ICE BUDGETS FOR ANTARCTICA AND CHANGES IN SEA-LEVEL

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ABSTRACT. Eight different ice budgets for the Antarctic Ice Sheet are examined. Five of these budgets call for rates of increase of the ice which are in surprisingly good agreement considering the wide dispersion of individual components of the budgets. The observed rise in sea-level of the world's oceans would appear to contradict the removal of water required to nourish the Antarctic Ice Sheet at the claimed rates. The thermal expansion of oceanic columns, caused by "climatic" warming of the oceans, has been invoked to resolve this contradiction but it appears that this is not large enough judging from the 30 yr. difference in water temperatures measured by the *Meteor* and the *Crawford* in two profiles across the tropical Atlantic Ocean.

RÉSUMÉ. Huit bilans de masse de l'Indlandsis Antarctique proposés par différents auteurs sont confrontés dans le présent article. Cinq de ces bilans de masse indiquent des valeurs d'accroissement de la glace qui sont en accord d'une façon assez surprenante si l'on considère la grande disparité des composantes individuelles des bilans de masse. L'élévation obtenue du niveau moyen des mers du globe semble être en contradiction avec le transfert d'eau nécessaire à l'alimentation de l'Indlandsis Antarctique dans les proportions indiquées. L'expansion thermique de masses océaniques, causée par le réchauffement climatique des océans a été invoquée pour expliquer cette contradiction; mais il semble que cette cause soit insuffisante, à en juger par les différences de température des eaux marines mesurées à 30 ans d'intervalle par le "Meteor" et le "Crawford" le long de deux profils à travers la zone tropicale de l'Océan Atlantique.

ZUSAMMENFASSUNG. Es werden 8 verschiedene Haushaltsberechnungen des antarktischen Inlandeises überprüft. 5 davon führen zu einer Zunahme des Eises, deren Zahlenwerte erstaunlich gut übereinstimmen, wenn man sich die grosse Streuung der Einzelkomponenten der Haushaltsberechnungen vor Augen hält. Die beobachtete Hebung des Wasserspiegels der Weltmeere scheint einer Entnahme von Wasser zur Ernährung des antarktischen Inlandeises in dem geforderten Mass zu widersprechen. Zur Erklärung dieses Widerspruchs wurde die Wärmeausdehnung ozeanischer Wassersäulen herangezogen, die durch eine „klimatische" Erwärmung der Ozeane verursacht wird. Doch scheint diese nicht gross genug, wenn man von den Änderungen der Wassertemperatur in 30 Jahren ausgeht, wie sie von den Forschungsschiffen *Meteor* und *Crawford* in zwei Profilen über den tropischen Atlantik gemessen wurden.

THE intensive investigation of Antarctica carried on during the International Geophysical Year of 1957-58, particularly in meteorology and glaciology, has had as one of its major goals the determination of the mass of ice and whether it is increasing or decreasing.

Based on earlier estimates by Sharp [1] and Gould [2] plus a few scattered observations of ice thickness made before the I.G.Y., an average thickness of 2,000 m. was assumed over the $13 \cdot 5 \times 10^6$ km.² area, which for an average density of 0·9 g. cm.$^{-3}$ amounted to $2 \cdot 43 \times 10^{22}$ g. [3] Later estimates by Crary [4] (1,950 m.) and Bauer [4] (2,130 m.) based on I.G.Y. data agreed fairly well with the earlier estimate; but there is not nearly so close agreement in the several ice budgets proposed by various investigators, or as to whether or not the ice is growing.

Eight different ice budgets are presented in Table I. The first budget shown, I, is that proposed by Kosack in 1956;[5] it is based on an average liquid precipitation of 20·1 cm. yr.$^{-1}$ or $2 \cdot 85 \times 10^{18}$g. yr.$^{-1}$ over all of Antarctica. Losses are incurred by blowing snow ($1 \cdot 20 \times 10^{18}$ g. yr.$^{-1}$), by calving of icebergs ($0 \cdot 55 \times 10^{18}$ g. yr.$^{-1}$), and by ablation (surface melting, run-off and evaporation, $2 \cdot 05 \times 10^{18}$ g. yr.$^{-1}$). No significant contribution is attributed to melting of ice shelves from below. These figures yield a net loss of $0 \cdot 95 \times 10^{18}$ g. yr.$^{-1}$, which, if released to the ocean with no other compensatory changes, would increase world sea-level by 2·6 mm. yr.$^{-1}$, since the area of all oceans including marginal seas is $360 \cdot 8 \times 10^6$ km.².

