(Reprinted from Nature, Vol. 261, No. 5562, pp. 679–680, June 24, 1976)

Hudson Bay, Lake Zissaga and the growth of the Laurentide Ice Sheet

THE Laurentide Ice Sheet, by far the largest of the Northern Hemisphere continental glaciers, has formed and disappeared several times during the Quaternary[1]. I suggest here that, at the times of its formation and early growth, the mass balance of the ice sheet depends strongly on the physical behaviour of Hudson Bay, which is in turn largely controlled by the growing ice. Rapid changes in the size, salinity, and ice and snow cover of Hudson Bay must all have important effects on the mass balance of the growing Laurentide Ice Sheet.

Ives *et al.*[1] have advocated the concept of 'instantaneous glacierisation', whereby continental glaciation in the Northern Hemisphere is initiated by the appearance of perennial snowfields on Baffin Island and in northern Labrador, and they present considerable field evidence in support of their views. I have taken the same position on theoretical grounds[2]; a region with a high albedo absorbs relatively little energy from the Sun, but constantly loses energy as outgoing infrared radiation. It thus has an energy deficit that can only be balanced with advected energy from the surrounding area. If a significant fraction of the energy available for advection is in the form of latent heat, and if the region is cool enough so that precipitation generally freezes, more snow will fall each year than melts, and the snowfield will grow into an ice sheet.

Because of its position, Hudson Bay must be an important source of moisture for the formation of perennial snowfields on Baffin Island and in northern Labrador and for their initial growth; at present, snow falls during all seasons, and the highest snowfall occurs during autumn and early winter, before Hudson Bay freezes[3,4]. Once ice sheets form and begin to grow, the sea level will fall, however, and this will decrease the size of Hudson Bay and its effectiveness as a moisture source. This negative feedback mechanism will retard or reverse the growth of the ice sheets, leading either to steady-state ice sheets or perhaps to systematic oscillations in ice sheet size.

This feedback relationship will operate only while Hudson Bay is an arm of the ocean. A growing ice sheet on Baffin Island will, however, eventually form an ice dam that will block Hudson Strait, as a study by Mahaffy[5–7] has suggested. This would transform Hudson Bay into an immense proglacial lake and alter its size, salinity, and direction of drainage. This lake is designated here as Lake Zissaga (from an Indian word for the onset of winter).

With Hudson Strait blocked by ice, Lake Zissaga will increase in size and decrease in salinity until it finds an outlet, flooding low lying land and eventually draining to the south through the Great Lakes. These changes will act in two ways to intensify the developing glaciation, depending on whether Lake Zissaga is frozen or not.

If the lake is not frozen, its increased size will make it a more effective moisture source for the developing ice sheet, and this will lead to renewed or augmented growth of the ice sheet kernels on Baffin Island and in northern Labrador, which can draw moisture from the lake to help balance their local energy budgets using latent heat.

If Lake Zissaga is frozen, it will no longer be an effective moisture source for the ice sheet kernels in the north, but it will have a high albedo and a large deficit in its local energy budget, which, as noted above, must be balanced using energy advected from the surroundings. If this advected energy includes large amounts of latent heat and therefore produces high snowfall, Lake Zissaga will become permanently ice covered and will become a new centre of growth for the Laurentide Ice Sheet.

There are several reasons why the permanent freezing of Lake Zissaga is not unlikely. Oceanographic data, although sparse, suggest that Hudson Bay now has an energy deficit of a few percent that is balanced either by movement of relatively warm water into Hudson Bay from the Atlantic, or by a net export of ice[8]. Neither of these mechanisms would operate for Lake Zissaga. Freezing would also be aided by the low salinity of the lake, as fresh water both freezes and melts at higher temperatures than salt water[9]. This would cause Lake Zissaga to remain frozen for a longer period each year than Hudson Bay does, and would increase the regional energy deficit because of the effect of the ice on the albedo. Yet another effect is that the inflow of warm water from the surrounding land areas would be reduced, because of the flooding of low areas and the consequent reduction in land area draining into the lake. For all of these reasons, it seems likely that Lake Zissaga, once it formed, would have a strong tendency to freeze over and stay frozen.

