles making up the system (*3, 4, 12–15*). Consequently, cataloging all the minima for a system of about 20 or more particles is simply not productive; the added information content of most of these data is negligible. Instead, a more efficient course is a statistical approach toward characterizing the topography of the surface and, from that information, inferring the associated thermodynamics and dynamics (*16–21*). Such an analysis shows how it is possible to interpret aspects of the behavior of a system of 15 to several hundred particles, possibly many more, from a statistical sample of minima and saddles on the potential surface of the system. The method links knowledge of the forces between particles and the tendency of the system to form an amorphous structure or glass, or a "focused" structure such as a crystalline lattice, a Mackay icosahedron (*22*), or a specific folded structure such as that of a biologically active protein.

K. D. Ball, R. S. Berry, F.-Y. Li, A. Proykova, Department of Chemistry, University of Chicago, 5735 South Ellis Avenue, Chicago, IL 60637, USA.
R. E. Kunz, Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstrasse 36, D-10623 Berlin, Germany.
D. J. Wales, University Chemical Laboratories, Cambridge University, Lensfield Road, Cambridge CB2 1EW, UK.

*To whom correspondence should be addressed.
†R. E. Kunz has also published in this field under the surname Breitengraser-Kunz.