The second budget, II (Table I), is based on an assumption of steady-state equilibrium, where the average liquid precipitation over Antarctica was taken as 12·0 cm. yr.$^{-1}$, [3] the larger of Loewe's two values.[6] The net water vapor transport southward across lat. 70° S., $1 \cdot 62 \times 10^{18}$ g. yr.$^{-1}$, fell as snow and was taken equal to the northern transport of snow and ice across lat. 70° S. by blowing snow, calving of icebergs and melting at the bottom of the large ice shelves characteristic of Antarctica.

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In the third budget, III, the water vapor transport is decreased to agree with a lower estimate of 7·0 cm. yr.$^{-1}$ of average liquid precipitation over Antarctica made by Rubin,[7] which agrees with an earlier estimate of Meinardus.[8] The transport of water vapor southward across lat. 70° S. is thus decreased to $0{\cdot}945 \times 10^{18}$ g. yr.$^{-1}$. The northward transport figures are also adjusted: the blowing snow transport figure, admittedly too large in budget II, is decreased to one-fourth of its value, following Vickers.[9] The calving rate, also admittedly too low in budget II, is increased by applying an average northward motion of 300 m. yr.$^{-1}$ of a 200 m. average thick ice shelf, values slightly less than those observed at Little America V.[10] To achieve mass balance only 17 per cent of Sverdrup's ocean energy transport into the Maudheim Is-Shelf[11] is found necessary, instead of the 100 per cent needed in budget II.

Another ice budget proposed by Lister[12] is presented in Column IV. The average liquid precipitation of 14·2 cm. yr.$^{-1}$ was computed by the present writer from Lister's average annual accumulation of 13·1 g. cm.$^{-2}$ plus his estimated evaporation and run-off values of 1·0 and 0·1 g. cm.$^{-2}$, respectively. The sizeable loss attributed to net evaporation has been questioned.[13, 14] Lister's budget indicates a net transport of $0{\cdot}83 \times 10^{18}$ g. yr.$^{-1}$ into Antarctica, or an increase of 0·341 per cent of the present ice mass each century. This increase, if maintained, would double the present ice mass in 29,300 yr. and would cause a lowering of the world sea-level by 2·3 mm. yr.$^{-1}$.

In Column V (Table I) is shown an ice budget proposed by Mellor.[15] The average precipitation and evaporation figures are nearly the same as Lister's but the blowing snow value is much larger and the melting rate much smaller. The net inward transport is larger, $1{\cdot}05 \times 10^{18}$ g. yr.$^{-1}$, and would lower sea-level by 2·9 mm. yr.$^{-1}$.

Table I. Various Ice Budgets for Antarctica* (unit 10^{18} g. yr.$^{-1}$)

	I. Kosack (*1956*)	*II. Wexler* (*1957*)	*III. Wexler* (*1960*)	*IV. Lister* (*1959*)	*V. Mellor* (*1959*)	*VI. Loewe* (*1959*)		*VII. Kotliakov* (*1960*)
				In (+)				
Precipitation (water equivalent, cm. yr.$^{-1}$)	2·85 (20·1)	1·62 (12·0)	0·945 (7·0)	1·920 (14·2)	2·000 (14·0)	1·27 (10·2)	2·00 (16·0)	2·65 (19·0)
				Out (−)				
Blowing snow	1·20	0·28	0·065	0·014	0·190	0·02	0·50	—
Calving	0·55	0·04	0·660	0·270	0·570	0·14	0·30	1·21
Shelf melting	—	1·30 (100 per cent Maudheim transport)	0·220 (17 per cent Maudheim transport)	0·675	0·048	0·00	0·00	0·00
Ablation	2·05	0·00	0·000	0·135	0·137	0·00	0·00	0·12
	3·80	1·62	0·945	1·094	0·945	0·16	0·80	1·33
Net transport	−0·95	0·00	0·000	+0·830	+1·050	+1·11	+1·20	+1·32
Per cent increase ice/100 yr.	—	0·00	0·000	+0·341	+0·434	+0·457	+0·494	0·544
Doubling time of ice (yr.)	—	—	—	29,300	23,000	21,900	20,300	18,400
Resulting change of world sea-level (mm. yr.$^{-1}$)	+2·60	0·00	0·000	−2·3	−2·90	−3·10	−3·30	−3·70

