The Water Budget in Antarctica

F. LOEWE

Institute of Polar Studies, The Ohio State University,
125 South Oval Drive, Columbus, Ohio U. S. A.

Abstract: Nearly the whole Antarctic ice sheet, including the attached ice shelves, shows a net accumulation. Factors other than precipitation influence the budget only to a small degree. In the inner parts of the ice sheet it is frequently difficult to establish the annual accumulation. Determinations by isotope frequency do not always agree with those derived from stratigraphic evidence. A mean accumulation of 15 cm water equivalent corresponding to 1900 gt/year (1 gt = 1 gigaton = 1 km^3 water) is rather on the low side.

The loss by runoff of meltwater or by evaporation in the border regions of prevailing ablation is small, 10 gt/year. The open ice sheet moves slowly; the ice loss is 50 gt/year. Glaciers move with varying speeds; an estimate of 520 gt/year from glaciers and ice streams is rather high. Ice shelves surround one-half of the continent. A high estimate gives 880 gt as their productivity. Some melting will occur at the bottom of the floating ice shelves and glaciers. The amount is not well known; it is estimated at 200 gt/year but will hardly exceed 300 gt/year. With a total loss of 1660 gt/year the final balance is slightly positive. In view of the uncertainties, gain and loss might be equal, but the budget will not be markedly negative. With the ice sheets of Antarctica and Greenland in balance, the present rise of sea level can be caused by the mass loss of the mountain glaciers combined with a warming of the ocean.

Introduction

The Antarctic ice sheet, which covers almost the whole Antarctic continent and the ice shelves attached to it, contains water in the solid state of the order of 25 million km^3, nine-tenths of the glacier mass on earth[40,48]. This body of ice exchanges continuously its mass with the atmosphere above and with the ocean outside the continent. Compared with the total ice mass involved, the exchange is slow, comprising about 1/10,000 of the mass per year. Some of the Antarctic ice will stay on the continent for the order of 100,000 years, the length of one of the periods of Quaternary ice extension. For this reason the response of the ice sheet in the extension and height to changes in the water budget will be sluggish; an overall imbalance might take a long time to influence the configuration of the ice edge[19]. The mass budget of the Antarctic ice sheet comprises addition and removal of ice. If the annual budget is considered, as will be done in the following discussion, the regions of prevailing addition—the accumulation area, and those of prevailing removal—the ablation area, are rather clearly separated. In the following discussion the Antarctic Peninsula north of a line from the western end of the Filchner Ice Shelf to the southern entrance to George

VI Sound will not be considered; it represents a rather independent unit in its glaciological regime.

A. Accumulation

The greatest part of the Antarctic ice sheet is a region of prevailing accumulation. Away from the borders, regions of bare rock or of prevailing ablation are overall of almost negligible size. The accumulation derives from the atmosphere. Part of such deposition might subsequently be removed from the surface by evaporation[28] and by snow drift[34]. Moreover, at the bottom of the ice sheet a small amount of ice, possibly a few mm per year, might be transformed by geothermal heat and friction into meltwater, and a small part of it might even reach the ocean[26,52].

Under Antarctic weather conditions reliable measurements over extended periods of precipitation from the atmosphere have hitherto proved impossible, and the likely values of precipitation will have to be indirectly established. There are, on the other hand, different ways to determine the accumulation which is the really important item in the annual water budget. Measurements of accumulation include, besides precipitation, the effects of rime formation, sublimation, snow drift and runoff; they need not singly appear in the mass budget but must be known if precipitation is to be determined from measurements of accumulation. Over extended regions of the accumulation area, evaporation and rime formation, and particularly their difference, are smaller than the accumulation by an order of magnitude[27,28,35,36]. Locally the mass transfer of blowing snow can be of considerable importance in the mass budget[6,34]. Extrapolation of accurate measurements of snow drift with wind speeds to 25 m/s to the conditions south of Port Martin in Adelie Land where stronger winds prevail for a quarter of the time, give an annual transport of the order of 200 million tons per km of coast. This may, however, be several times too high as with the highest speeds the drift might not be able to remove enough snow to produce "saturated" drift condition. As the height and density of the drift snow increases strongly with increasing wind speed, at places with more moderate wind the transport is much weaker. On the average the annual mass loss by drifting snow might be only 3–4 million tons per km of coast line; this represents only a few percent of the accumulation. Altogether in the area of prevailing accumulation the actual precipitation is slightly bigger than the measured accumulation[24]. This does not apply to a narrow border zone in which the net accumulation is only small because ablation prevails seasonally.

