If the ice is 20,000 years old, then the bottom temperatures in these three different cases would be, respectively, $-4 \cdot 9°$ C., $-12 \cdot 7°$ C. and $-5 \cdot 5°$ C. However because of the loss of geothermal heat through the ice, especially in the early stages, the actual temperatures would be several degrees lower.

There is, however, considerable doubt whether Mr. Fisher's "bubbly" ice would be similar to that found at the great pressure existing under 3,000 m. of ice. At the bottom of the Maudheim hole at 100 m., Schytt [4] found ice of density 0·885 containing air bubbles, mostly round, with a mean diameter of about 0·5 mm. At a pressure 30 times greater, the air bubbles would be even smaller and hence the effect on thermal conductivity probably negligible. It is hoped that further light on this problem can be cast by measurements of thermal conductivity on the ice recovered from 300 m. in the Byrd hole.

United States Weather Bureau
Washington 25, D.C., U.S.A.
28 September 1959

HARRY WEXLER

Dr. G. de Q. Robin has also sent to the *Journal of Glaciology* copies of letters between himself and Dr. Wexler concerning the same article,[1] and with the permission of Dr. Wexler we are publishing the following extracts.

In his opening letter, Dr. Robin says that he does not favour the glacial growth hypothesis for several reasons: (*i*) the age of 10,000 years required seems much too small, since most glacial geologists would probably say that the Antarctic ice sheet has persisted throughout the Pleistocene although it has fluctuated in size; (*ii*) the depth of the glacier makes it probable that this area was initially covered by sea; and (*iii*) the analysis given by Wexler has not taken into account the effect of changing surface elevation on the mean ice temperature. At present ice temperatures appear to decrease by 1° C. for each 100 m. rise in elevation. If this effect was present during the growth of the ice sheet, one would expect the temperature in the bore hole to increase by 1° C. for each 100 m. depth—or about two-thirds of this gradient if the Earth's crust were adjusting itself to the ice load. For these reasons, he (Dr. Robin) thinks that the flow hypothesis gives a better explanation of the approximately isothermal layer.

In his reply, Dr. Wexler says that, with regard to (*i*), he feels that the last 10,000 years have seen a marked growth in ice thickness in the Pacific sector of Antarctica for the following reasons: the storms which over the millennia built up the ice on the Indian Ocean side of Antarctica were more and more deflected by the high obstacle they created and moved with higher frequency into the Pacific sector via the Ross Sea. This resulted in cessation of growth in the original ice sheet, and in certain portions actual wastage—as shown by the retreat of the ice from the Taylor, Victoria and other dry valleys near McMurdo Sound and the raising of beach levels in that area (e.g. Marble Point) by about 20 m. The storms entering the Ross Sea area brought copious quantities of heat and moisture into the interior of the Pacific sector of Antarctica. The prevailing north-east winds through a thick portion of the troposphere and the heavy snows at Byrd Station attest to this prevailing flow from the ocean.[5] The prevailing southerly winds found on the west sides of the cyclones in McMurdo Sound and the Victoria Land plateau would strongly favour ablation. Another sign pointing to the comparatively young age of the ice in this region of Antarctica is the deep trough in the snow surface extending hundreds of miles parallel to, and near, the foot of Horlick Mountains. The bottom of this trough is only about 750 m. above sea level as compared with 1,500 m. in the neighbourhood of Byrd Station. From the strong prevailing surface north-east winds, averaging some 20 knots (10 m./sec.), and the persistent drifting snow entering this trough, one would expect it to fill in about 10,000 years. Using rough figures for the size of the trough and if we take Loewe's [10] snow transport figure of 2×10^{10} g. m.$^{-1}$ yr.$^{-1}$, then 10,000 years would be required to fill the trough. It would not appear that the maintenance of this trough could be explained by an under-ice ocean current between the Ross and Weddell Seas, since the Thiel-Neuberg airborne traverse during the past season showed the ice along the meridian 130° W. to be grounded from lat. 79·8° S. to 84·8° S.

With regard to (*ii*), if the Byrd basin had originally been covered by sea this would certainly have changed the initial conditions and probably the entire approach used, but as the snow accumulated more and more on the "Byrd Ice Shelf", what would have happened to the water underneath? Would it have gradually frozen *in situ* or squirted up the slopes in response to the tremendous growing pressure, and then frozen? Dr. Wexler leaves this problem to others, but feels he should be allowed to attempt to

https://doi.org/10.3189/S0022143000023790 Published online by Cambridge University Press

solve a model which violates no physical principle, and the correctness of which can neither be proved nor disproved.

