12 The Record of Paleoclimatic Change and Its Greenhouse Implications

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Perhaps the most important contribution of paleoclimate analysis to the ongoing debate concerning our future in the "greenhouse" is that associated with the issue of rapid climate change. The ultra-low-frequency variability derivative of the 100 kyr cycle of the late Pleistocene is now a rather well understood consequence of the nonlinear response of the system to orbital insolation forcing (e.g., see Tarasov and Peltier, 1997, 1999 for detailed discussion and Berger, Chapter 8 in this volume), but no similar degree of understanding may be claimed for the millennium and shorter-period variability that is evident in the $\delta^{18}0$ atmospheric temperature proxy from the Summit, Greenland, ice cores during the interval of time known as Oxygen Isotope Stage 3. This is a critical gap, especially inasmuch as it has been suggested that these Dansgaard-Oeschger (D-O) oscillations might also be induced under the enhanced greenhouse conditions that we expect will be characteristic of the future.

The only explicit theory of the D-O oscillation in the current literature is that based on a highly reduced model of the global thermo-haline circulation (Sakai and Peltier, 1995, 1996, 1997, 1999), in which it is shown that the THC should "fibrillate" in response to application of a supercritical freshwater forcing applied to the high latitudes of the North Atlantic basin. In this model the D-O oscillation occurs through a simple Hopf bifurcation when the buoyancy flux is somewhat weaker than would be required to arrest the deep circulation completely. That such an enhancement of the high-latitude buoyancy flux might be expected under ice-age conditions follows from the fact that the basin was then bounded on the west and east by the massive Laurentide and Fennoscandian/Barents Sea ice sheets, respectively. As evidenced by the episodic occurrence of Heinrich events (Heinrich, 1988), during which intense discharges of icebergs from these ice sheets apparently covered the high-latitude North Atlantic with massive amounts of freshwater, the idea that enhanced buoyancy flux might indeed have been characteristic of the stage 3 period is not at all unreasonable. The enhanced buoyancy of the surface water is not associated with increased P$-$E (Precipitation minus evaporation), as could well be the case in the warmer "enhanced greenhouse" world of the future, but rather with the enhanced surface "run-off" carried by the berg-flux.

The idea that such high-latitude freshwater forcing could be a major determinant of climate system variability has of course become the prevalent view in connection with the Younger Dryas climatic reversal that occurred during the Last Glacial Maximum (LGM)-to-Holocene transition (e.g., Broecker and Denton, 1989, and see Broecker, Chapter 5 in this volume). High-latitude foraminifera-based sea surface salinity (SSS) reconstructions by Duplessy et al. (1991), and others subsequently, have indeed established that high-latitude Atlantic SSS was strongly depressed during glacial conditions in the regions where North Atlantic deep water (NADW) forms today (see Chapter 14 by Duplessy in this volume). An important recommendation for future research is that more-detailed analysis with more fully anticulated models be performed to test the robustness of the above referenced theory of the D-O oscillation. Because the ice-mechanical instability through which Heinrich events are generated appears to be entrained to the D-O oscillation, it would appear necessary to develop a sound theory of the latter in order to better understand the details of the former.

The issue of the mechanism(s) underlying rapid climate change is not one that we might reasonably expect to be entirely settled on the basis of models; the level of complexity involved is simply too high for us to be overly sanguine of success through this means alone. What is also required is a concerted program of data analysis, perhaps focused on the most recent 2000 years of Earth history but including further work on the YD event. In this, and on the basis of the most recent literature, it would seem important to pay particular attention to the relative phasing of events in the Northern and Southern Hemispheres (see Chapter 5 [Broecker] and Chapter 15 [Jouzel] in this volume). That an out-of-phase relationship existed during the YD now seems to be well established on the basis of the intercomparison of accurately time-constrained data from the Greenland and Vostok Antarctica ice cores. One possible explanation of such a relationship between the hemispheres posits a complementarity of the deepwater production rates between them. When NADW production rate is high, the Northern Hemisphere is warm. When this rate falls and the Northern Hemisphere is cooled in consequence, the rate of Antarctic bottom water (AABW) production increases to compensate, and the Southern Hemisphere is thereby warmed. Broecker has suggested that support for this view is found in the ^{14}C age of abyssal waters. In an enhanced program focused on the most recent 2000 years of Earth history, an appropriate primary target might be the so-called Little Ice Age during which there occurred a distinct maximum in the extent of mountain glaciers. Although the cost would be high for the sufficiently high frequency sampling of the Vostok core to support such a focused effort, this should nevertheless be carefully considered.

Paleoclimate inferences also continue to provide important constraints on the mechanics of the global carbon cycle. In this regard, however, a significant further gap in understanding continues to be that related to the mechanism(s) responsible for the glacial-to-interglacial variation of atmospheric carbon dioxide concentration. The recently constructed models of the 100 kyr ice-age cycle, which are successful in explaining this phenomenon as a nonlinear response to orbital insolation forcing (Tarasov and Peltier, 1997, 1999), employ the Vostok measurements of the variation of atmospheric CO_2 concentration from Eemean to Holocene to enhance the insolation signal and strongly suggest that the observed $[CO_2]$ depression during the glacial period is required in order to understand the continental ice volumes that are inferred to have been characteristic of the LGM epoch based on the observed sea level depression. There is still no entirely satisfactory mechanistic model that can correctly predict the observed variation of [CO_{2-}] as a combined effect of the solubility pump and the biological pump. The magnitude of the problems that continue to bedevil our understanding of biospheric feedbacks on climate is also clearly evident in the fundamental disagreements that have arisen in connection with the identification of particular continental surfaces as being either sources or sinks of this trace gas in the modern climate system (see in particular Chapter 4 by Heimann in this volume).

An important issue in paleoclimatology remains outstanding, providing a cogent reminder of the extent to which the climate system continues to provide challenges to the scientific imagination. This issue relates to the theory of ice-age occurrence in the more remote past. Recent analysis has focused on the late pre-Cambrian glaciation that occurred approximately 700 million years ago. Paleomagnetic evidence has been widely construed to suggest that this glaciation occurred not at high latitude but rather at extremely low latitude. The debate concerning mechanism has recently come to be polarized between two extreme views. In one, the so-called snowball Earth hypothesis, the entire surface of the Earth is imagined to have become ice-covered (e.g., as most recently discussed by Hoffman et al., 1998). In the other view, the obliquity of the orbit is imagined to have been so large at that time that only the lowest latitudes were susceptible to glacial advance (Williams et al., 1998; see also Kasting, Chapter 13, in this volume). Neither of these hypotheses has yet been subjected to particularly rigorous test, although the snowball hypothesis is gaining intellectual momentum (e.g., see Hyde et al., 2000). This most recent work, however, which was based on the neoproteriozoic continental reconstruction of Dalziel (1997), strongly suggests the fully glaciated "hard snowball" scenario of Haffman et al. (1998) to be as unlikely as the high obliquity scenario of Williams et al. is unnecessary. The detailed GCM reconstructions of the climate of that era discussed in Hyde et al. do lead to glaciation of the continental fragments that then existed at low latitude, but this occurs in the presence of a substantial equatorial refugium of open water.

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