Accumulation is measured in snow and firn by stakes[44] and by stratigraphic studies in pits and of drilled cores. The determination of isotope frequencies gives information even in outwardly structureless ice. The isotopes show a seasonal variation or give by the identification of artificial isotopes from nuclear explosions at least a reference level. In the greater part of the interior, melt layers are absent, and it becomes difficult to detect the annual stratification. Small differences in the relation between wind and slope cause at short distances big changes in accumulation[49]. In regions of very small accumulation—less than 5 cm of water per year in the innermost parts—or of very heavy winds like the slopes near 140°E, the wind might be able to remove locally all the accumulation of one year. In order to obtain a representative value it becomes necessary to use a considerable number of well-distributed stakes. The variations of the stable isotopes (D, O^{18}) do not always agree satisfactorily with the visually fixed annual stratification[38]. This is not surprising. The isotope proportion in the ice depends upon the temperature at which in the atmosphere crystallization has occurred. This can vary very much even within the same season on account of temperature changes at one level and of different levels of crystallization[30,31]. The annual temperature variation at cloud level is much smaller than near the surface (Byrd Station monthly means at 3 km, 10°, at the surface, 25°), resulting in smaller isotope differences; moreover the mean temperature of solidification might systematically differ from the general mean of the month at that level. For instance, at Vostok (78°S, 107°E) and Pionerskaya (70°S, 96°E), temperatures at 5 km are on overcast days slightly higher than on clear ones.

In view of the rarity of direct observations of accumulation, an indirect method can be tried. The accumulation appears outside the border regions rather closely related to the mean annual temperature of the air[7] which is close to the firn temperature at a depth of 10 m[33]. The latter has been measured at many places; 256 observations of temperature and accumulation give the relation $\log_{10} A = 1.95 + .0235\, t$, where A accumulation in $g\,\mathrm{cm}^{-2}\,\mathrm{year}^{-1}$, t annual temperature in °C. This gives a mean accumulation of 13–14 cm water[33].

For all these reasons the amounts of the annual accumulation in the accumulation area are not yet quite definitely established. Recent estimates tend toward a mean value of 15 cm of water per year; this is probably rather too low than too high[16,23,32,35]. It gives, with an area of prevailing accumulation of $12.6 \times 10^6\,\mathrm{km}^2$, about 1.9×10^{12}t or 1900 gigatons (gt), with 1 gt = 1 km^3 of water. This is less than 1/10,000 of the ice mass of Antarctica.

B. Ablation

The presence or absence of surfaces of prevailing ablation along the coast depends much more upon slope and gravity wind than upon the temperature. Locally the ablation of ice—even the warmest parts of the coast have only 600–700 hours above freezing point in the year—by melting and evaporation can amount to 50 cm per year[10,32]. But compared with the whole extent of the Antarctic ice sheet the regions of prevailing surface ablation are small. The accumulation area extends in most parts right to the coast, and includes also the horizontal ice shelves. It is also important that the bulk of the ice is right to the coast at a temperature below freezing point. Meltwater that is not formed quite near the edge and which disappears into crevasses freezes again and does not contribute to the loss of mass. A loss by runoff and evaporation of 10 gt, corresponding to 22 cm of ice ablated from a 5 km wide ring around half the continent, is probably much too high, but still remains quite insignificant compared with the accumulation. This is different from the conditions of the Greenland ice sheet on which runoff removes more than half the accumulation, and of the former Quaternary ice sheets.