He admits that (*iii*) is a good point, and that he had not taken into account the effect of changing surface elevation on the mean ice temperature; if it is true, then a "climatic" warming such as he had assumed would have to be superimposed on the decreasing temperature caused by colder accumulation as the ice grew in height. However, the figure of 1° C. per 100 m. quoted by Robin is based on measurements made on plateaus, and probably does not obtain in a deep, slowly filling basin because of the effect of cold air drainage into it and the resulting favorable conditions for maximum radiant cooling. The famous cold pools of air in the Austrian Alps caused by drainage of cold air from the slopes [6] can be compared with the conditions in Marie Byrd Land before the basin had filled up to a height equal to that of the walls, roughly near sea level,[7] and for this part of the process a decrease of 1° C. per 100 m. need not necessarily obtain. Thus for the first half of the growth of the Marie Byrd ice there should be no appreciable decrease of temperature with increasing growth, but there would be for the next 1,500 m. when the ice surface became convex. If the "initial" temperatures are based on these assumptions then, for the initial temperatures to be isothermal implies a climatic warming of 10° C. in 5,000 years. New measurements in the bore hole in December 1958 showed a drop of only 0·03° C. in the lower 500 ft. (150 m.) as compared with 0·38° C. through the same interval in January 1958 shortly after the hole was drilled. Apparently the middle portion of the hole had not come to thermal equilibrium immediately following the drilling. This climatic warming is just what one might expect if storms were more frequent in recent millennia in the Pacific sector of Antarctica in accordance with the reasoning given above; also, judging from the increase in Little America annual temperatures of 2·6° C. since 1912, the warming process is still continuing,[8] though not at the same rate, of course. He does not claim that the warming in Little America is typical of a large portion of that sector of Antarctica any more than the phenomenal rise of Spitsbergen annual temperature (6° C. since 1912) is typical of the Arctic, but he does believe that the warming trend in this part of Antarctica has existed for some time and that it is probably due to the higher frequency of storms entering Ross Sea and bringing in vast quantities of warm, moist marine air into the interior of the continent.

Dr. Robin's next letter makes two comments in reply to Dr. Wexler: (a) That the trough between Byrd Station and the Horlick Mountains which Wexler takes to be an area which is filling up with snow, can be explained on glacier flow theory as being due to a deep subglacial floor in this region (which will be checked by the I.G.Y. traverse), and to a closer approach to the edge of the grounded ice as one moves south from Byrd Station. (b) For Wexler's glacial growth theory to hold, two criteria must be valid: first that the ice sheet at Byrd Station is somewhere between say 7,500 and 12,500 years old, and secondly, in order to produce an approximately isothermal condition in the top 1,000 ft. (300 m.), the climatic warming must have kept closely in step with the increasing surface elevation (2° to 3° C. per 1,000 years say). On the other hand the glacier flow theory of the isothermal state of the upper layers requires only that the ice sheet is old enough for substantial flow to occur, that is older than say 15,000 years. Dr. Robin considers this to be a more probable situation, particularly in view of the geologists' views on the age of the Antarctic Ice Sheet.

In his last letter, Dr. Wexler states that he now thinks the age of the Byrd ice may be larger than he earlier estimated because of the following new information: the annual water accumulation at Byrd Station [9] is about half that assumed in his paper. He had taken the figure of 30 cm. $yr.^{-1}$ from an early radio message; apparently this referred to snow accumulation, not water equivalent. Therefore, if the average accumulation over the life of the Byrd ice were 15 cm. $yr.^{-1}$ instead of 30 cm. $yr.^{-1}$, it would require 20,000 years instead of 10,000 years to build up a 3,000 m. thick layer. The slower growth of ice would mean a greater loss of geothermal heat; perhaps 10,000 years of it instead of 2,000 for the doubled accumulation. It would also mean that the warming of 10° C. referred to earlier in the correspondence would have taken place in the past 10,000 years instead of 5,000 years and that Robin's figure of 15,000 years for the flow theory to be valid should rise to 30,000 years.

With regard to the time for filling up the trough near the foot of the Horlick Mountains by blowing snow, implicit in the calculations was the assumption that the precipitation (not accumulation) has been the same at the crest and in the trough, but that some of the precipitation reaching the crest is blown into the trough by the prevailing north-easterly winds. Actually, because of the topography and nearness of the crest to the ocean, more precipitation would fall on the crest than in the trough, perhaps by a factor 2 or 3. Apart from any glacier flow, the rate of filling of the trough will depend on the relative precipitation rates at the crest and the trough and on the wind transport of snow from crest to trough.

