Is the Antarctic ice sheet growing thicker?

BY

JOHN HOLLIN
Department of Geological and Geophysical Sciences,
Princeton University, New Jersey, U.S.A.

ABSTRACT

The Antarctic ice sheet has existed for several million years, it has fluctuated but never disappeared, and the last major retreat of its margin ended several thousand years ago. The evidence is discussed for and against a subsequent growth of the ice sheet centre, on a time scale of thousands of years. The evidence includes ice- and sand-wedges, cavernous weathering and lichens, all to the ice edge; possibly advancing glaciers flowing from the ice sheet into the McMurdo Oasis; positive mass budgets for the ice sheet and for individual drainage basins; a possible sea-level fall over the last 4000 yr (that the Netherlands and Gulf Coast show a sea-level rise may be because they are sinking now as part of collapsing "peripheral bulges" stretching further than usually imagined, though not as far as the Equator as has been suggested), though part of this fall may be due to a post-Hypsithermal cooling; the aseismicity of Antarctica; temperature profiles in the ice sheet; strain networks on the ice surface; deep coring studies; ice position surveys; and gravity data. The most likely causes for a growth of the ice sheet would be a post-18,000 BP accumulation increase over Antarctica, or else a build-up in one or more basins towards a mechanical surge.

Introduction

This meeting of the SCAR Working Group on Glaciology follows a smaller meeting of the SCAR Sub-committee on Quaternary Studies. The Quaternary workers send their best wishes to the Glaciologists, and stress the opportunities for co-operation between the two groups. The Quaternary papers, discussions and resolutions are being prepared for publication by the Sub-committee's Convener, Professor E. M. van Zinderen Bakker of the University of the Orange Free State (van Zinderen Bakker, 1969). This paper begins with a brief review of the Quaternary history of the Antarctic ice sheet. The main part of the paper discusses the evidence, much of it glaciological, for and against a current thickening of the ice sheet centre on a time scale of thousands of years. The final part reviews very briefly the possible causes for such a build-up.
History of the ice sheet

In brief, the main features of the history of the ice sheet as a whole seem to be:

1. That it has existed for several million years, in fact from before the Quaternary.
2. That during this time it has fluctuated by limited amounts but has never disappeared.
3. That the last major fluctuation was a retreat of the margin, which seems to have largely ended several thousand years ago.

The evidence for the age of the ice sheet includes potassium-argon dated volcanics overlying glacial features (Armstrong et al., 1968) and ice-rafted débris in circum-Antarctic marine cores dated by magnetic reversals (Hays and Opdyke, 1967). The evidence for fluctuations includes stratigraphic studies of multiple glaciation in the "dry valleys" of south Victoria Land ("the McMurdo Oasis") by numerous United States and New Zealand parties, summarized by Nichols (1966) and continuing. The evidence for limited fluctuations and against disappearance comes from biostratigraphic studies in marine cores (Hays, 1965) and from thermoluminescence studies on land (Zeller, 1966). The evidence for the retreat includes ice- and sand-wedge growth studies (Berg and Black, 1966) and radio-carbon dates (liable to be a few hundred years too old, because of the low radio-carbon content of the Antarctic seas). Important dates reported include 4600 ± 200 BP on an elephant seal embedded at 13.5 m in marine beaches which rise to 20 m (Nichols, 1966). In case these beaches reflect, not retreat, but an upward bulge marginal to an increase in thickness of the ice sheet centre (Hollin, 1962a, p. 193), such as is discussed in this present paper, more definite evidence for retreat at the margin comes from dates on algae in morainal pounds, again discussed by Nichols (1966) and by Denton et al. (1969).

This last major retreat of the margin was probably caused by:

1. The rise of sea-level between 18,000 and 6000 BP as the northern ice sheets disappeared; the rise probably cut back the edge of the Antarctic ice sheet for both budgetary and mechanical reasons (Hollin, 1962a).
2. An increased advection of sensible and latent heat from the north, as the ice sheets disappeared.
3. Summer radiation greater than today's, according to Milankovitch's calculations for 75°S (Zeuner, 1959).

