Basic Morphometric Characteristics for Antarctica and Budget of the Antarctic Ice Cover

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Abstract: On the foundation of the latest cartographical materials, obtained in the period of IGY and following years I. A. Suyetova carried out the complex of cartometrical works and received the following values:

1. The area of Antarctica.
2. The average altitude of the ice and rock surface in relation to the ocean level.
3. The volume and thickness of the ice of the ice sheet of Antarctica.
4. Perimeter of Antarctica.

The valuation of the Antarctic perimeter as well as the latest glaciological facts allowed to make new attempts in calculating the budget of the Antarctic ice sheet.

The analysis of facts necessary for calculation of the budget allowed to calculate maximum and average square miscalculations. The average square miscalculation shows the positive ice-budget of Antarctica. The valuation of the maximum miscalculation shows the equilibrium of ice in Antarctica.

The most recent maps were used for measuring the area of Antarctica, for defining the mean elevation of its ice and rock surface, the thickness and volume of the ice sheet and the ice budget.

On the whole, for this object the following cartographic material was used:

1. Antarktida, 1:3,000,000. Ministerstvo morskogo flota SSSR, Soyuzmorniiproyekt, Moscow, 1961.
2. Geomorphological map of Antarctica compiled for Atlas Antarctiki, Moscow, 1965.
3. Podlyodny rel'yef Antarktidy, 1:10,000,000, compiled for Atlas Antarctiki, Moscow, 1965.
4. Polar navigation charts, 1:2,188,800 scale, SP5, SP6, SP7, SP8. U.S. Navy Hydrographic Office, Washington, D. C., 1963.

In addition, larger scale Soviet and foreign maps up to and including those of 1964 were used for certain regions.

New estimations of the cotinent area, its mean elevation, volume and thickness of Antarctic ice were being computed as new maps were being published. When analyzing these values it is evident that the extreme values of the continent area differ from each other by 1.6 million km^2. Values of mean elevation of the ice Antarctica (mean value is 2250 m) are the most similar. The quantitative characteristics of mean elevation of the rock Antarctica are very contradictious (the extreme values vary from −160m to +900m). The ice volume values also greatly vary (difference between extreme figures is 14 million km^3). Such difference in the quantitative characteristics may be explained by inadequate precision of the used cartographic material, deficiency in the measuring technique, as well as the various definitions of the notion of the words "area of Antarctica".

The notion of the word "continent", conformably to Antarctica, may be considered from the different points of view.

It is more advisable to measure the continent area in the following variants: basic measuring (1, 2, 3, Table 1) and secondary measuring (1a, 2a, 2b, 2c, Table 1).

Table 1. Area of Antarctica.

		km^2
1.	Including Alexander Island; but excluding ice shelves, ice rises and other islands on the continental shelf	12,393,000 ± 5,500
1a.	Including the larger ice rises and islands with heights of over 500m (Alexander, Bear, Berkner, Roosevelt, Ross, and Thurston Islands); but excluding ice shelves and all smaller ice rises and islands	12,480,000
2.	Including ice shelves, islands and ice rises joined to the continent by ice shelves; but excluding other islands on the continental shelf	13,975,000
2a.	Including islands and ice rises jointed to the continent by ice shelves; but excluding ice shelves themselves and other islands on the continental shelf	12,513,000
2b.	Including all islands and ice rises on the continental shelf; but excluding the ice shelves	12,535,000
2c.	Including ice shelves and all islands and ice rises on the continental shelf	13,997,000
3.	Including the whole continental shelf	16,355,000
4.	The ice shelves alone excluding islands and ice rises	1,460,000
5.	The ice shelves, including islands and ice rises within them	1,582,000

Areas of squares, bounded by principal meridians and parallels, were computed and a planimeter was used for irregular areas. Table 1 shows the measured areas corresponding to various alternative definition of Antarctica together with the standard deviation at an average.