The Antarctic ice sheet borders along most of its circumference directly on the ocean. The extent of rock as a coastal feature is quite small, at best a few hundred kilometers, including parts of the coast skirted by a permanent icefoot which, however, does not drain the ice sheet itself. Except at isolated places, like the ice-free valleys of South Victoria Land, ice moves everywhere outward and is ultimately removed. Part of it will be detached as ice and part of it will be melted. The amount of melting along the ice fronts is unknown. During part of the summer the sea water can locally reach temperatures above 0°C[55]. Moreover melting of sweet water ice can also occur in the saline sea water at a lower temperature. But the amount of melting would only be of interest if the loss of mass of the ice sheet was otherwise determined from the size of detached icebergs, for instance by aerial photography. This has been attempted only exceptionally[14].

In most cases the loss has been estimated from the speed of the ice motion measured near the edge of the ice[2]. For this purpose generally three types of the ice border have been distinguished, the ice sheet proper, ice streams and valley glaciers, and floating ice shelves. The ice sheet forms the coast for 10,500 km, the ice shelves for the same distance, and outlet glaciers for about 3000 km[3,35]. This refers to the length of the active coast line. Small indentations and promontories have been excluded.

The ice sheet itself has a small velocity. An insufficient number of measurements close to the coast exists; published ones give mainly values of 25–50 m per year[33]. A mean speed of over 200 m/year as recently assumed, is very likely to be too high[12]. The thickness of the ice sheet can be estimated from the height above sea level; with a mean height of 25 m and a proportion of the protruding to the submerged part of 1:4.5, corresponding to a mean density of 0.84, the mean height of the ice front is 140 m. This gives with a mean speed of 40 m/year an annual discharge of 62 km^3 or about 50 gt, a small amount.

The ice streams move with considerably higher velocities which vary, however, considerably. The frontal movements of a number of them have been surveyed. The speeds show only a slight correspondence with the width of the glaciers. The highest measured velocity is 1400 m/year on the Denman Glacier, 99°E[8,12]; no known Antarctic glacier approaches the speed of some big ice streams in Greenland. The reason for the difference is not known. Near the fronts of many Antarctic glaciers depressions and embayments extending at right angles to the movement follow each other at rather uniform distance. This is shown in striking photographs from the air[12]. It is claimed that the width of these ribbons represents the displacement during one year, similar to the ogives of mountain glaciers. The speed of many glaciers between 45°E and 160°E has been derived from their spacing. In some cases the speeds found from these morphological features correspond reasonably well with directly measured movements near the front. It is, on the other hand, not easily understood why Antarctic glaciers should have such annual rhythm. The Store Qarajaq Glacier, an outlet of the Greenland ice sheet and in every respect comparable to the big Antarctic ice streams, has no marked seasonal variation of speed[13]. The reasons given for the seasonal variations of speed in temperate glaciers, varying bottom and internal friction on account of meltwater or the pressure changes caused by seasonally varying accumulation and ablation, hardly apply in the Antarctic. Nor will the presence or absence of sea ice near the front be able to markedly affect the motion.

It has been suggested that as these depressions and cracks in the glacier are zones of weakness, icebergs will separate preferentially along these lines. If they are annually recurring features, it might be possible to determine the annual advance of the glacier from the width of the detached icebergs[14]. Where a comparison with direct measurements of displacement has been possible, the correspondence is rather satisfactory. A mean annual speed of the ice stream fronts of 400 m is probably not far from the truth. The thickness of the glacier fronts is rather little known. A mean height above sea level of 40 m leads with a density of 0.88 to a total thickness of 300 m. As the floating glacier tongues have a tendency to spread and thin, this might be too small. Observations from the western side of the Ross Ice Shelf give considerably higher values[47]; but the presence of the thick Ross Ice Shelf must dam the glaciers back. Three thousand km of ice stream front gives with a speed of 400 m/year and a thickness of 500 m, 600 km^3/year or 520 gt/year.