Hollin (1962a) thought that, following the last major retreat, the ice sheet had probably reached a steady state, apart from some minor adjustments at the margin. He considered two possible causes of thickening in the centre, but thought they were unlikely to be very important:

1. Since 18,000 BP, during and after the retreat, a warmer atmosphere above Antarctica, holding more moisture and circulating more vigorously,
might have led to an increase in the accumulation rate. A calculation by Meinardus suggests that an increase of temperature by 5°C and wind by 24 per cent would have combined to double the accumulation over Antarctica. The capacity of air to hold moisture depends strongly on the temperature, particularly when the latter is low (see any vapour pressure tables), and the above result seems not unreasonable. However, according to Nye the thickness of an ice sheet should depend on the accumulation rate only to the one-sixth power, so that the doubling should have caused a thickness increase by only 10 per cent or so. Moreover, such an increase might have been accommodated by rapid "kinematic waves", and Hollin thought it would have been more or less completed by now.

(2) Robin (1955) suggested that ice sheets might build up until friction and the blanketing of geothermal heat caused them to melt at the base and "surge", in an essentially mechanical cycle unrelated to climate. But Hollin (1962b) thought it unlikely that the whole ice sheet would be building up in phase, and thought that the surges would tend to occur only in relatively small "drainage basins".

However, the idea that the ice sheet centre may be thickening, on a time scale of thousands of years, has continued to appear in the literature: for the climatic reason (Loewe, 1960; Schytt, 1961; Gow, 1965) or for the surge reason (Wilson, 1964; Weertman, 1966). Therefore, this paper examines more closely the evidence for and against such a thickening.

Evidence for and against a thickening of the ice sheet centre

First, a few general points should be made:

(1) This paper is concerned with the evidence for growth over a period of thousands of years, during and/or since the last major retreat of the margin. Since that retreat, there is evidence for a worldwide "Hypsithermal" warm time, "Neoglacial" cool time (Porter and Denton, 1967) and, in the last 100 yr or so, another warm time. It is important to differentiate the superimposed effects of these relatively brief events from those we are looking for.

(2) The evidence from any one place should be evaluated with caution; to begin with in terms of the local glacio-meteorology. For example, an ice advance in the high mountains of East Antarctica might well turn out to be due to an accumulation increase and therefore to a warming. But an advance in the Antarctic Peninsula might indicate chiefly an ablation decrease, and therefore a cooling. If an accumulation increase has caused or is causing a built-up in Antarctica, this could be complete in a relatively self-contained mountain glacier, but still continuing in the ice sheet centre.

(3) Similarly, the evidence should be interpreted first in terms of the local drainage basin. The major drainage basins of Antarctica are illustrated in the paper by Giovinetto et al. (1966). They are defined from available elevation data, on the assumption from theory and field evidence
that, over distances say ten times its thickness, ice flows in the direction of its greatest surface slope. If surges are a cyclic phenomenon, each basin may have its own period, and be at a different stage of its build-up. However, this is not to say that a particularly big surge might not affect other basins: (a) by "capturing" some drainage, (b) by raising sea level abruptly, pushing back the "grounding line" between the ice shelves and the ice sheet, so reducing the total shear force under the latter and causing other surges, or (c) by cooling the Southern Ocean.

(4) Probably few glaciers are ever in a perfectly steady state: for example kinematic waves may be moving down them all the time. Evidence is needed that reflects their trends over thousands of years.

Turning now to the evidence, this is given by subjects. In general, we begin with investigations completed or in progress, and end with suggestions for the future.