Permanent freezing of Lake Zissaga will result in a sudden southward shift in the area of maximum snow accumulation on the growing Laurentide Ice Sheet. It will extend the area with a large energy deficit much closer to the Gulf of Mexico, which is an important source of warm, moist air masses that nourish the growing ice sheet while balancing its regional energy budget. This southward shift will significantly change the relationship between the growing ice sheet and the oceans from which it derives both moisture and energy. The magnitude of the total energy deficit over the ice sheet will increase considerably, and at the same time the energy gradient between the ice sheet and the oceans will intensify, both because of the increased total deficit and because of the decreased distance between them. These changes will increase the rate of accumulation of snow on the ice sheet, and they may also alter the oscillation period between stadial and interstadial periods.

Another possibility is that the ice dam may be somewhat unstable during its early phases, so that the accumulation of water in Lake Zissaga could cause the dam to break before the lake freezes to the bottom. If the ice cover were floating at the time the dam broke, much of the ice could be swept away during the draining of the lake; this would restore a low surface albedo and eliminate the local energy deficit required to drive a continental glaciation. Such a mechanism provides a plausible, although not yet proven, way to account for the short but dramatic global coolings that Flohn[10] has termed "abortive glaciations".

The concept of 'instantaneous glacierisation' may thus be extended to include not only the initial formation of ice sheet kernels on Baffin Island and in northern Labrador, but also the freezing of Lake Zissaga and its sudden transformation from a large proglacial lake into a large, thin, growing ice sheet.

If the Laurentide Ice Sheet originated in the North, as Ives and his coworkers have suggested[1], then Lake Zissaga must have existed, and it must have been an important factor in the development and growth of the Laurentide ice. The episodic nature of Northern Hemisphere continental glaciation during the Quaternary must be in part a response to the huge perturbations to the global climatic system introduced by the permanent freezing of Lake Zissaga.

If all of this is true, then local geographical conditions may allow small ice sheets such as those that grew on Baffin Island to produce significant environmental changes far beyond their own margins, and these changes must be understood before we can reach a complete understanding of the dynamics of ice ages.

I would like to thank the Yugoslav Council of Academies and the USNAS for support.

DAVID P. ADAM*

Slovenska Akademija Znanosti in Umetnosti, Ljubljana, Yugoslavia

Received October 23, 1975; accepted May 7, 1976.

*Permanent address: US Geological Survey, Menlo Park, California 94025.

[1] Ives, J. D., Andrews, J. T., and Barry, R. G., *Naturwissenschaften*, **62**, 118 (1975).
[2] Adam, D. P., *Quat. Res.*, **5**, 161 (1975).
[3] Thompson, H. A., in *Science, History and Hudson Bay*, Pt **1**, ch. 5 (Queen's Printer, Ottawa, 1968).
[4] *Atlas of World Water Balance and Water Resources of the Earth* (USSR National Committee for the International Hydrological Decade, Leningrad, 1974).
[5] Mahaffy, M. A., thesis, Univ. Colorado, Boulder (1974).
[6] Andrews, J. T., *et al.*, *World met. Org. Publ.*, **421**, 87 (1975).
[7] Barry, R. G., Andrews, J. T., and Mahaffy, M. A., *Science*, **190**, 979–981 (1975).
[8] Barber, F. G., in *Science, History and Hudson Bay*, Pt **1**, ch. 6 (Queen's Printer, Ottawa, 1968).
[9] Lardner, M. M., in: *Science, History and Hudson Bay*, Pt **1**, ch. 6, Pt 2 (Queen's Printer, Ottawa, 1968).
[10] Flohn, H., *Quat. Res.*, **4**, 385–404 (1975).