Better knowledge of the border of the Antarctic ice sheet during the last twenty years has shown that floating ice shelves girdle almost one-half of its coasts. Some measurements of their speed exist. The big ice shelves show a considerable motion. Recent measurements give for the eastern half of the Ross Ice Shelf, 800 m, for the western, 1500 m per year; the latter value is probably too high[41,42,53]. A mean of 1000 m might be used. The Filchner Ice Shelf has at the eastern part of its border comparable speed, from 1100 to 1500 m per year[25]. No measurements exist for the bigger western part. The Amery Ice Shelf has near its edge a speed of 1200 m/year[4,5]. The smaller ice shelves move considerably less

Table 1. Water budget (in gt) of Antarctic ice sheet.

Accumulation	Ablation	
1900	Melting and evaporation	−10
	Ice sheet	−50
	Glaciers	−520
	Ice shelves	−880
		−1460
	Bottom melting	−200
		−1660

fast; the Maudheim Ice Shelf about 300 m/year[45], the Brunt Ice Shelf not quite 400 m[1]. As the greater part of the ice shelf fronts belong to narrow shelves, a mean speed of 500 m/year will not be too small. The thickness of the ice shelves near their border is of the order of 200 m. With a length of 10,500 km, the shelf ices produce 1050 km^3/year, or, with a density of 0.84, 880 gt. Thus the water balance of the Antarctic ice sheet becomes so far (in 10^9t or gigatons)(Table 1):

The tentative budget closes with a deficit of 440 gt; one-quarter of the accumulation is excess. It should be stressed that the estimate of accumulation is among the lower ones while the ablation values of Table 1 are rather on the high side. Nor does it appear likely that the "productive" ice border is longer than 24,000 km.

One item is, however, still missing from the ablation side of the budget. There may be some melting on the lower side of ice shelves and floating ice tongues[39]. Undoubtedly even with a very weak circulation of sea water below the ice shelves, enough heat for considerable melting would be available[43]. The question is, how far inward such circulation could extend. Direct observations of the melting rate do not exist. Some ice shelves might increase even near the front by ice accretion at the bottom[11,18]. This has been claimed for parts of the McMurdo Ice Shelf, but it has recently been doubted because as drilling cores show, the shelf consists throughout of sweet water ice[17]. There seems to be agreement that the melting rate decreases toward the interior of the ice shelves.

It might be possible to determine the rate of melting indirectly. If the strain rates at the surface of the ice shelf are measured, it becomes possible, under far-reaching assumptions, to determine the thinning of a floating ice shelf[1,53,54]. The difference with the actually-observed thickness changes might allow calculation of the melting rate at the bottom. It has also been suggested that by establishing the heat budget of a floating ice shelf, it might become possible to determine the heat available for bottom melting and hence the melting rate itself[21,51]. Recent estimates give near the edge of the Ross Ice Shelf an annual ablation of 60 cm water equivalent[9], and a similar value for the Maudheim Ice Shelf[46]. Smaller rates are given for the Brunt Ice Shelf in the Weddell Sea[1]. The melting might vanish in the Ross Ice Shelf 70 km inward from the edge. In the inner parts of the bigger ice shelves, melting might even be replaced by accretion; but the sweet water ice at the lower surface of the ice shelf near its edge means that there must be a net loss of substance below the shelf. We estimate a mean loss by melting of 25 cm water over a width of 60 km along 10,500 km of ice shelves. This gives 155 gt. We use the higher value of 200 gt. Other estimates go as high as 300 gt. It follows that even with addition of bottom melting the budget of the Antarctic ice sheet will hardly balance. The mass of the Antarctic ice sheet seems at present to increase. It should be pointed out again that the estimates of gain were on the low side, those of loss generally on the high side. In view of the uncertainty of the basic data, particularly of the speed of the ice shelves and of the rate of melting at their lower side, it might still be possible to arrive at a balanced budget. About the same condition seems at the moment to exist in the mass economy of the Greenland ice sheet which also appears to be in a balanced state[29] notwithstanding a tendency to frontal recession of some outlet glaciers[50]. But it appears almost impossible to arrive at a loss of mass of the Antarctic ice sheet comparable with that of the mountain glaciers of the world during the last century.