As a result of measuring, values, determing the area of Antarctica, its ice shelves and islands, were obtained.

A general error in measuring the area of Antarctica is equal to ± 5490 km^2. The extreme error, *i. e.* the trebled mean quadratic one is equal to 16,470 km^2. It is evident that the latter figure more closely characterizes the precision of the value we obtained. It stands to reason that the result of measuring does not present the existing area, it shows only the area of the depiction of the object in the given map. The computed error characterizes the technical precision of measuring and gives an estimation of the precision of a map.

Changing of the depiction of the area of Antarctica is always inevitable since the cartographic works are always in progress, and besides that, the boundaries of glaciation, consisting of 92% of the continental perimeter, are constantly changing. To predict the order of such changing is impossible.

The area of Filchner Ice Shelf and the coastal band of the West Antarctica between 152° and 72° W are the least investigated. Taking into account the data of the latest investigations made by the U.S.A. which show the new state of the coastal line in this area, we made re-estimation of the area of Antarctica and its ice shelves. Estimation of the total area of Antarctica diminished by 16,826 km².

This difference is small as it is close to the extreme error obtained when measuring the area of Antarctica according to the recent cartographic material. Therefore, it may be assumed that the obtained value of the area of Antarctica will be satisfactory for a number of years.

The notion of the word "relief", conformably to Antarctica, has a double meaning. The first, it is a relief of an ice surface of the "ice" Antarctica, and the second, it is a bedrock relief of the "rock" Antarctica.

For determination of the volume and mean elevation of both the ice and rock Antarctica the graphic method, the plotting of the hypsographical curve of the continent surface, was used. For determination of mean elevation of the East and West Antarctica (both the ice and rock ones), corresponding hypsographic curves were plotted.

After plotting the hypsographic curves for the ice and rock Antarctica it becomes possible to estimate the volume and thickness of ice in Antarctica. The ice volume over the continental area without ice shelves is equal to the difference between the ice and rock continent volumes. Dividing the ice volume (km³) by the area of Antarctica (km²), we obtain the estimation of mean thickness of ice (Fig. 1).

An error of estimation of mean elevation of the ice and rock Antarctica may be determined very approximately since the isohypses were plotted after widely spaced altitude determination net and some areas had no altitude determinations at all, so the isohypses were plotted hypothetically.

The obtained value of mean quadratic error when computing mean elevation of the ice Antarctica is $\pm$ 85 m.

The value of the probable error when measuring mean elevation of the rock Antarctica is approximately $\pm$ 200 m.

A general error, when computing the ice volume of Antarctica by summing up the errors of estimation of the area and mean elevation of the rock and ice Antarctica, makes up 20% from the total ice volume.

The obtained values of the volume and mean elevation of the ice and rock Antarctica, as well as the ice volume and ice thickness are shown in the Tables 2, 3 and 4.

Two thirds of the continent elevation relatively to sea level form the ice cover and one third is the bedrock. This is the explanation of the fact that the hypsographic curve of the ice Antarctica surface is prominent in contrary to the