(1) At many places in Antarctica where the terrain and climate are suitable, patterned ground (particularly ice- and sand-wedge polygons), large-scale cavernous weathering and lichens are found. If their development decreased fairly steadily towards zero at the edge of the ice, this would suggest a shrinking ice sheet, but the author has found no reports of this in the mountains and nunataks near the ice sheet centre (as opposed to the margin). If they continue fairly uniformly right to the ice edge, this suggests a steady or growing ice sheet. Lichens to the edge have been reported from the Sør Rondane Mountains (van Autenboer et al., 1964), Dronning Maud Land (Schytt, 1961) and Tottenfjella (Arduz, 1964). All these are mountain areas within a few hundred kilometres of the coastline, and the ice profiles would be expected to be well adjusted by now to budgetary changes thousands of years ago, so that a steady state rather than growth seems more likely. Also, Schytt argues that the locally extensive moraines on the ice show no sign of a "bulging" that might represent growth, for example towards surges. On the other hand, the fact that these areas are all close to one another suggests that something in common may be causing the ice in them to thicken a little. Suppose the world-wide warming by about 1°C between say 1875 and 1940 A.D. (for evidence supporting this in Antarctica see Hollin, 1962a, p. 180) and the associated circulation changes caused a roughly 20 per cent increase in accumulation in these areas (for evidence for such an increase in parts of Antarctica but against it for the continent as a whole see Hollin, 1962a, p. 184, and Giovinetto and Schwerdtfeger, 1966). The accumulation in these areas is of the order of 20 g cm\(^{-2}\) yr\(^{-1}\), so that an increase of 20 per cent sustained over the 65 yr above would have caused a build-up by 2.6 m, perhaps increased by drifting in some parts of the mountains.

If it can be shown, perhaps by excavation, that patterned ground, etc. continue for greater distances under the ice, this will suggest a growing ice sheet. Cavernous weathering at Mount Chapman in the centre of west Antarctica (Koerner, 1964) does in fact appear to continue under the ice.
However, a difficulty with cavernous weathering and perhaps with patterned ground is that they may survive being over-ridden by "cold" glaciers, and may therefore reappear after a retreat to suggest a non-existent advance. Such a survival appears to have occurred in the Sør Rondane Mountains, where van Autenboer found erratics in the cavernous hollows, and this is a point that should be noted in future studies.

(2) The dry valleys of south Victoria Land show signs of glaciation from three sources: from the east, possibly by a Ross Ice Shelf grounded by the sea level falls during the northern glaciations; from local valley glaciers; and from the west, from the high polar plateau and the ice sheet centre. A preliminary report by Denton and Armstrong (1968) says that "Interpretation of radiocarbon dates . . . suggests that the last expansion of Ross Ice may possibly fall within late Wisconsin time. . . . Following dissipation of Ross Ice from McMurdo Sound, both Taylor and Wright Glaciers have expanded to their present positions, which are more advanced than any attained throughout the time span required for the last two major expansions of Ross Ice." Further reports may show whether these glaciers are steady now or still advancing. Berg and Black (1966) suggest that the Beacon Valley lobe of Taylor Glacier is steady now (but on a time-scale of only 200 yr) following an advance for almost 2000 yr, but their ice-wedge growth dating technique is still at an early stage of development. A. T. Wilson (1969) concludes that Wright Glacier must be advancing, because there is much less salt in front of it than would have accumulated (from its melt water) if it had been steady for hundreds of years. It could be argued that this is because the glacier is retreating rather than advancing, but Denton and Armstrong’s and Berg and Black’s results amongst others are against any current retreat in this area. Since the Taylor and Wright glaciers are fed from the west, from the high ice sheet, this suggests that the latter may be growing. If it can be shown that any advances from the west occurred only since 18,000 BP, this will favour a post-18,000 accumulation increase as their cause. If it can be shown that they were in progress before 18,000 BP, this will favour a build-up for a surge as their cause.