If the mass of the two big ice sheets on earth remains stable, it seems unlikely that the annual rise of sea level of about 1 mm can be explained by the diminution of the rest of the land-based ice. All glaciers and smaller ice sheets would have to lose the equivalent of 60–70 cm of water each year and would completely disappear in 500 years. But it will be admitted that European glaciers lose at present substance at about this rate[15,20,22,37,56]. A rise of sea level might also be due to other reasons than an increase in the mass of water, for instance a tectonic lift of part of the oceanic floor or a relatively small rise in oceanic temperatures which has indeed been observed in some parts of the ocean[27].

We arrive at the conclusion that at first sight the Antarctic ice sheet seems to have a positive mass balance; more ice is collected than removed. Some of the items of the budget are still uncertain and a case can be made for a balanced Antarctic ice budget. But it appears very unlikely that the Antarctic ice sheet loses at present mass at a rate comparable to that of the mountain glaciers. The rise of sea level can be explained without a mass contribution from the Antarctic ice sheet.

References

1. ARDUS, D. A.: Surface deformation, absolute movement and mass balance of the Brunt Ice Shelf near Halley Bay. Brit. Ant. Surv. Bull., **6**, 21–41, 1965.
2. BARDIN, V. I. and V. I. SHILNIKOV: Productivity of East Antarctic coast. Sov. Antarct. Exped. Inf. Bull., **23**, 28, 1960.
3. BARDIN, V. I. and I. S. SUYETOVA: Length of Antarctic coast line. Antarctic, March 1965, p. 31.
4. BUDD, W.: Glaciological survey of the Amery Ice Shelf. Antarctic, **4** (3), 158–159, 1965.
5. BUDD, W.: The dynamics of the Amery Ice Shelf. J. Glaciol., **6** (45), 335–358, 1966.
6. BUDD, W., R. DINGLE and U. RADOK: The Byrd snow-drift project. Outline of basic results. Am. Geoph. Union, Ant. Res. Series, **7**; Univ. Melbourne, Meteol. Dept., Publ. **6**, 1966.
7. BULL, C.: Mean annual surface temperature. Antarctic Map Folio Series. Folio 2. Physical characteristics of the Antarctic ice sheet, map. 5. American Geographical Society, 1964.
8. CHEREMINKH, G. D.: Some additional remarks to the methods of determination of movement velocities of the glacier surface according to the materials of the aerophotosurvey. Results of the Researches in the Program of the IGY. Glaciol. Res., **9**, 179–182, 1963.
9. CRARY, A. P. and H. CHAPMAN: Additional glaciological measurements at the abandoned Little America station, Antarctica. J. Geophys. Res., **68**, 6064–6065, 1963.

10. CROHN, P. W.: A contribution to the geology and glaciology of the western part of Australian Antarctic Territory. ANARE Reports, Ser. A, **3**, 103 p., 1959.

11. DEBENHAM, F.: A new mode of transportation by ice. The raised marine muds of South Victoria Land. J. Geol. Soc. Lond., **75**, 51–76, 1920.

12. DOLGUSHIN, L. D.: Movement velocities of the Antarctic glaciers according to repeated aerophotosurveys and morphological data. Results of the Researches in the Program of the IGY. Glaciol. Res., **9**, 164–178, Moscow, 1963.

13. DRYGALSKI, E. VON.: Grönland-Expedition der Ges. f. Erdkunde zu Berlin 1891–1893. p. 276, Berlin, 1897.

14. EVTEEV, S. A.: Approximate computation of glacier velocity from the width of the icebergs produced. Sov. Antarct. Exped. Inf. Bull., **19**, 251–252, 1960 (Elzevier, 1965).

15. FINSTERWALDER, R.: Measurements of glacier variations in the eastern Alps, particularly in the Gurgl area. Int. Ass. Scient. Hydrol., Commission of Snow and Ice, Symposium of Obergurgl. Publ. **58**, 7–15, 1962; Discussion in IASH Bull. 8 (2), 57–58, 1963.