* Some inconsistencies in the figures in the first two rows are due to differences in the area of Antarctica used by the various investigators.

Two ice budgets based on minimum and maximum values, proposed by Loewe,[6] are shown in Column VI. Loewe took average liquid accumulations of 10·0 and 12·0 cm. yr.$^{-1}$, which, when added to minimum and maximum blowing snow values, gave average liquid precipitation values of 10·2 and 16·0 cm. yr.$^{-1}$, respectively. Melting from the surface or from the bottoms of ice shelves contributed very little, if at all, to the loss of ice while net evaporation was considered to be zero. The net inflows of $1\cdot 11 \times 10^{18}$ and $1\cdot 20 \times 10^{18}$ g. yr.$^{-1}$, respectively, would lower sea-level by 3·1 and 3·3 mm. yr.$^{-1}$, respectively.

Finally, in Column VII there is shown a budget proposed by Kotliakov,[17] based on an average liquid precipitation of 19 cm. yr.$^{-1}$. A loss of $1\cdot 21 \times 10^{18}$ g. yr.$^{-1}$ by calving is the largest of all estimates shown in Table I. No shelf melting figure is included. The net gain of $1\cdot 33 \times 10^{18}$ g. yr.$^{-1}$ would result in a lowering of sea-level by 3·7 mm. yr.$^{-1}$.

Thus it is seen from Table I, that budgets IV to VII (Lister, Mellor, Loewe, and Kotliakov) all agree that the Antarctic Ice Sheet is growing at rates which are in remarkably close agreement, considering the wide divergence of the figures from which they were derived. The average increase is $1\cdot 10 \times 10^{18}$ g. yr.$^{-1}$.

The first budget indicates a loss of Antarctic ice. The next two budgets, II and III, are based on approximate mass balance for which Robin [18] gives the following supporting arguments:

i. Domed shapes of the ice sheet.
ii. Scarcity of freshly exposed rock surfaces (which would be evidence against recent, i.e. within past few centuries, lowering of the ice).
iii. Small values of world-wide changes in mean sea-level.

With respect to Robin's third point, the net accretions to the Antarctic Ice Sheet shown in budgets IV–VII would call for reduction of the mass of the oceans such that sea-level would *lower* by 2·3 to 3·7 mm. yr.$^{-1}$, if the following conditions were fulfilled:

i. No isostatic upward movements of the coasts.
ii. No tectonically caused upward movements of coasts.
iii. No compensatory warming and expansion of the world's oceans.

Both isostatic and tectonic movements are known on several coasts and attempts have been made to eliminate these effects from long-term measurements of sea-level to obtain the eustatic changes of sea-level, that is, variations in sea-level caused by changes in the water cycle between ocean and land, assuming that the total mass of water substance in the ocean–atmosphere–surface land layer remains constant.

Hela [19] has summarized eustatic sea-level changes determined by various investigators and the results are shown in Table II.

