Dust: Climate’s Rosetta Stone

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THE RECORD preserved in the Greenland ice cap has revealed a remarkable characteristic of the Earth’s climate system hitherto unknown and unsuspected, namely, that it is capable of jumping back and forth between quite different states. Even more surprising is that these jumps can be accomplished in just a few decades. During the last glacial period, temperatures on Greenland’s high plateau were six to ten degrees Celsius lower during millennial duration episodes of intense cold than during the alternating intervals to moderate cold. The dust and sea salt contents of the ice underwent abrupt threefold shifts. Spurred by this discovery, geologists began a search to see whether these changes are recorded elsewhere on the planet. Columbia’s Gerard Bond showed that each of Greenland’s intervals of intense cold was matched by a pulse of debris carried to the northern Atlantic by icebergs. Colorado’s Julian Sachs and Scott Lehman, using alkenone paleothermometry, showed that surface ocean temperatures in the region around Bermuda underwent four-to-five-degree Celsius jumps matching those for Greenland. Rich Behl and Jim Kennett of the University of California astounded the paleoclimate world by demonstrating that these events had profound impacts on surface water temperature and deep water dissolved oxygen gas (O$_2$) content in the Santa Barbara basin. German scientists extended the geographic range of the impacts by showing that, just as off California, these jumps raised and lowered the O$_2$ content of thermocline waters in the Arabian Sea. Columbia’s Pierre Biscaye, using isotopic tracers, pinned down the source of the dust contained in Greenland ice. It came all the way from Asia’s Gobi Desert. Ed Brook and Jeff Severinghaus, while postdoctoral fellows in Mike Bender’s Rhode Island laboratory, showed that sympathetic changes in the atmosphere’s methane content likely reflected changes in the warmness and wetness of tropical soils and

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swamps. The conclusion drawn from these studies is that the impact of these abrupt climate jumps was surely felt throughout the north temperate zone and perhaps in the tropics as well.

This discovery not only raised the question, what had triggered these past jumps, but also led to a concern that the ongoing buildup of greenhouse gases in our atmosphere might trigger yet another such jump. The situation is complicated by the absence of such a jump during the present interglacial (i.e., the last ten thousand years). Rather, these jumps were confined to times when Canada and Scandinavia were covered with large ice sheets. Does this mean that, until these ice sheets re-form, our planet is immune to these climatic insults?

Until recently I felt that the answer to this question was no. My reasoning was as follows. Evidence from sea-floor sediments suggests that the jumps in climate were triggered by reorganizations of the ocean’s large-scale circulation. The deep sea is ventilated by cold waters sinking to the abyss from the surface in polar regions. In today’s ocean, surface waters in the northern Atlantic vie for dominance in deep-water production with those in Antarctica’s Weddell and Ross seas. The reorganizations involved shifts in dominance of deep-water production from one end of the planet to the other. My thought was that during times of interglaciation, such as the one we currently enjoy, the ocean became trapped in its northern Atlantic dominant mode. However, joint ocean-atmosphere models, when forced with increasing greenhouse gases, suggest that deep-water production will weaken significantly if CO₂ levels reach three times their pre-industrial level. I took this as a warning that by adding greenhouse gases to the atmosphere we might trigger yet another reorganization of ocean circulation, and that this reorganization might bring about a large disruption in our planet’s climate.

But new information has caused a change in my thinking. First of all, my Lamont-Doherty colleague, Gerard Bond, has shown that a curious cycle in the composition of debris dropped from melting icebergs runs through periods of interglaciation as well as periods of glaciation. Bond has chased this 1,500-year cycle back 150,000 years (one hundred cycles). During glacial time, his cycles are coincident with the large climate jumps discussed above. Does this mean that the cycle that underlies the abrupt punctuations of the glacial climate is operative during interglacials as well as glacials? If so, why during glacial time did these seesaws in deep-water production lead to very large climate changes, while during interglacials they led to changes so small that they fail to show up in the Greenland ice-core record?

A second finding that influenced my thinking is that the Medieval Warm–Little Ice Age oscillation in climate (the most recent of Bond’s
cycles), which had such a strong impact on the Viking Greenland colony, appears to have had the opposite impact on temperatures on Antarctica. Gary Clow of the U.S. Geological Survey employed the down-borehole temperature profile at the Taylor Dome site on Antarctica to reconstruct the air temperature history for the last several thousand years. The results showed that air temperatures were 3°C Celsius warmer during the time of the Little Ice Age than during the time of the

Figure 1. The ratio of heavy oxygen atoms ($^{18}$O) to light oxygen atoms ($^{16}$O) in the Greenland ice record the changes in air temperature that have occurred over the last 110,000 years (the lower the $^{18}$O, the colder the air temperature). The calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$) concentrations in the ice provide a measure of the rate at which continental dust fell on Greenland, and those of chlorine ($Cl^{-}$) and sulfate ($SO_4^{2-}$), a measure of the input of sea spray aerosols. It will be seen that, at times when $^{18}$O indicated very cold air temperatures, the fallout rates of both dust and aerosols were tenfold larger than now, and that, at times of intermediate cold, the fall rates were intermediate between the low rates characterizing periods of interglacial warmth and those characterizing periods of intense cold.
Medieval Warm. This finding is consistent with the record for glacial
time when the millennial-duration climate oscillations in Antarctica
were antiphased with respect to those in Greenland. In other words,
warm episodes in Antarctica correlate with cold episodes in Greenland
and vice versa. My interpretation is that this antiphasing is a conse-
quence of the seesawing in deep-water production.

What is it that sustains Bond’s 1,500-year cycle? I suspect that it is
the necessity that the Atlantic export the salt left behind as a result of
the loss of water evaporated from its surface and carried across Eur-
Asia by the westerlies and across Panama by the trades. Rather than
operating smoothly, our great ocean-atmosphere machine chooses to
oscillate. During 750-year-duration episodes of dominance of deep-
water formation in the northern Atlantic, the excess salt is actively
exported in deep water, which flows around the tip of Africa. During
the 750-year-duration episodes of deep-water formation in the South-
ern Ocean, this export slows.

After some struggles, I have come up with a possible scenario that
might explain why seesawing of deep-water formation produces very
large climate changes during times of glaciation, but only very modest
ones during times of interglaciation. It involves changes in the steep-
ness of the latitudinal thermal gradient caused by changes in the posi-
tion of the limit of sea ice in the northern Atlantic. When deep-water
formation in the northern Atlantic is dominant, the glacially expanded
sea ice front is pushed northward in the Norwegian Sea. When domi-
nance shifts back to the Southern Ocean, this sea ice quickly reforms.
The consequence of these shifts would be to change the frequency of
wind events capable of lofting continental dust and sea salt aerosols
high into the atmosphere. Not only would these particles reflect away
sunlight but, as recently demonstrated by an Israeli scientist, they
would lead to smaller-sized drops in clouds, and thereby to a higher
cloud reflectivity. So we have a way to alternately cool and warm the
north temperate zone! As it is well known that dust production was
tenfold greater during glacial times, I would attribute this increase to
steepened temperature gradients related to the equatorward extension
of continental glaciers and sea ice. If so, all that is required to create
the millennial duration oscillations in dust lofting is a means to modu-
late this excess. The sea ice–storminess tie is one way to do this job.

Were this scenario to prove to be the correct one, then a green-
house-induced reorganization of deep-water flow would be less of a
threat, because, coming on the heels of a significant polar warming,
there would be even less sea ice than now. As I am the one who first
raised a warning flag in this regard, it is a relief to be able to declare
that it may have been a false alarm.