Taylor and Wright glaciers are fed from a part of the ice sheet which is almost within the "Western part of the Ross Ice Shelf drainage system", for which Giovinetto et al. (1966) have found a probably positive mass budget (see below). Therefore, the following calculation may be useful. Giovinetto et al. found a mean accumulation over their basin of 5.5 g, and a mean discharge equal to half the accumulation. This suggests a possible build-up of say 3 cm yr$^{-1}$ in this area. From the high ice sheet, the glaciers fall into the valleys roughly 2000 m in 50 km, i.e. with a general profile of 1 in 25. If this profile is conserved, the build-up will cause an advance of 75 cm yr$^{-1}$. There are numerous reasons why the profile is probably not conserved, but the calculation gives some very rough idea of what to look for in the dry valleys.
(3) Estimates of the mass budget of the whole ice sheet and shelves remain uncertain, chiefly because of the difficulty of estimating the amount of calving and of bottom melting beneath the ice shelves. For example, Bardin and Suyetova (1967) found a total annual accumulation of 2420 km$^3$ of ice and an ablation of 1450 km$^3$, giving a surplus (such as most other workers have found) of 970 km$^3$; however, they noted possible errors of 960 km$^3$ in the data. In this situation, it may be more useful to study individual drainage basins in more detail, and this has been done now for four of them: the Western Ross system of Giovinetto et al. mentioned above, the Lambert Glacier area (Budd et al., 1967), part of Terre Adélie (Lorius, 1962), and part of Wilkes Land (Budd, 1966). In each case there was an apparent budget surplus: in the first two cases well over the probable error. The results of Giovinetto et al., and Budd et al. are particularly useful: first because they were able to measure the outflow at points near the "grounding line" (where the ice begins to float), so that the problem of bottom melting was almost avoided; and second because they were able to describe their probable and possible errors in some detail, so that the criticism by Bauer (1967) seems unjustified. For their point G3, Budd et al. found that the accumulation upstream might be many more than three times the outflow. If a result such as this were to be substantiated by future work, it seems to this author that it would be unlikely to be due to any conceivable accumulation increase, and would favour a build-up towards a surge.

(4) If the ice sheet or parts of it are thickening, then sea level should be falling. A valuable discussion of sea level changes during the last 10,000 yr, more especially in the last 6000 yr or so since the northern ice sheets finally disappeared, has been published by Jelgersma (1966). She points out that the differing data available (chiefly radio-carbon dates on coastal shells and peats) have led to three schools of thought: that the sea level has in general fallen and oscillated, that it has remained roughly steady, and that it has continued to rise. Of the data she quotes in her paper, those supporting a falling sea level, by roughly 3 m, are actually more widespread, from New Zealand, Australia, Ceylon and North Africa, than those supporting a rise, by several metres, which are chiefly from the Netherlands and the Gulf Coast of the United States. However, Jelgersma does not favour the falling data because most of them come from where there are mountains near the coast, and she favours the locally more detailed results from the Netherlands and Gulf.

As more data accumulate on the question of sea level during the last 6000 yr, the anomalous results, due for example to collecting errors or tectonic movements, should fall out naturally. Meanwhile, however, dates favouring a fall do continue to appear: it is impossible to assess these here, but for example dates of a few thousand years BP on beaches up to a few metres in Brazil (van Andel and Laborel, 1964) and Senegal (Elouard et al., 1967) illustrate the points that these dates are widespread and do not
all come from mountainous areas. It seems to the author that the truly anomalous results in Jelgersma's discussion may be from the Netherlands and Gulf, for the reason that these may be within the much discussed ice-marginal "peripheral bulges", collapsing now as mantle material flows back northwards to the isostatically rising areas of the Baltic and Hudson's Bay. (For the Netherlands at least, this is not a new idea).

The argument that a marginal bulge may extend as far as the Gulf meets no difficulty as far as the volumes of rock involved are concerned. A recent estimate of the ice age ice mass by Voronov (1964) suggests $30 \times 10^6$ km$^3$ for North America and Greenland combined. We may subtract $2.6 \times 10^6$ for the mass remaining in Greenland (Bauer, 1955). Let us assume a mantle to ice density ratio of 3.5. Even if the ensuing bulge did extend from the ice margin out to the radius of the Gulf, its average thickness would have been over 250 m. In practice of course some of the isostatic depression that caused the bulge would have been accommodated by elastic compression and perhaps by phase change, so that the thickness above is a maximum. Also, the bulge would have been highest near the ice and lower towards the Gulf. But this draws attention to some field data favouring the bulge argument: that the apparent sea level rise or land sinking appears to increase northwards from the Gulf through Virginia and New Jersey (Scholl and Stuiver, 1967, Fig. 7). As far as the mechanical feasibility of a wide bulge is concerned, Burgers and Collette (1958), in an early study of the collapse of the bulge around the smaller Scandinavian ice sheet, suggested for after 5770 B.C. a sinking of up to 12 m at the maximum radius (2916 km) to which they took their calculations.