TABLE II. EUSTATIC RISES OF SEA-LEVEL (FIRST FIVE VALUES FROM HELA;[19] DATES ADDED BY PRESENT WRITER)

Gutenberg [20]	(1941)	$1\cdot 1 \pm 0\cdot 8$ mm. yr.$^{-1}$ (roughly 1880 to 1930)
Thorarinsson [21]	(1940)	0·5 or more mm. yr.$^{-1}$ (few decades before 1940)
Kuenen [22]	(1945)	0·5 mm. yr.$^{-1}$ (1832 to 1942)
Kuenen [22]	(1945)	1·2 to 1·4 mm. yr.$^{-1}$ (1880 to 1930)
Dietrich [23]	(1954)	$1\cdot 14 \pm 0\cdot 28$ mm. yr.$^{-1}$ (1890 to 1950)
Hafemann [24]	(1960)	$1\cdot 18 \pm 0\cdot 18$ mm. yr.$^{-1}$ (~300 A.D. to present)
Maksimov [31]	(1960)	1·22 mm. yr.$^{-1}$ (1900 to 1950)

Apart from Thorarinsson's value and Kuenen's first value there is surprisingly good agreement among the other four investigators of an eustatic rise of sea-level of about 1·18 mm. yr.$^{-1}$. Thorarinsson's value of 0·5 mm. yr.$^{-1}$ was computed by applying estimates of average losses of some five glaciers studied in Iceland, Spitsbergen, Sweden, and Switzerland to all other glaciers of the world with the exception of the whole of Antarctica and the accumulation area of the Greenland Ice Sheet. In the following discussion we shall disregard the possible effect of changes in the Greenland accumulation area so that we can apply Thorarinsson's results directly to the problem of changes in the Antarctic Ice Sheet.

Despite this good agreement Hela states ". . . the present rate of eustatic rise of sea-level remains uncertain". As an alternative to an increase of *mass* of ocean water and a resulting

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rise of sea-level caused by melting of glaciers, he cites the possibility of an increase of *volume* (with mass constant) because of heating and thermal expansion of the oceans. According to Munk and Revelle [25] a heating by 1° C. of the *entire* ocean would raise the surface by 600 mm. Thus, the observed rise of 1·18 mm. yr.$^{-1}$ might be explained by a warming of the total ocean by 0·002° C. yr.$^{-1}$.

In absence of oceanic heating, if the Antarctic Ice Sheet is growing at a rate which removes water from the oceans so that sea-level would drop at the rate of 3·06 mm. yr.$^{-1}$ (the average of the values given in Columns IV–VII in Table I), then the compensatory melting of ice elsewhere in the world must amount to an increase of sea-level by 4·24 mm. yr.$^{-1}$ to give the observed eustatic sea-level rise of 1·18 mm. yr.$^{-1}$. If the 4·24 mm. yr.$^{-1}$ rise in sea-level is *not* eustatically caused but is of thermal origin, this would mean a warming of the entire ocean by 0·007° C. yr.$^{-1}$.

It is difficult to prove whether an oceanic warming of this rate has occurred. It is equivalent to the added absorption by the oceans of 1 per cent of the total earth's receipt of solar radiation.[26] Hoinkes [27] cites the warming of surface water in the North Atlantic, summarized by Bjerknes,[28] of 0·3° C. in the 36 yr. from 1890-97 to 1926-33, or 0·008° C. yr.$^{-1}$, as supporting evidence for the thermal explanation of the rise of sea-level. Thus Hoinkes concludes, as do Loewe and Mellor, that the growth of the Antarctic Ice Sheet does not necessarily contradict the observed rise in sea-level.

However, a word of caution is necessary; Bjerknes's warming figure cited above is only for surface waters of the North Atlantic. What about the deep waters? Data on long-term climatic changes of deep ocean temperatures are scarce but Fuglister,[29] in comparing temperatures in the *Meteor* profiles VI (lat. 16° S.) and VIII (lat. 8° S.) with observations taken 30 yr. later by the *Crawford*, concludes ". . . the deep water is a little cooler, perhaps a little more saline and has lost some oxygen. The bottom Antarctic water is warmer and more saline." Scaling off from Fuglister's profiles the average temperature differences over the 5,000 m. deep ocean gives the results in Table III. These values are probably too large since they include relatively large seasonal effects in the top few hundred meters. The average annual temperature increase of 0·0009° C. from Table III, if representative of all oceans, is too small by a factor of 7 to account for the thermal vertical expansion of the oceans by 4·24 mm. yr.$^{-1}$ needed to agree with the observed rise of 1·18 mm. yr.$^{-1}$ and the estimated depletion of the world's oceans by 3·06 mm. yr.$^{-1}$ to support the estimated growth of the Antarctic Ice Sheet.