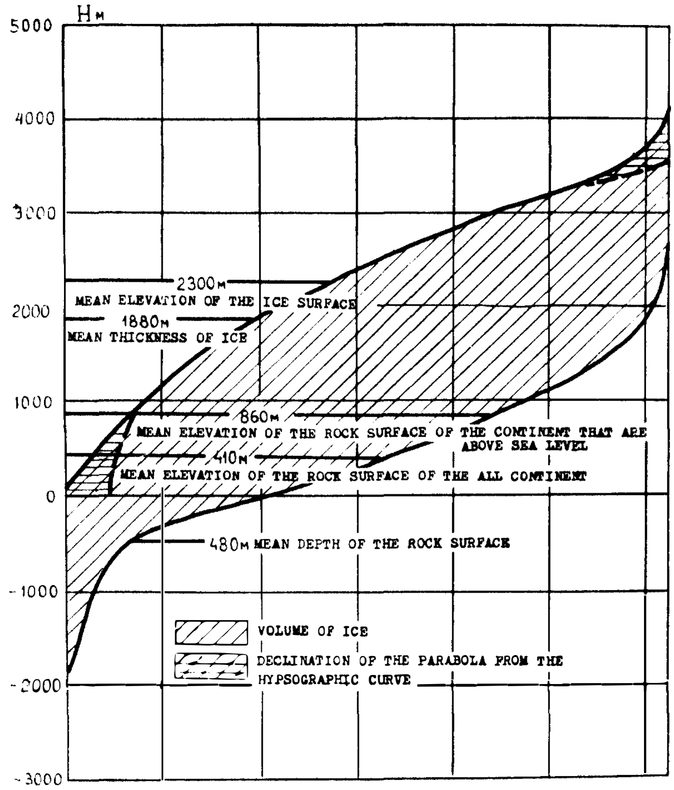

Fig. 1. Hypsographic curve of the ice and rock surfaces of Antarctica excluding ice shelves.

hypsographic curves of other continents and the rock Antarctica itself having concave form. Such distinction is explained by difference in substance and process of formation of the rock and ice surfaces of the continent.

On analyzing the hypsographic curve of the ice Antarctica we have confirmed the conclusion firstly made by V. MEINARDUS (1926), that the largest part of the hypsographic curve is of parabolic form. A general equation of parabola, applicable to the hypsographic curve of Antarctica, may be written down as $S=0.9h^2+0.9$ where S is an area in million km², h is altitude in km. The parabola parameters are as follows: $a=0.9$; $b=0$ and $c=0.9$. They were obtained on the basis of the hypsographic curve analysis. Declinations of the parabola from the hypsographic curve are observed in the lower part up to 800 m above sea level, because in this area of small ice thickness of the ice cover the bedrock relief influence is strong, and in the upper part, from 3300 and higher, because of nunataks, rising over the ice cover (Fig. 1). If the hypsographic curve is of parabolic form the profile of the Antarctic ice cover has an elliptic form:

$$\frac{r^2}{3.66}+\frac{h^2}{12.8}=1$$

Table 2. Area, volume and mean elevation of the ice surface.

	Including ice shelves			Excluding ice shelves		
	Volume km³	Area km²	Mean elevation m	Volume km³	Area km²	Mean elevation m
All Antarctic continent	28,591,000	13,975,000	2,040	28,530,000	12,480,000	2,300
The West Antarctica	3,028,000	3,532,000	850	2,980,000	2,297,000	1,290
The East Antarctica	25,563,000	10,443,000	2,450	25,550,000	10,183,000	2,500

Table 3. Area, volume and mean elevation of the rock surface.

	Volume km³	Area km²	Mean elevation m
Parts of the continent that are above sea level, including islands	+7,112,000	+8,276,000	+860
Parts of the continent that are below sea level	−2,031,000	−4,204,000	−480
All continent, including the larger ice rises and islands with height of over 500 m	+5,081,000	12,480,000	+410
Including the whole continent shelf	+4,492,000	16,355,000	+270
The West Antarctica that is above sea level	+ 711,000	+ 773,000	+920
The West Antarctica that is below sea level	−1,031,000	−1,524,000	−680
All West Antarctica	− 320,000	2,297,000	−140
The East Antarctica that is above sea level	+6,401,000	+7,503,000	+850
The East Antarctica that is below sea level	−1,000,000	−2,680,000	−370
All East Antarctica	+5,401,000	10,183,000	+530

Table 4. Mean thickness and volume of ice.

	Volume km³		Thickness m	
	Excluding ice shelves	Including ice shelves	Excluding ice shelves	Including ice shelves
All Antarctica	23,449,000	24,031,000	1,880	1,720
The West Antarctica	3,300,000	3,830,000	1,440	1,080
The East Antarctica	20,149,000	20,201,000	1,980	1,930

Semi-axes of the computed ellipsis are equal to $R=1905$ km (a large semi-axis) and $H=3560$ m (a small semi-axis). These values are the radius of the base and maximum altitude of the elliptical ice dome.