The discussion above suggests another sea level test for Antarctic build-up. If there has indeed been a world-wide fall of say 3 m because of this, then because the area of the sea is roughly thirty times that of Antarctica this implies an average build-up of 90 m. This in turn implies an isostatic outflow of up to 30 m. This raises the possibility, mentioned earlier, that some of the raised beaches around Antarctica may be due to an Antarctic marginal bulge rather than to the last major retreat; and that, further north, the sometimes unusually high Post-glacial sea levels there, e.g. 4-5 m on Kerguelen (Bellair, 1966), may be due to this. Post-glacial sea levels around Antarctica should be studied with this possible bulge in mind, first because it is another test for the build-up, and second because the effects of it would have to be subtracted from the local evidence for a world-wide fall.

Turning from the local data bearing on sea level, it may be noted that the only two more general approaches to the problem, by Schofield (1964) and Munk and MacDonald (1960) both suggest a fall. Schofield's method is summarized in his abstract: "The altitudes of dated shorelines in parts of Fennoscandia result from the algebraic sum of isostatic emergence and eustatic submergence. As the isostatic emergence differs systematically from place to place, the eustatic rise can be calculated within narrow limits." He found a sea level between 2.6 and 6 m above the present
4000 yr ago. Munk and MacDonald, analysing ancient eclipse data, found a residual change in the length of day which seemed best explained by a fall of sea level by 2 m in the last 2000 yr. McConnell (1968), in a paper which should be valuable in analysing the mechanical feasibility of a wide marginal bulge, implied that this change in the length of day might be explained by the collapse of marginal bulges extending right to the Equator. However, the previously mentioned evidence from Brazil and Senegal that the land there has been rising (relative to sea level) is, at first sight, against this.

In summary, the references and arguments above suggest a possible overall sea level fall of say $4 \pm 2$ m (the author prefers the lower values) during the past 4000 yr, probably with minor oscillations. However, the possibility has now to be examined that such a fall might have been the result, not of a specifically Antarctic build-up, but of a world-wide glacial build-up, especially in Greenland, by a decrease of ablation following the Post-glacial "Hypsithermal" warm peak. This is a large problem beyond the scope of this paper: it could be solved, probably, by compiling the evidence of glacial variations, filling in the gaps by means of glacio-meteorological calculations, then adding up the ice masses involved. But one preliminary argument against this possibility is that the detailed brief climatic variations within the period since 4000 BP, although they were almost as large as any in post-Hypsithermal time, (see e.g. Ahlmann, 1953), have had no large, unambiguous effect on the detailed sea level record (Porter and Denton, 1967). Another possible cause of a fall, by up to 1 m, may have been a post-Hypsithermal cooling and contraction of the oceans (Munk and Revelle, 1952).

Finally, however, note the possibility that the glacial and temperature controls on sea-level discussed above may in fact have been overshadowed by a completely different control: by the delayed isostatic response of the oceans and continents to the post-18,000 BP loading of the former with 100 m of melted ice. Bloom (1967) considered the possibility that the loading might have caused a locally varying submergence at the coasts, and he has emphasised the detailed data favouring a rising sea-level. Wellman (1964) thought that the movement of material up under the continents might have caused emergence at the coasts, and be the explanation for the falling sea-levels emphasised in this present paper. Both these effects might be measured in metres, and until their relative importance is evaluated it may be impossible to find the true Antarctic component of sea-level change. For note that this may be small. For example, a budget surplus as large as 50 per cent in the arid central 1/3 (average accumulation 4 g cm$^{-2}$ yr$^{-1}$) of the continent where any build-up is likely to be concentrated would have caused a sea-level drop of only 60 cm in 4000 yr.

(5) Evison (1967) argues that the singular aseismicity of Antarctica is caused by a build-up of the ice sheet. He thinks that the increasing pressure of the ice is inhibiting earthquakes by increasing the normal stress
across fractures, and by restricting the polymorphic volume expansions possibly involved in some earthquakes.

