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LETTERS TO THE EDITOR

The Energy Requirement of a Growing Ice-Sheet: Comment on "Ice ages and the thermal equilibrium of the earth, II" by David P. Adam

When water changes state, it absorbs or releases large amounts of latent heat. At the present time water evaporates from the oceans or moist land-surfaces, the latent heat of vaporization being supplied by solar radiation. When this water vapor condenses and falls out of the atmosphere as rainfall, the latent heat is released and forms a major heat-source for the atmosphere. The released latent heat is eventually lost to space as infrared radiation, while the rainfall returns to the sea as river flow.

If an ice sheet grew in a previously desert area, or as a result of a large increase in precipitation, then the flow of water vapor would increase as would also the transfer of latent heat, resulting in vast increases in atmospheric energy budgets, such as those described by Adam (1975). The sites of the major Wisconsinan ice sheets have at present reasonable rainfall, and it would seem likely that the ice sheets grew as a result of the present observed rainfall falling mostly as snow. Snowfall rather than rainfall implies a colder climate, therefore lower water vapor content, and hence a lower annual precipitation than at present. Newell (1974) gives a formation time for the Wisconsinan ice sheets of about 8000 years, which would allow them to accumulate with precipitation rates lower than at present and also with some summer melting. It would seem likely that though an extensive snow cover can be established very quickly, the growth of an ice sheet is relatively slow.

When precipitation falls as snow, there is an additional release of heat resulting from the latent heat of fusion of water. During the growth of continental ice sheets, the only additional heat released is the heat resulting from the latent heat of fusion of water (80 cal g^{-1}), since all other latent heat transfers would have taken place anyway if the snow fell as rain in a nonglacial climate. Thus, only the marginal increase in atmospheric heating is of interest during the formation of ice sheets and not the total heat flux. The "heat of glaciation" quoted by Adam is too high, and should be reduced to the marginal increase in atmospheric heating over the present observed values. This suggests that Adam's value should be reduced by 0.118 to 3.78×10^{21} kcal. Now the latent heat of fusion released by the formation of the continental ice sheets came from the oceans and was radiated to space. Thus, the formation of the Wisconsinan ice sheets would cause a total oceanic cooling of between 2° and 3°C. As ocean temperatures fell, so would evaporation rates, leading to decreased precipitation rates and a fall in latent heat transfer and atmospheric warming. So eventually, the energy fluxes would come into balance, and the ice sheets would cease to grow. The heat of glaciation calculated by this method is small when compared with daily latent heat release (9.0×10^{20} cal day^{-1}) over the world.

Some oceanic cooling probably preceded the growth of continental ice sheets; therefore, the cooling of the oceans by the withdrawal of the heat of glaciation should be less than the total observed cooling. The ocean temperature fall, calculated by my method is reasonable, and does not conflict with the observations.

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Reply to Comments by J. G. Lockwood

In studying ice age energy budgets, Dr. Lockwood prefers to examine departures of ice age energy fluxes from present conditions, whereas I prefer to consider total fluxes. This is partly a matter of personal taste; I feel that my approach is simpler and more likely to be productive. One notable weakness in his approach is that it cannot be used to study the modern conditions upon which it depends.

The "heat of glaciation" is defined in my paper as "the amount of heat released during condensation and freezing of the snow that formed the ice sheets" (Adam, 1975, p. 162), and I am not in error simply because Lockwood would have preferred that I define something else. Newell and Herman (1973) have independently used almost the same figure as I did, although they gave it no name.

I did not specifically describe any "vast increases in atmospheric energy budgets." However, conservation of energy requires that the area of an ice sheet must have a balanced regional energy budget; whatever outgoing energy losses cannot be met using local absorbed solar radiation or local cooling must be met with advected sensible and latent heat. It has not been determined whether this would require vast increases in atmospheric energy budgets or not. It does seem likely that there would be some increase in the vicinity of the ice sheet, which represents a massive heat sink.

During the early stages of glaciation, much of the energy advected over the ice sheet must have been in the form of latent heat, and precipitation may well have exceeded present rates, especially over the forming glaciers; later on, after the oceans had cooled in response to the growth of the ice sheets, less of the available energy could be used for evaporation, and global precipitation was probably less than at present.

It is important to realize that the global energy budget during times of glaciation behaved in a very dynamic way in response to the shifting balances among global energy sources, sinks, and storage and transfer mechanisms. It is thus misleading to take studies such as those by Newell and others (1975) and Kraus (1973) that are based on data from a brief interval, particularly a climatically extreme interval such as the glacial maximum, and use the results as representative of general "ice age conditions" (see also Hammond, 1976). Such results are only applicable to times when global climatic boundary conditions were the same as those used for the analysis.

Lockwood's reference to total oceanic cooling of between 2° and 3°C is apparently a reference to my calculation that the removal of the entire heat of glaciation from the oceans would cool them throughout their depth by over 23°C. Even a 3°C cooling of the world ocean from top to bottom is probably too large, however, and most of the observed cooling must have been concentrated in the warm waters near the surface. The point of the original calculation was that stored oceanic heat cannot completely account for the energy required to fuel a continental glaciation. Most of the required energy must have come from current annual absorbed solar radiation. In my model, this energy is treated explicitly, whereas Lockwood would treat it implicitly as a part of the present conditions from which he measures departures. Again, our approaches differ.

If, as Lockwood implies at the end of his discussion, there are observations with which my model is in conflict, I would welcome a specific list of them.

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