Reports

Continental Ice Sheets: Conditions for Growth

Abstract. *The conditions required for the development of major ice sheets in eastern Canada appear to have been approximated by those of the Little Ice Age in the 17th through the 19th centuries. Former extensive snowbanks from this period have been mapped from lichen-free terrain visible on Earth Resources Technology Satellite imagery. The climatic changes required to initiate the necessary snow line lowering may involve only a minor summer cooling. Simulations with an ice-flow model reproduce plausible ice centers, but the rate of ice sheet buildup is slower than that suggested by geological evidence of world sea level lowering from 120,000 to 115,000 years before the present.*

Recent minor climatic fluctuations at high latitudes, evidenced by climatic records in northeastern Canada and satellite imagery of the extent of snow cover (*1*, *2*), have led to renewed interest in the mechanisms of climatic change and the question of ice age inception. This concern is heightened by the implications that even small climatic changes would have for human survival in many areas of the world (*3*). In a geological context it is recognized that the present global climate is interglacial in character (*4*), although generally showing a deterioration over the last 5000 years since the thermal maximum, and that this condition will eventually terminate to usher in the "first future glaciation." Moreover, the geological and biological records show that glacial epochs have averaged 90,000 years in length, whereas the peak warmth of other nonglacial intervals, comparable with present-day conditions or warmer, has lasted only 10,000 years (*5*). There is evidence to suggest that the shift in climate from a nonglacial to a glacial mode may occur quite abruptly, perhaps in little more than a century or so, according to some sources (*6*, *7*).

The basic causes of glacial epochs are not known. Climatic changes are explained in both deterministic and stochastic terms, or in some combination of the two (*8*). In our present state of knowledge of the atmosphere, resolution of this problem is not likely to be swift or simple (*9*). However, other questions on the specific mechanisms of ice sheet growth can usefully be posed, with the expectation of more immediate answers. These include: the location and manner of ice sheet inception, the rate of snow and ice accumulation, and the necessary climatic conditions. These questions have been posed in the context of a research project at the Institute of Arctic and Alpine Research, University of Colorado, dealing with the inception of the Laurentide ice sheet.

Until recently, ice sheets were thought to have formed in the Northern Hemisphere by the amalgamation and spreading out of glaciers which built up in the coastal mountains of eastern North America and Fennoscandinavia. However, geological and climatological considerations (*10–12*) lend strong support to the view that the major continental ice sheets of at least the Late Pleistocene glaciation developed on the extensive upland plateaus of Baffin Island, Labrador-Ungava, Keewatin, and the Queen Elizabeth Islands in North America, as well as on those of Fennoscandinavia, by widespread snow line lowering. There is visible field evidence (discussed below) in support of the idea that this process took place during the climatic deterioration of the Little Ice Age in the 17th through the 19th centuries. Such snow line lowering would initiate extensive snow cover, modifying the regional surface energy budget through the high reflectivity of the snow cover to solar radiation and thereby causing atmospheric cooling. An increased proportion of the precipitation would therefore reach the ground in frozen form and the atmospheric circulation would be modified, presumably in such a way as to create a mode of positive feedback. Experiments by J. Williams (*13*), using the National Center for Atmospheric Research global circulation model with a snow cover in summer comparable with that of the present winters, are indicative of the type of atmospheric circulation patterns that must have occurred. Her results also bear a strong resemblance to climatic reconstructions for the early 1800's over the North Atlantic (*14*).

Early meteorological records, supported by historical and geological evidence, show that during the 17th through the 19th centuries Europe and other areas bordering the North Atlantic, the eastern Canadian Arctic, Alaska and the Yukon, China, and Japan (*15*) experienced climatic deterioration and the growth of montane glaciers, in some areas to their maximum postglacial extent. Flohn (*16*) has suggested that this interval can be designated as an "abortive glaciation." Field work in the early 1960's in north central Baffin Island (*17*) led to the identification of extensive areas of lichen-free terrain on upland surfaces. In these areas the moss and lichen cover was apparently killed and stripped off by the development of thin permanent snowfields. Radiometric and lichenometric analyses suggest that the period of snow cover began 500 to 300 years before the present (B.P.) and ended some 70 years ago as a result of a climatic amelioration (*18*), al-