Conceivably with a large enough precipitation difference, the trough would never fill and could, in fact, become more marked. Indeed, the unequal precipitation rate is probably why the crest and trough formed in the first place. If we assume the trough precipitation to be half that at the crest during the 20,000 years that the ice has presumably been building up to its present thickness, then the trough would have reached its present average depth of 750 m. below the crest if the annual precipitation at the crest has been 17·5 cm. and if 2·5 cm. of this has been blown from crest to trough (thus giving an annual accumulation of 15 cm. on the crest and 11·25 cm. in the trough). If we approximate to the crest and trough by a flat plateau 500 km. wide beside a flat valley also 500 km. wide (together comprising the 1,000 km. from Executive Committee Mountains to Horlick Mountains), then the transport of snow from crest to trough necessary to effect the gains and losses cited above is $1 \cdot 25 \times 10^{10}$ g. m.$^{-1}$ yr.$^{-1}$, which is smaller than Loewe's figure of 2×10^{10} g. m.$^{-1}$ yr.$^{-1}$ given in his *Études de glaciologie en Terre Adélie, 1951-52*,[10] but more than twice as large as another transport figure of Loewe's, $0 \cdot 47 \times 10^{10}$ g. m.$^{-1}$ yr.$^{-1}$ cited by Vickers.[11] This last figure is based on a wind speed of 35 knots (17·5 m. sec.$^{-1}$) which is probably too large for the average wind speed in Marie Byrd Land. Nevertheless, if we accept the figure of $1 \cdot 25 \times 10^{10}$ g. m.$^{-1}$ yr.$^{-1}$, the crest should be growing relative to the trough at a rate of 3·75 cm. yr.$^{-1}$.

The crest-trough elevation difference would remain constant if the annual precipitation rates were 20 cm. and 10 cm. respectively and if the annual gain and loss by blowing snow was 5 cm. This would require a wind transport by blowing snow of $2 \cdot 5 \times 10^{10}$ g. m.$^{-1}$ yr.$^{-1}$, a greater value than Loewe's large estimate. In view of these considerations based on an estimate that the precipitation at the trough is half that at the crest, Dr. Wexler states that the presence of the trough need not signify that the Byrd ice is younger than 20,000 years. When more complete measurements are available for the accumulation in the trough and on the crest and of the wind transport of snow into the trough, this method might indeed be used to give an independent estimate of the age of the Byrd ice.

REFERENCES

1. Wexler, H. Geothermal heat and glacial growth. *Journal of Glaciology*, Vol. 3, No. 25, 1959, p. 420-25.
2. Fisher, J. E. Ice pyramids on glaciers. *Journal of Glaciology*, Vol. 1, No. 7, 1950, p. 373-77.
3. Birch, F., *and* Clark, H. The thermal conductivity of rocks and its dependence on temperature and composition. *American Journal of Science*, Vol. 238, No. 8, 1940, p. 529-58; No. 9, 1940, p. 613-35.
4. Schytt, V. Glaciology. II. *Norwegian-British-Swedish Antarctic Expedition, 1949-52. Scientific Results* (Oslo, Norsk Polarinstitutt), Vol. 4, 1958, p. 147.
5. *see: U.S. I.G.Y. General Report Series*, No. 1, 1958.
6. Geiger, H. *The climate near the ground*. Cambridge, Mass., Harvard University Press, 1950. Chapters 18-20, particularly figure 89.
7. *see: U.S. I.G.Y. Glaciological Report Series*, No. 1, 1958. Particularly figure 7.
8. Wexler, H. A warming trend at Little America, Antarctica. *Weather*, Vol. 14, No. 6, 1959, p. 191-97.
9. Vickers, W. W. Antarctic snow stratigraphy. *Transactions. American Geophysical Union*, Vol. 40, No. 2, 1959, p. 181-84.
10. Loewe, F. *Études de glaciologie en Terre Adélie, 1951-1952*. Paris, Hermann, 1956. (*Expéditions Polaires Françaises. Résultats Scientifiques*, No. 9.)
11. Vickers, W. W. Wind transport of Antarctic snow. *Transactions. American Geophysical Union*, Vol. 40, No. 2, 1959, p. 162-67.

REVIEWS

ARCTIC SEA ICE. Proceedings of the Conference conducted by the Division of Earth Sciences and supported by the Office of Naval Research. National Academy of Sciences—National Research Council, Washington, D.C. Publication 598, December 1958. 271 pages, illus., maps. 28 cm.

The conference on Arctic sea ice, held at Easton, Maryland, U.S.A., 24-27 February 1958, comprised six daytime sessions, and several evening papers on aspects of sea ice not entirely related to particular topics. The particular topics were classified thus: (1) Distribution and character of sea ice; (2) Sea ice observing and reporting techniques; (3) Physics and mechanics of sea ice; (4) Sea ice formation, growth and disintegration; (5) Drift and deformation of sea ice, and (6) Sea ice prediction techniques. Sea ice operations were discussed at the evening meetings.