ABRUPT TERMINATIONS OF LATE PLEISTOCENE ICE AGES: A SIMPLE MILANKOVITCH EXPLANATION

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ABSTRACT. Abrupt changes of climate known as Terminations mark the end of a number of late Pleistocene ice ages. This paper argues that Terminations were a normal part of the climate system's response to orbital forcing during the late Pleistocene, and that it is unnecessary to invoke special mechanisms which operate only during these episodes of rapid change.

Two types of abrupt climatic change can usefully be distinguished. Type 1 is a simple state change, i.e., a rapid and statistically significant change in some observed measure of the climate system's state that occurs in the absence of any fundamental change in the system's structure, or any long-term change in its external boundary conditions. Familiar examples of this type occur as part of the annual cycle: the first killing frost, and the onset of the monsoon. Type 2 is a rapid change of climate that reflects a long-term change in the system's boundary conditions. Such events must occur occasionally, for example, as slow, tectonically driven changes in geography permit new modes of atmospheric or oceanic circulation.

This paper considers abrupt changes in climate that occurred at the end of several late Pleistocene ice ages. Kukla (1970) found evidence for a number of these abrupt warming events in the soil sequence of central Europe, where the stratigraphic boundary between an ice-age loess and the overlying interglacial soil is sharply marked by a boundary line (a "Markline"). Broecker and van Donk (1970) found isotopic evidence for the same sequence of climatic events in deep-sea cores. Each event in this sequence was called a Termination, and was numbered in (reverse) order beginning with Termination 1, approximately 12,000 years ago.

The main point of this paper is that Terminations are abrupt climate changes of Type 1. They are a normal part of the climate system's response to Milankovitch forcing in the same way that an abrupt onset of a monsoon is part of the system's linear and non-linear response to the annual march of the sun. There is, however, this difference: that whereas the seasonal cycle can be satisfactorily modeled as a response to forcing at one frequency (the annual cycle) and its harmonics, the

Figure 1. Model of $\delta^{18}O$ variations over the past 400,000 and next 25,000 years. The model curve is the sum of six components, each of which is an orbital curve multiplied by an appropriate gain and shifted by an appropriate phase (see Imbrie, 1985, for details). Roman numerals indicate Terminations I - IV, which occur about 12, 128, 245 and 339 KY B.P. in the data (Imbrie et al., 1984) and in the model.