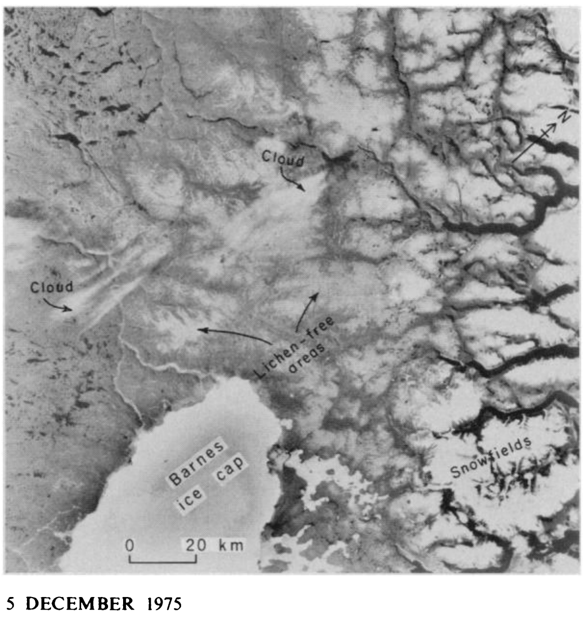

Fig. 1. North central Baffin Island as viewed by Earth Resources Technology Satellite I (27 August 1973, multispectral scanner band 5). The image shows light-toned lichen-free areas north of the Barnes ice cap and present-day snowfields to the east.

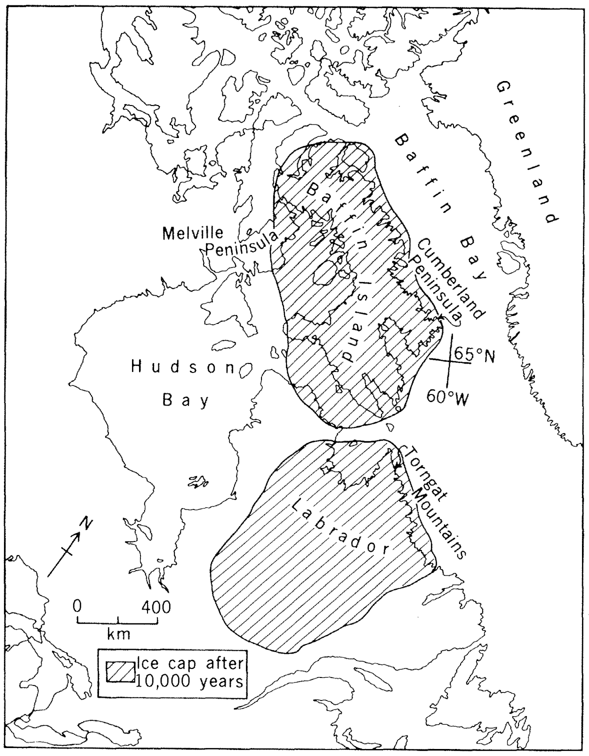

Fig. 2. Outline of the ice caps over eastern Canada simulated by Mahaffy's model after 10,000 years with a snow line lowering of about 500 m and two to three times the present-day precipitation.

though the removal of snow cover seems to have occurred earlier in north central Baffin Island by comparison with the Cumberland Peninsula. The trimline bordering these lichen-free areas can be mapped from the 1 : 1,000,000 Earth Resources Technology Satellite (ERTS) imagery, principally bands 5 and 6 (*19*), as illustrated in Fig. 1. During this period of snow cover in central Baffin Island, most of the land surface above an elevation of 600 m (about 140,000 km^2) was snow- or ice-covered, compared with 37,000 km^2 today (*20*), and similar extensive areas were affected in Labrador-Ungava and possibly in Keewatin.

The climatic changes required to initiate the buildup of such snowfields may be quite small. Andrews and Miller (*21*) estimate that on Baffin Island the difference between the modern snow line and that at glacial maximum is about 400 m. Indeed, even the recent climatic fluctuation, with a cooling of 1° to 2°C over Baffin Island since the 1950's (*1*) and a lowering of the elevation of the 0°C summer isotherm in the free atmosphere over the Queen Elizabeth Islands during the 1960's (*22*), appears to have produced identifiable responses in snow cover in both these areas (*23*). Simulation studies with the ice mass balance–energy budget model of L. D. Williams (*24*) indicate that the Little Ice Age snow line can be reproduced by a climate in which summer temperatures were 1.5°C less than present or the winter accumulation of precipitation was greater than at present by a factor of about 2.