The ice Antarctica is the highest continent in the world. Its mean elevation together with the ice shelves is 2040 m, and, therefore, 2.8 times higher than the mean elevation of the rest continents all together that comprises 730 m without Antarctica.

Due to the large elevation of the continent, the volume of Antarctica, consisting of 28.591 million km^3, is larger than that of other continents with exceptions of Europe and Asia. This is because of the enormous thickness of the Antarctic ice.

If one can imagine the Antarctic ice cover melted then the ocean would submerge only a part of the rock continent, which is below sea level. Then the East Antarctica would be a continent, and the West Antarctica would evidently consisted of three archipelagoes of islands.

Taking into account that the mean value of sinking under ice load is equal to about 0.5 km (according to Ushakov, Khain and Kapitza, 1965) one can suppose that mean elevation of the whole rock Antarctica with 12.480 million km^2 area would comprised $410+500$ m, *i. e.* about 900 m.

Thus, one can suppose that the pre-glacial rock Antarctica bearing no ice load was an exceptionally high continent.

Results of comparison of the morphometric characteristics of Antarctica with those of other continents, continental character of the earth crust, as well as the analysis of isostatic processes of elevation, prove acceptability of the name "continent" both for the rock and ice Antarctica.

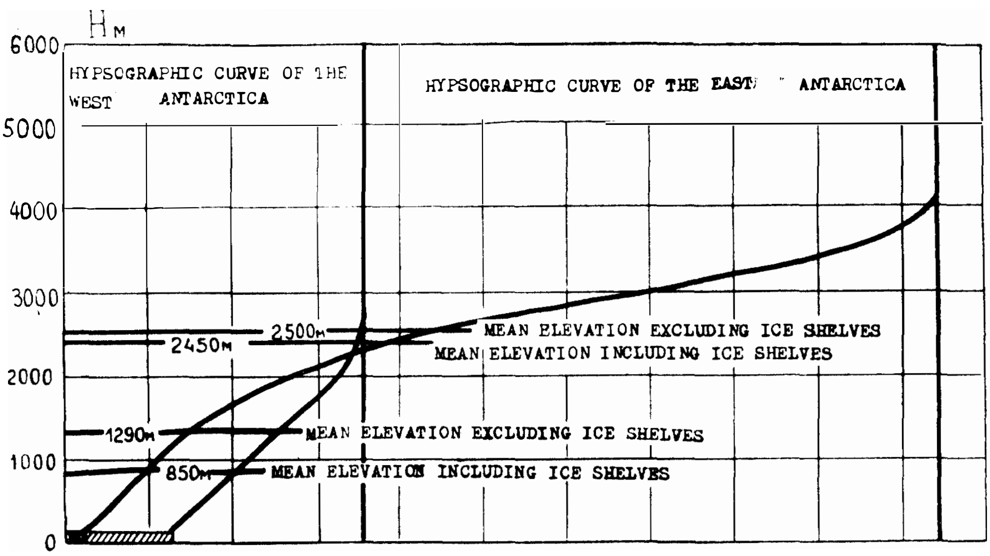

Fig. 2. Hypsographic curve of the western and eastern Antarctica.

Results of comparison of hypsographical curves of both the East and West Antarctica show their sharp difference (Fig. 2). The hypsographical curve of the West Antarctica is of a concave form and is approaching by its form to the hypsographical curve of the continents not covered with ice. The hypsographical curve of the East Antarctica is of prominent form and is approaching to the hypsographical curve of the whole ice continent of Antarctica. The hypsographical curve of the West Antarctica shows the contrasts of bedrock heights; the hypsographical curve of the East Antarctica shows comparatively constant predominance of the heights. The indicated difference is, first of all, the result of the various processes being happened in surface formation of both the ice and rock West and East Antarctica.