16. GIOVINETTO, M.: The drainage systems of Antarctica: Accumulation. Am. Geophys. Union. Antarct. Res. Ser., **2**, 127–155, 1964.

17. GIOVINETTO, M., E. S. ROBINSON and C. W. M. SWITHINBANK: The regime of the western part of the Ross Ice Shelf drainage system. J. Glaciol., **6** (45), 55–68, 1966.

18. GOW, A. J., W. F. WEEKS, G. HENDRICKSON and R. ROWLAND: On the mode of uplift of the fish and fossiliferous remains of the McMurdo Shelf, Antarctica. CRREL Res. Rep., **173**, 16 p., 1963.

19. HAEFELI, R.: Welche Zeit ist notwendig, um unter gegebenen Akkumulations-und Ablationsverhältnissen einen Eisschild von der Grösse des grönländischen Inlandeises oder der Antarktis aufzubauen? Polarforschung, **33**, 176–178, 1963.

20. HOINKES, H. and R. RUDOLPH: Mass balance studies on the Hintereisferner, Ötztal Alps, 1952–1961. J. Glaciol., **4** (33), 266–280, 1962.

21. JENSSEN, D. and U. RADOK: Heat conduction in thinning ice sheets. J. Glaciol., **4** (34), 387–397, 1963.

22. KASSER, P.: Notes on the new map of the Aletsch Glacier. Bull. Int. Ass. Scient. Hydrol. 8 (2), 113–114, 1963.

23. KOTLYAKOV, V. M.: The measurement of mass accumulation of the ice cover in Antarctica. Glac. Research Symp., Section 9 of IGY program. Glaciology, **5**, 7–26, Acad. of Sciences USSR, Moscow, 1960.

24. KOTLYAKOV, V. M.: On the relationship between precipitations and their accumulation on Antarctic ice sheet. Results of Researches in the Program of IGY. Glaciol. Res., **13**, 12–18, 1964.

25. LISIGNOLI, C. A.: Movimento de la Barrera de Filchner, Antartida. Instituto Antartico Argentino. Contribucion No. **81**, 17 p., Buenos Aires, 1964. (Transactions Am. Geophys. Un., **45**, 1964).

26. LLIBOUTRY, L.: Bottom temperature and basal low velocity layer in an ice sheet. J. Geophys. Res., **71**, 2535–2544, 1966.

27. LOEWE, F.: Beiträge zum Massenhaushalt des antarktischen Inlandeises. Pet. Geogr. Mitt., 269–274, 1961.

28. LOEWE, F.: On the mass economy of the interior of the Antarctic ice cap. J. Geophys. Res., **67**, 5171–5177, 1962.

29. LOEWE, F.: Das grönländische Inlandeis nach neuen Feststellungen. Erdkunde, **18**, 189–202, 1964.

30. LORIUS, C.: Obergurgl Symposium, Discussion. Bull. Int. Ass. Scient. Hydrol., **8** (2), 102, 1963.

31. LORIUS, C.: Le Deuterium, possibilités d'application aux problèmes de recherche concernant la neige, le névé et la glace dans l'Antarctique. Comité National Français des Recherches Antarctiques, **8**, 102 p., 1963.

32. MELLOR, M.: Mass balance studies in Antarctica. J. Glaciol., **3** (26), 522–533, 1959.

33. MELLOR, M.: Remarks concerning the Antarctic mass balance. Polarforschung, **5**, 179–180, 1963; more fully mimeographed.

34. MELLOR, M.: Blowing snow. Cold Regions Science and Engineering. Part III, Sect. A 3c, 79 p., Cold Regions Research and Engineering Laboratory, Hanover, 1965.

35. RUBIN, M. J.: Atmospheric advection and the Antarctic mass and heat budget. Am. Geophys. Un., Geophysical monograph, **7**, Antarctic Research, 149–159, 1962.