TABLE III. AVERAGE TEMPERATURE RISES (° C.) BETWEEN METEOR AND CRAWFORD STATIONS (1927–1957)

	Atlantic Ocean	
	Western basins	*Eastern basins*
Lat. 8° S. (Profile VIII)	0·04° or 0·0013° yr.$^{-1}$	0·04° or 0·0013° yr.$^{-1}$
Lat. 16° S. (Profile VI)	0·02° or 0·0007° yr.$^{-1}$	0·01° or 0·0003° yr.$^{-1}$

If we accept an average warming of the oceans by 0·001° C. yr.$^{-1}$ and a release of water from melting glaciers outside of Antarctica amounting to a sea-level rise of 0·5 mm. yr.$^{-1}$ (Thorarinsson's minimum value), then we can compute the change of sea-level caused by changes in the Antarctic Ice Sheet as shown in Table IV.

TABLE IV. EUSTATIC AND THERMAL CHANGES OF SEA-LEVEL

Observed eustatic rise of sea-level	+1·18 mm. yr.$^{-1}$
Correction for thermal expansion caused by +0·001° C. yr.$^{-1}$ ocean warming	−0·60 mm. yr.$^{-1}$
Correction for rise in sea-level caused by melting of non-Antarctic ice (Thorarinsson's minimum)	−0·50 mm. yr.$^{-1}$
Change of sea-level caused by variation of the Antarctic Ice Sheet	+0·08 mm. yr.$^{-1}$

Expressed in terms of the mass of ice removed from Antarctica each year, this eustatic increase of sea-level by 0·08 mm. yr.$^{-1}$ amounts to an ice loss of $0{\cdot}029 \times 10^{18}$ g. yr.$^{-1}$. If a value of 1·2 mm. yr.$^{-1}$, or more than twice Thorarinsson's minimum value for water released by non-Antarctic glaciers is used, then the rate of growth of the Antarctic Ice Sheet is equivalent to −0·62 mm. yr.$^{-1}$ change in sea-level or an increase of ice by $0{\cdot}224 \times 10^{18}$ g. yr.$^{-1}$, about one-fifth of the average of the net transport values shown in Columns IV–VII of Table I. A decrease of about 10 per cent in the estimated average precipitation values in these columns would wipe out this increase.

If there were no oceanic warming, then from Table IV the change in the Antarctic Ice Sheet would be between $-0{\cdot}246 \times 10^{18}$ and $+0{\cdot}007 \times 10^{18}$ g. yr.$^{-1}$ depending on whether Thorarinsson's minimum value or 2·4 times that value were used.

Another possibility to be considered in studying changes in sea-level is that the storage of water vapor in the atmosphere may change. On the average there are about 30 mm. of precipitable water vapor in an atmospheric column of 1 cm.^{2} cross-section area. Because of climatic warming the atmospheric capacity for water vapor may increase. Willett [30] estimates that the average world temperature from 1850 to 1940 has increased by 0·8° C. If this temperature increase is translated into saturation vapor pressure increase, maintaining the same value of average relative humidity, then the resulting increase in precipitable water vapor would be 1·6 mm. in 90 yr. or 0·0018 mm. yr.$^{-1}$, much too small compared with the other terms listed in Table IV.

Kuenen [22] has examined the possibility of the surface water supply being increased by juvenile water from the earth's interior but concludes it is less than $0{\cdot}0002 \times 10^{18}$ g. yr.$^{-1}$.

In view of the uncertainties of the various components of water exchange between ocean, atmosphere and land, and the lack of adequate data on long-period thermal changes at all depths of the world's oceans, it seems risky at this time to state that the Antarctic Ice Sheet is either increasing or decreasing.

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