Complete melting of the Antarctic ice cover would cause elevation of the world ocean sea level by 59 m, the melting of all recent glaciers, volume of which in water equivalent consists 24.241 million km^3, would rise sea level by 66 m.

For measuring the perimeter of Antarctica we used all the Soviet and foreign large scale maps. 23,680 km of the coastal band of Antarctica were measured on the materials of airphoto survey (1:40,000) and 1:100,000, 1:200,000, 1:250,000 and 1:500,000 maps. 4680 km of the coast were measured on the 1:1,000,000 and 1:1,500,000 maps. 1670 km of the West Antarctica coast were measured on the US 1:3,000,000 map (1962). The micrometer compasses were used for every type of the coast. The coastal lines and cross-sections of 117 outlet glaciers, 73 ice shelves, 168 areas of ice shield edge (continental ice barrier), as well as the coastal outcrops were measured.

Discharge of snow and ice masses of the Antarctic ice cover takes place mainly by means of movement of ice to the ocean where it calves icebergs.

Estimation of ice flow from the Antarctic shores was carried out with due regard for every particular ice formation along the coast. We used the data obtained by BARDIN and SHILNIKOV, 1962; DOLGUSHIN, 1963; VOLKOV, 1963; BOKANENKO and AVSYUK, 1963; ZUMBERG and SWITHINBANK, 1962, 1964; RUBIN, 1962; STUART and

Table 5. Ice discharge.

Type of coastline	Length km	Length % of total	Annual discharge into the sea km³ water	Annual discharge into the sea % of total	Annual discharge into the sea per km of coast (km³ water)
Outlet glaciers	2,860	9.5	260	22	0.091
Ice shelves	13,660	45.5	730	62	0.053
Ice wall	11,090	37.0	190	16	0.017
Rock outcrops	2,420	8.0	—	—	—
	30,030	100.0	1,180	100	0.043*

* per km of total ice coastline.

This data have been used together with the most acceptable values for accumulation and ablation to estimate the ice budget (Table 6).

HEINE, 1961; CRARY, ROBINSON, BENNET and BOYD, 1962; BARDIN and SUYETOVA, 1965.

Estimation of ice flow, summarized according to the types of the ice coast is given in Table 5 (transferred in water volume).

For estimation of the budget of Antarctica let us compare the obtained values of ice flow with the data on annual accumulation and submarine melting in Antarctica which we consider the most acceptable (Table 6). We do not take into consideration catastrophic calving of icebergs.

Table 6. Comparison between the value of ice flow and the data on accumulation and submarine melting.

	Mass input km^3 water	Mass output km^3 water
Precipitation including that over the Antarctic Peninsula (DOLGUSHIN and others, 1964)	2,420	
Calving (BARDIN and SUYETOVA, 1965)		1,180
Submarine melting of ice shelves		250
Possible bottom melting in the central zone of the ice sheet (ZOTIKOV, 1962)		20
Budget	+970 km^3	

Since we do not know a character of errors assumed in our initial data we used two ways of estimating the precision of the computed ice discharge in Antarctica. Assuming the errors of the initial data as systematical, *i. e.* keeping their value and sign, we computed the possible maximum error that was equal to $\pm 960.10^9$ ton per year.

Supposing the errors assumed in measuring the coastal line length, thickness and rate of ice flow as casual, we computed mean quadratic error both for determination of discharge and budget as a whole. We obtained the value of mean quadratic error for the budget equal to $\pm$ 170 km^3, and the value of maximum error equal to $\pm$ 510 km^3.

Analysis of all initial data, used for computing the budget, as well as the calculation of the error made by two ways, allowed us to make the following conclusions: a) the value of mean quadratic error in measuring points out the positive budget of the Antarctic ice; b) the value of the possible maximum error in the budget points out the equilibrium state in glaciation of Antarctica.

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