36. RUSIN, N. P.: Evaporation and condensation in Antarctica. Bull. Inst. Arct. Antarct. Sci. Res., **13**, 17, 1959.

37. SCHYTT, V.: Mass balance studies in Kebnekajse. J. Glaciol., **4** (33), 281, 1962.

38. SHARP, R. P. and S. EPSTEIN: Comments on annual rates of accumulation in West Antarctica. Ass. Int. Hydrol. Scient., Commission des Neiges et Glaces. Symposium d'Obergurgl, Publ. **58**, 273–285, 1962; Bull. Ass. Int. Hydrol. Scient., **8** (2), 101–102, 1963.

39. SHUMSKIY, P. A, and I. A. ZOTIKOV: On the mass and heat exchanges on the Antarctic ice shelves. Int. Ass. Scient. Hydrol., Publ. **61**, Berkeley Meeting, 225–231, 1963.

40. SHUMSKIY, P.A., A. N. KRENKE and I. A. ZOTIKOV: Ice and its changes. Res. in Geophys., **2**, 425–460, 1964.

41. STUART, A. W. and A. J. HEINE: Glaciological work of the 1959–1960 U. S. Victoria Land traverse. J. Glaciol., **3** (30), 997–1002, 1961.

42. STUART, A. W. and C. BULL: Glaciological observations on the Ross Ice Shelf near Scott Base, Antarctica. J. Glaciol., **4** (34), 399–414, 1963.

43. SVERDRUP, H. U.: The currents off the coast of Queen Maud Land. Norsk Geogr. Tidsskr., **14**, 239, 1953.

44. SWITHINBANK, C.: The use of stakes in measuring the accumulation of snow on glaciers. Int. Ass. Scient. Hydrol. Meeting Rome IV, 128–131, 1956.

45. SWITHINBANK, C.: The movement of the ice shelf at Maudheim. Norw.-Br.-Swed. Antarc. Exped. 1949–51. Scient. Results, Vol. III, Glaciology I C, Oslo, 1958.

46. SWITHINBANK, C.: Maudheim revisited. The morphology and regime of the ice shelf 1950–1960. Norsk Polarinstitutt, Årbok 1960, p. 28–31, Oslo, 1962.

47. SWITHINBANK, C. W.: Ice movement of valley glaciers flowing into the Ross Ice Shelf, Antarctica. Science, **141**, 523–524, 1963.

48. THIEL, E. C.: The amount of ice on planet earth. Am. Geophys. Un., Geophys. Monograph, **7**, Antarctic Research, 172–175, 1962.

49. VICKERS, W. W.: A study of ice accumulation and atmospheric circulation in western Antarctica. Thesis, Dept. of Geogr., McGill Univ., Montreal, 1965.

50. WEIDICK, A.: Glacial variations in West Greenland in post-glacial time. Bull. Int. Ass. Scient. Hydrol., **8** (1), 75–82, 1963.

51. WEXLER, H.: Heating and melting of floating ice shelves. J. Glaciol., **3** (27), 626–645, 1960.

52. ZOTIKOV, I. A.: Bottom melting in the central zone of the ice shield on the Antarctic continent and its influence upon the present balance of its ice mass. Bull. Int. Ass. Scient. Hydrol., 8 (1), 36–44, 1963.

53. ZUMBERGE, J.: Horizontal strain and absolute movement of the Ross Ice Shelf between Ross Island and Roosevelt Island, Antarctica, 1958–1963. Am. Geophys. Union Ant. Res. Series, **2**, Antarctic Snow and Ice Studies. NAS Publ. **1197**, 65–81, 1964.

54. ZUMBERGE, J. H. and C. W. SWITHINBANK: The dynamics of ice shelves. Geophys. Monograph, **7**, Antarct. Research, 197–208, Washington, Am. Geophys. Union, 1962.

55. ZVEREV, A. A.: Anomalous sea water temperatures in Olaf Prydz Bay. Sov. Antarct. Exped. Inf. Bull., **6**, 269–271, 1959.

56. ØSTREM, G.: Mass balance studies on glaciers in western Canada, 1965. Geogr. Bull. Canada, 8 (1), 81–107, 1966.