Early estimates of ice sheet growth indicated that the Laurentide ice sheet took about 20,000 years to build to full size (*25*), although Lamb and Woodroffe (*11*) suggested that ice sheets became established (about 70,000 years B.P.) and grew sufficiently within 1000 to 5000 years to survive the St. Pierre interstadial dated at ± 65,000 years B.P. Recent studies (*26*) show a rapid drop in the world sea level to a minimum at about 115,000 years B.P. The rate of sea level lowering has been estimated to be 5 m per 1000 years (*27*). Other evidence for extreme rates of climatic change from interglacial to glacial comes from the work of Kennett and Huddlestun (*7*) who suggested that a major cooling occurred in less than 350 years at about 89,500 years B.P., perhaps correlative with parallel changes reported from Greenland (*6*) and southern France (*28*). Despite the widely differing dates (120,000 to 115,000, 90,000, and 70,000 years B.P.), these lines of evidence appear to point to some geological events resembling Ives' concept (*10*) of "instantaneous glacierization" of the high plateaus in the Canadian Arctic by snowpack accretion within only a few hundred years.

Studies by Loewe (*29*) indicate that, in order to account for the accumulation of glacial snow in Labrador-Ungava and Keewatin, a cooling of at least 6°C in summer supplemented by some increase in total precipitation is required. Between about 125,000 and 115,000 years B.P., accumulation on the Greenland ice sheet doubled if we use the reassessment of the Camp Century $\delta^{18}O$ record and chronology of Andrews *et al.* (*30*). To achieve significant additional precipitation greater winter storminess is probably necessary (*31*), and in this respect the eastern Canadian Arctic and Subarctic are favorably situated. In addition, the existence of a snow cover producing winterlike atmospheric circulation patterns all year will also augment summer snowfall in high latitudes. Using the ice mass balance–energy budget model, L. D. Williams (*32*) estimated that glacierization of presently empty cirques on eastern Baffin Island would be achieved, for example, either by an 80 percent increase in snowfall or by combined changes such as a 20 percent increase in snowfall accompanied by a 1°C cooling in summer and a 10 percent increase in cloudiness. Increased precipitation is more probable if the sea surface temperatures remain high during the stage of glacial inception (*33*). However, if the recent climatic fluctuation is any guide, we must note that Rodewald (*34*) reports a 2°C cooling between 1951–1955 and 1968–1972 in August in the western North Atlantic, which amounts to 1/6 of the estimated difference between present and full glacial sea surface temperatures in the vicinity of the Gulf Stream (*35*). Although such short-term trends may be an unreliable indicator of longer-term changes, this evidence suggests that it may be difficult to sustain high sea surface temperatures during the initial phase of a glacial period. This finding is in agreement with Newell's (*36*) suggestion that continental ice sheets developed (over an 8000-year period), as a result of an atmospheric regime of somewhat increased poleward atmospheric energy transport combined with a decrease of poleward oceanic heat flux; Newell's suggestion was made in an effort to account for the calculated deficit of energy in middle and high latitudes.

To evaluate the physical likelihood of a rapid ($\leq$ 5000 years) buildup of a major continental ice sheet, Mahaffy (*37*) has developed a three-dimensional ice-flow model. The model uses the Glen flow law of ice, where the strain rate $\dot{\epsilon}$ is given by