(6) Temperature profiles from the upper parts of the ice sheet should show whether its elevation is increasing. Robin, in a paper in this Symposium, concludes that the elevation at Byrd Station is not changing by more than ± 10 m/10^3 yr. For the Byrd accumulation rate of 15 g cm^-2 yr^-1, this means a budget imbalance of less than 7 per cent. But, in another paper at the Symposium, he feels that downstream from Byrd Station the presence of a large body of trapped water beneath the ice favours a growth of the ice sheet there. Research is continuing in the Byrd drainage basin.

(7) A Franco-Soviet expedition has established and measured six strain pentagons in the centre of the east Antarctic ice sheet (Shumsky and Bauer, 1965). Remeasurement of these should show whether the ice is stretching at the rate required to dispose of the accumulation, or whether it is thickening or thinning.

(8) Deep coring studies, such as that which has reached the ice base at Byrd Station (Gow, 1968), should yield information on the ice history of Antarctica for tens or hundreds of thousands of years. Isotope, chemical and particulate studies should show the age of the ice recovered. Before this can be used to determine the accumulation rate, a correction will have to be made for the unknown vertical strain rate in the ice. This should be appreciable, and it should be possible to design an instrument to actually measure it. Eventually, from such studies, it should be possible to see if there has in fact been an accumulation increase in Antarctica. Of course, the discovery of such an increase would not rule out the possibility of a build-up for a surge. Evidence of past surges should show up in the cores as a gross disturbance of the stratigraphy, and in particular as an anomaly in the oxygen-isotope record of temperature, because of the sudden elevation change involved in a surge.

(9) For the future, Mercer's (1962) suggestion should be kept in mind, of establishing many more fixed points near the ice edge, from which the exact boundary and elevation of ice lobes can be measured. This is something that can be done by any small party that happens to be working in the mountains or oases.

(10) Perhaps more could be done with gravity in Antarctica, either to look for a long-term sinking at individual ice or rock points, or to isolate isostatic anomalies from the general data. Up to now, no such anomalies have been found, but of course they would be small, because any build-up would be slow compared with the isostatic response.

Review of the possible causes for a thickening

None of the evidence above proves that the Antarctic ice sheet is thickening. However, the mass budget data in particular do strongly suggest a build-up in at least two separate drainage basins. The sea level data may support a build-up but, at the same time, the maximum probable
fall of say 4 m in 4000 yr suggests a maximum budget surplus of 25 per cent for the ice sheet as a whole (1 mm yr\(^{-1}\) sea level fall = 30 mm Antarctic build up, which from 150 mm yr\(^{-1}\) present accumulation leaves 120 mm discharge). Obviously all the investigations above should be intensified, and I hope that this paper will stimulate new investigations: perhaps there is some simple test for build-up that has so far eluded us.

As was mentioned at the beginning, the simplest and most likely causes for a thickening seem to be a post-18,000 BP accumulation increase or else build-ups for a surge. From the numerous factors discussed by Hollin (1962a), it is possible to select more complex reasons: for example, an accumulation increase might, by increasing the flow of cold into the ice sheet, be simultaneously reducing its velocity. However, by the time the field evidence justifies speculations as complex as this, it will be possible to test their validity on computer models of the thermal and mechanical state of the ice sheet.

Looking ahead, suppose that deep coring studies show that there has indeed been an accumulation increase over Antarctica as a whole. The theoretical response to this increase can be calculated then by the methods of Nye (1963). This will show if the build-up can account for the latest data on the possible fall of sea level. If it cannot, this will concentrate our attention on particular drainage basins, where the possibility of build-ups for surges or other reasons can be studied by mass budget, surface strain, deep temperature and glacial geological methods. Note incidentally that a build-up does not imply a stagnant ice sheet: merely one that grows at a non-steady state, until it finally surges or otherwise adjusts itself.

In a separate paper (Hollin, 1969), the author has summarized some evidence from the past, particularly from the Carboniferous, suggesting that ice sheet surges can in fact occur. This should encourage us to continue the search for evidence for and against an Antarctic thickening.

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**References**


