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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 magni-

tude 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 CO₂ 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 ¹⁰Be 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).

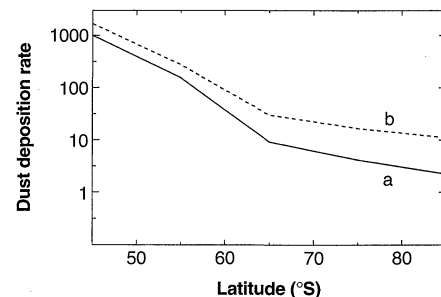


Fig. 1. Modeling of the deposition of dust and aerosols in Antarctica with the 2D model described in (16). Curve a is for the present atmosphere and curve b is for the LGM atmosphere. Dust deposition rate is in arbitrary units.

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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).

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

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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, Ar₁₉ 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.

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