$$\dot{\epsilon} = A\tau^n$$

where τ is the shear stress, and A and n are constants. In the experiments n = 3.5 and A was selected to represent a basal temperature of –5° to –10°C. The model has been used with considerable success to simulate the Barnes ice cap (6000 km^2) over the last 2500 years of its history. To simulate conditions of a rapid spread of snowfields over the eastern Canadian Arctic, the model was used with an input data and computational grid spacing of 50 km over Baffin Island, Keewatin, and Labrador-Ungava with a maximum accumulation of 1 m of water equivalent (two to three times the present amounts) and a snow line lowered to 300 m from its present elevation of 800 m or more over the plateaus of Baffin Island. In future experiments a function will be incorporated into the model to increase basal ice temperatures in response to geothermal heat flux as the ice sheet thickens and modifies the thermal gradient. Under these circumstances, the ice sheet would tend to spread more rapidly. Preliminary results in the present simulation experiment indicate that after 4000 years of buildup the ice sheet had a volume of 0.3×10^6 km^3 and covered Baffin Island, with smaller ice caps in Labrador-Ungava. However, the volume in the ice sheet at this stage was equivalent to a rate of sea level lowering of only $\simeq 0.25$ m per 1000 years. After 10,000 years, ice sheets covered most of Baffin Island and north central Labrador-Ungava (Fig. 2) with an area of 1.78×10^6 km^2 and a volume of 3×10^6 km^3. This volume figure represents a world sea level lowering of 7.5 m; this figure is an order of magnitude smaller than the total amount suggested from the Barbados work (*26, 27*), but in the last 2000 years of the model experiment the equivalent rate of lowering of sea level is 3 to 5 m per 1000 years. The increase in the volume of the ice sheet is strongly nonlinear and consists of an initial 3000 to 5000 years of slow buildup followed by an accelerating phase of growth. Although some of these data add a measure of support to the dramatic events centered around 115,000 years B.P., nevertheless there still appear to be severe physical constraints on such rapid sea level lowering based on considerations of atmospheric circulation conditions and the global energy balance. It is hard to visualize appropriate circulation regimes to provide the necessary input of snow accumulation (*31*) recurring over thousands of years. Even more critical, the rates proposed for the uptake of water into the ice sheets match the fastest rates of return of water into the ocean system during deglaciation, despite the fact that the energy requirements of the processes determining ice sheet accumulation (evaporation, freezing, and precipitation) are approximately seven times greater than for the melting process. In the present study we have not attempted to deal with this more fundamental problem.

In summary, a study of recent climatic fluctuations and Little Ice Age conditions in the eastern Canadian Arctic illustrates the climatic sensitivity of the area and provides significant clues on the likely mechanism and location of the growth of continental ice in North America during the last glaciation. The immediate mechanism is in all probability the widespread and rapid lowering of the snow line over the upland plateaus of Baffin Island and north central Labrador-Ungava. Little Ice Age conditions appear to provide a useful analog of glacial inception. Lichen-free areas demarcating permanent snowfields in Baffin Island during the Little Ice Age have been mapped from ERTS imagery, and a snow line lowering of 200 to 600 m has been determined from these maps.

Geological evidence suggests a rapid sea level lowering of 5 m per 1000 years during the early ice sheet buildup that bottomed out about 115,000 years B.P. Simulations with an ice flow model give results within the correct order of magnitude after 10,000 years of growth, with a snow line lowering of about 500 m and two to three times the present-day precipitation, but these simulations are orders of magnitude too small for the first 4000 years. Further study of physical processes in the atmosphere-ocean-cryosphere system is required to resolve these apparent discrepancies.

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References and Notes

1. R. S. Bradley, *Arctic* **26**, 230 (1973).
2. S. A. Bowling, in *Climate of the Arctic*, G. Weller and S. A. Bowling, Eds. (Univ. of Alaska Press, Fairbanks, 1975), pp. 91–97; G. J. Kukla and H. J. Kukla, *Science* **183**, 709 (1974).
3. R. A. Bryson, *Science* **184**, 753 (1974); D. Winstanley, B. Emmett, G. Winstanley, paper presented at the American Society of Civil Engineers Conference, Biloxi, Mississippi, 1974.
4. G. J. Kukla, R. K. Matthews, J. M. Mitchell, *Quat. Res. (N.Y.)*. **2**, 261 (1972).
5. C. Emiliani, *ibid.*, p. 270.
6. W. Dansgaard, S. J. Johnsen, H. B. Clausen, C. C. Langway, *ibid.*, p. 396.
7. J. P. Kennett and P. Huddlestun, *ibid.*, p. 384.
8. W. Q. Chin and V. Yevjevich, *Can. Inland Waters Dir. Sci. Ser. No. 39* (1974).
9. E. N. Lorenz, *J. Appl. Meteorol.* **9**, 325 (1970).
10. J. D. Ives, *Arctic* **10**, 67 (1957).
11. H. H. Lamb and A. Woodroffe, *Quat. Res. (N.Y.)* **1**, 29 (1970).
12. J. D. Ives, J. T. Andrews, R. G. Barry, *Naturwissenschaften* **62**, 118 (1975).
13. J. Williams, *J. Appl. Meteorol.* **14**, 137 (1975).
14. H. H. Lamb and A. I. Johnson, *Geophys. Mem. (Lond.)* (1966); J. Bjerknes, *World Meteorol. Organ. Tech. Note 66* (1955), pp. 77–88.
15. E. L. Ladurie, *Times of Feast, Times of Famine* (Doubleday, New York, 1971); G. H. Miller, *Quat. Res. (N.Y.)* **3**, 561 (1973); G. H. Denton and W. Karlen, *ibid.*, p. 155; S. Wen-hsiung, *Bull. Am. Meteorol. Soc.* **55**, 1347 (1974); T. Yamamoto, *J. Meteorol. Soc. Jpn. (Ser. 2)* **49** (special issue), 798 (1971).
16. H. Flohn, *Quat. Res. (N.Y.)* **4**, 385 (1974).
17. J. D. Ives, *J. Glaciol.* **4**, 197 (1962).
18. G. Falconer, *Geogr. Bull.* **8**, 194 (1966).
19. J. T. Andrews, C. Wright, P. T. Davis, in preparation.
20. C. Wright, thesis, University of Colorado (1975).

