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Reply to J. G. Lockwood

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The comments made by Dr Lockwood raise interesting questions regarding the energy balance accompanying the ice ages, but also reveal several misunderstandings.

Contrary to his second sentence, I do not "assume that the latent heat of fusion released during the growth of the Würm/Wisconsin continental ice-sheets was absorbed by the oceans, since there might be radiative balance at the top of the atmosphere", but rather maintain that *if* a radiative balance were to prevail at all times (which I strongly doubt), then the latent heat must be absorbed by the oceans. I further open for consideration the possibility suggested by preliminary theoretical results (Saltzman and Vernekar, 1975, henceforth called S-V) that, contrary to our intuitions, the imbalance could be such that the net radiation is negative during an interglacial period and positive during a glacial period. In this case, the temperature of the ocean should be rising during a significant part of the period of glacial growth and during maximum glaciation, consistent with Newell's (1974) scenario. There is no question that if paleotemperature analyses of the deeper ocean water fail to reveal a relative warmth during the ice age, there must be a negative radiation balance during glacial growth and mechanisms such as described by Lockwood could very well be dominant.

The point is, however, that these mechanisms *need not be dominant*. For example, the tendency for an increase in mean air temperature due to the latent heat of snow formation can be balanced not only by an enhanced long-wave radiative loss to space, but also by other more subtle and complex effects involving changes in other parts of the whole system. In this connection, there might be (i) a reduction in the horizontal flux of heat from lower latitudes, (ii) a slightly higher static stability *in situ*, or at lower latitudes related to the above decrease in heat flux, that tends to inhibit an upward heat flux from the surface, or (iii) an enhanced *downward* long-wave radiative flux. Similarly, the proposed decrease in the greenhouse effect due to reduced water vapor in the ice age (with which I concur, cf. S-V), could be largely compensated for, if not reversed, by the fact that the earth's surface and atmosphere are radiating at somewhat lower temperatures.

Concerning Lockwood's second paragraph, we should recall that since we are dealing with an integral over the entire climatic-system (atmosphere, ocean, and cyro-lithosphere) and assume water in all forms is conserved, all that is relevant in computing the latent heat release is the *net change in water vapor and ice*. Even though there may have been decreased rainfall during the ice age (with which I again concur, cf. S-V), there would be no net cooling of the entire climatic-system if, as is almost certain, there was a simultaneous decrease in *evaporation*.

Finally, to return to our question regarding the true nature of the paleo-ocean-temperature changes, it is worth noting that recent evidence is quite mixed. Shackleton and Opdyke (1973) present a strong argument for a mid-depth Pacific Ocean cooling in phase with the ice age surface cooling, a result which is contrary to the conjecture made in my paper. However, other studies by Streeter (1973), Schnitker (1974), and Duplessy, Chenouard and Vila (1975) would seem to imply a warmer deep ocean temperature during the Würm/Wisconsin in the North Atlantic Ocean. From another viewpoint, recent radiation measurements from satellites (Gruber, 1977) seem to reveal a negative net radiation balance of the same magnitude as found by S-V (see Saltzman, 1977) for the present, interglacial period, which if not completely a consequence of instrumental and sampling errors, would also be supportive of the conjecture made. In the last analysis, the results of continuing observational studies such as these will

play the decisive role in determining our understanding of the integral energetics of the ice ages, but an unravelling of the mechanisms that lead to these integral results will depend on the development of refined theoretical models taking quantitative account of the full complex of possible interactions within the entire climatic system.

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