Report of working group 5:
Possible causes for the Younger Dryas: a brief survey

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The attempt to find a 'cause' for the Younger Dryas cold spell presupposes that we define the phenomenon. That is, we would like to know about the global distribution of timing and amplitude. While the data are not yet in for such a definition, it is quite clear that the Younger Dryas Event (YDE) reflects a major cooling of the northern North Atlantic and the bordering land areas to the east. This cooling followed a warm period initiated about 13 000 radiocarbon years ago and ending about 11 000 year BP.

A useful distinction between different types of causes would seem to be 'external' versus 'internal' causes. An external cause would call on a stimulus from outside of the system. An internal cause would derive from control mechanisms inside the system, mechanisms that are linked in such a fashion as to cause a nonlinear response to gradual warming at the end of the last glacial, resulting in pulsed deglaciation. Milankovitch forcing (Berger et al., 1984) would not be considered an external cause in this context, since we rely on internal nonlinear amplification to express the Younger Dryas phenomenon.

External causes are events intruding from space or from below the crust. Examples are (1) variation in solar output, asteroid impact, near-by supernova radiation; (2) major volcanism, earthquakes. There is evidence that solar output changes through time, providing for climatic cycles of various periods (Rampino et al., 1987). The cycle identified by Dansgaard et al. (1971), with a period of 2600 years, would seem to have the right wavelength for being effective, after amplification through positive feedback. There seems to be no evidence for an impact event 11 000 radiocarbon years ago. There was a supernova event nearby, about 11 000 years ago (Brandt et al., 1971) which might have impacted the chemistry of the atmosphere, with ramifications for climatic change. Major volcanism did indeed occur in association with the Younger

Dryas period. The Laacher See eruption (Schmincke, 1988) is close to the onset of the YDE, but apparently preceded the onset of cooling by about 200 years (Hajdas et al., this volume). It is conceivable that repeated eruptions caused sufficient cooling to stop melting of ice, thus terminating the Allerød. Increased earthquake activity is expected for the period of deglaciation, because of isostatic adjustments. Earthquakes can produce tsunamis, which can trigger ice calving events, which in turn could set off a chain of changes within the climatic system leading to cooling, from covering the Nordic Seas with icebergs and fresh water (Mercer, 1969; Ruddiman and McIntyre, 1981).

Internal causes are part of cause-and-effect chains, involving threshold events, positive feedback, and lagged negative feedback. Catastrophic increase of calving rates (at the onset of the Bølling) would be considered a threshold effect, if a slow rise in sea level results in collapse of marine-based ice (Denton and Hughes, 1981). The large-scale influx of freshwater from proglacial lakes, with or without icebergs, could affect the heat exchange between ocean and atmosphere (Rooth, 1982; Ruddiman, 1987). Another type of threshold has been invoked with respect to deep ocean circulation: at some level of meltwater input, deep convection is affected in such a fashion as to reduce heat input from the 'deep conveyor' mechanism (Broecker and Denton, 1989).

Positive feedback derives mainly from albedo and greenhouse effects. These mechanisms amplify small changes, so that a relatively minor cooling (at the end of the Allerød), from some unidentified cause, could result in the onset of a major cold spell such as the Younger Dryas. Even at the end of the Allerød, ice sheets were still extensive in North America and Scandinavia; they could have acted as a stimulus for a return to quasi-glacial conditions, through albedo feedback (and associated wind patterns). There is no convincing evidence for a role of greenhouse gases in producing the Younger Dryas. Isostatic adjustment to ice loading or unloading provides an important example for lagged negative feedback: as ice builds up (or wastes) the land slowly sinks (or rises), opposing the buildup (or decay) but with a lag of thousands of years. In the case of the Younger Dryas, it is conceivable that uplift in glaciated regions made ice more stable toward the end of the Bølling-Allerød period.

One approach to finding the cause(s) for the Younger Dryas cold spell is to study the reason(s) for the present anomalous situation in the northern North Atlantic realm, which is unusually warm compared with other regions at the same latitudes. The crucial mechanism is the cross-equatorial transfer of heat in surface and near-surface waters, from the South Atlantic to the North Atlantic, and the transport of much of this heat to the far north. One related factor, and most important, is the strength and heat content of the Gulf Stream, which, together with the associated wind systems, feeds heat into the Icelandic Low, setting up a heat pump for high latitudes ('Nordic heat pump', Berger, 1990). Shutting down this pump leads to major cooling (Johnson and Andrews, 1979). The deep conveyor is part of this pumping system. Shutting down the cross-equatorial heat flow during the Younger Dryas may be the most important single factor in providing for an extended cold period.

Anomalously high seasonality in the northern North Atlantic and associated coastal regions is part of the pattern of anomalous heat flow to the Nordic realm. Seasonality is at the heart of Milankovitch forcing. Thus, we may assume that any mechanisms increasing seasonality (i.e. summer warmth) will favor Milankovitch-driven climatic change. Since the Younger Dryas constitutes an exception to Milankovitch expectations (it is cold when warm-forcing is at or near its maximum), we must look to processes decreasing seasonality in the Younger Dryas (i.e. cool summers). Conversely, seasonality should be greater before and after the cold spell. There is evidence from tree-ring patterns for increased seasonality just after the Younger Dryas (Kromer et al., this volume).

In principle, we are looking for mechanisms, then, providing for positive feedback on Milankovitch forcing in the case of Bølling-Allerød and Preboreal, and a lack of such mechanisms in the case of the Younger Dryas period. If meltwater generation provides for positive feedback on warming, this would be the ideal situation (Berger and Jansen, this volume). This principle is unfavorable for postulated processes that have a negative feedback for meltwater production, such as the deep conveyor mechanism. Alternative conveyor processes may be more promising (Jansen and Veum, 1990).

The task as far as gathering the evidence is to establish, in detail, the sequence of warming and cooling, relative to meltwater generation, for a sufficiently large region to capture the essential elements of the system responsible for moving heat into the North Atlantic.

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