J. T. Andrews and G. H. Miller, *Arct. Alp. Res.* **4**, 45 (1972).

22. R. S. Bradley, *Nature (Lond.)* **243**, 398 (1973).
23. ——— and G. H. Miller, *ibid.* **237**, 385 (1972); G. Hattersley-Smith and H. Serson, *J. Glaciol.* **12**, 417 (1973).
24. L. D. Williams, in *Long-Term Climatic Fluctuations* (World Meteorological Organization–International Association of Meteorology and Atmospheric Physics Symposium, Norwich, England, August 1975) (World Meteorological Organization, Geneva, in press).
25. H. Weertman, *J. Glaciol.* **5**, 145 (1964); R. G. Barry, *Geogr. Bull.* **8**, 319 (1966).
26. R. P. Steinen, R. S. Harrison, R. K. Matthews, *Geol. Soc. Am. Bull.* **84**, 63 (1973).
27. S. Mangion and R. K. Matthews, *Geol. Soc. Am. Abstr.* **6**, 855 (1974).
28. J. C. Duplessy, J. Labeyrie, C. Lalou, H. V. Nguyen, *Nature (Lond.)* **226**, 631 (1970).

F. Loewe, *Arct. Alp. Res.* **3**, 331 (1971).

30. J. T. Andrews, S. Funder, C. Hjort, J. Imbrie, *Geology* **2**, 355 (1974).

R. G. Barry, *Geogr. Ann.* **42**, 36 (1960); W. A. R. Brinkmann and R. G. Barry, *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **11**, 77 (1972); J. T. Andrews, R. G. Barry, R. S. Bradley, G. H. Miller, L. D. Williams, *Quat. Res. (N.Y.)* **2**, 303 (1972).

L. D. Williams, *Arct. Alp. Res.* **7**, 169 (1975).

33. D. P. Adam, *J. Res. U.S. Geol. Surv.* **1**, 587 (1973).
34. M. Rodewald, *Beil. Wetterkarte* 119/73, SO 29/73 (1973).
35. E. W. Wahl and R. A. Bryson, *Nature (Lond.)* **254**, 45 (1975).
36. R. E. Newell, *Quat. Res. (N.Y.)* **4**, 117 (1974).
37. M. A. Mahaffy, thesis, University of Colorado (1974).
38. Valuable contributions to the Laurentide Project were also made by P. T. Davis, J. D. Ives, L. D. Williams, and C. Wright. The study is supported by National Science Foundation grant GA-40248.

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Storm Wave Climates at Cape Hatteras, North Carolina: Recent Secular Variations

Abstract. *Mid-Atlantic coastal wave climates have undergone significant change within the last three decades. The duration and frequency of storms generating high waves and the length of the winter storm wave season have increased. These changes may, in part, account for the observed trend in shoreline erosion along the east coast of the United States.*

The U.S. Army Corps of Engineers has assigned more than 86 percent of the shoreline along the Atlantic coast of the United States to the categories of erosion or critical erosion (*1*). Numerous engineering measures have been implemented along the mid-Atlantic to check the continuing recession of the shoreline. This erosional trend has been attributed to a variety of factors including (i) the current sea level rise; (ii) the reduced supply of new sands from inland sources; (iii) human activities that alter the coastal geomorphology; and (iv) a lower average central pres-