CONTRIBUTION TO THE KNOWLEDGE OF THE ANTARCTIC ICE SHEET: A SYNTHESIS OF GLACIOLOGICAL MEASUREMENTS IN TERRE ADÉLIE*

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ABSTRACT. This paper is a synthesis of glaciological investigations conducted in Terre Adélie, mainly during the I.G.Y. The surface and bedrock profiles have been obtained along a 500 km. line roughly perpendicular to the coast; the mean annual temperature has been studied as a function of altitude, and mean accumulation has been related to distance from the coast and surface slope. Stratigraphic studies made at Station Charcot again raise the problem of the determination of mean accumulation in certain parts of the Antarctic plateau; they provide a quadratic relationship between density and depth. The snow-drift studies lead to the following conclusions: wind velocity and density of drifting snow are functions of height above the surface, and the total transport depends on wind velocity. Lastly, measurements have been made of glacier flow near the coast. The paper ends with a schematic study of the mass balance in Terre Adélie; accumulation seems to be slightly larger than ablation, a result that is to be contrasted with the observed coastal retreat near Dumont d'Urville base.

RÉSUMÉ. Cet article constitue une synthèse des mesures glaciologiques réalisées en Terre Adélie, notamment au cours de l'A.G.I. Les profils de la surface et du socle rocheux ont été obtenus le long d'un axe de 500 km approximativement perpendiculaire à la côte; le gradient des températures moyennes annuelles est étudié en fonction de l'altitude et l'on montre que l'accumulation moyenne est liée à la distance à la côte et à la pente. Les études stratigraphiques effectuées à la Station Charcot reposent le problème de la détermination de l'accumulation moyenne dans certains secteurs du plateau antarctique; elles permettent d'expliciter une relation du second degré entre la densité et la profondeur. L'étude de la chasse-neige permet de formuler les points suivants: la vitesse du vent et la densité de chasse-neige sont fonctions de la hauteur au dessus du sol; la quantité transportée dépend de la vitesse du vent. On rapelle enfin les mesures de vitesses de déplacement à la côte. On établit ensuite un schéma du bilan de masse en Terre Adélie; l'accumulation semble un peu supérieure à la somme des differentes formes d'ablation envisagées, contrairement à ce que l'on observe actuellement dans la région de la base Dumont d'Urville.

ZUSAMMENFASSUNG. Die vorliegende Arbeit stellt eine Zusammenfassung der in Adélie-Land ausgeführten glaziologischen Messungen, insbesondere während des I.G.J., dar. Die Profile der Oberfläche und des Felsuntergrundes erstrecken sich längs einer Achse von 500 km Länge ungefähr senkrecht zur Küste. Der Gradient der mittleren Jahrestemperaturen wurde in seiner Abhängigkeit von der Höhe untersucht; es zeigt sich, dass der mittlere Auftrag von der Distanz zur Küste und vom Gefälle abhängt. Die stratigraphischen Untersuchungen in der Station Charcot tragen zu dem Problem der Bestimmung des mittleren Auftrages in gewissen Zonen des Antarktisches Inlandeises bei; sie erlauben, eine quadratische Beziehung zwischen Dichte und Tiefe zu formulieren. Aus der Untersuchung des Schneefegens können folgende Schlüsse gezogen werden: Windgeschwindigkeit und Dichte des Schneefegens sind abhängig von der Höhe über der Oberfläche; die transportierte Schneemenge hängt von der Windgeschwindigkeit ab. Schliesslich wird auf die Messungen von Fliessgeschwindigkeit des Eises an der Küste eingegangen. Mit dem Versuch, den Massenhaushalt von Adélie-Land zu erfassen, schliess die Abhandlung: Der auftrag scheint die Summe der verschiedenen in Betracht gezogenen Ablationsvorgänge leicht zu überwiegen; dieses Ergebnis steht im Gegensatz zu den derzeitigen Beobachtungen in der Station Dumont d'Urville.

GENERAL CONSIDERATIONS

During the I.G.Y. glaciological investigations were conducted in Terre Adélie (Antarctica) along a line through Dumont d'Urville base (lat. 66° 40′ S., long. 140° 01′ E.) and Station Charcot (lat. 69° 22·5′ S., long. 139° 01′ E.) whence it extended to "Terme Sud" (lat. 71° 08′ S., long. 139° 11′ E.), a distance of about 500 km. approximately perpendicular to the coast (Fig. 1). This route includes the two main geographical divisions of the Antarctic Continent: (a) The plateau, remarkable for its high altitude, gentle slopes, very slight snow accumulation, homogeneous relief and low temperatures. These characteristics occur continuously beyond point B 35 (altitude 2,256 m.a.s.l., distance to coast 258 km.). (b) The coastal area, extending from the sea to point B 10 (altitude 868 m.a.s.l., distance to coast 28 km.), with steep slopes and more substantial accumulation. The prevailing higher temperature favours the appearance of melting features, the surface morphology is clearly differentiated

* This paper is a short summary of a book now in the press.

by the action of stresses induced by the existence of rocky outcrops and above all by the presence of areas where the ice is flowing rapidly, producing crevasses.

Ice Volume in Terre Adélie

Ice thickness was determined at each surface point using altimetric, seismic and gravimetric profiles (Fig. 2). Altitudes were obtained for 124 stations by barometric surveying (Valtat and others, 1960). Seismology (reflection shots) was used for the determination of

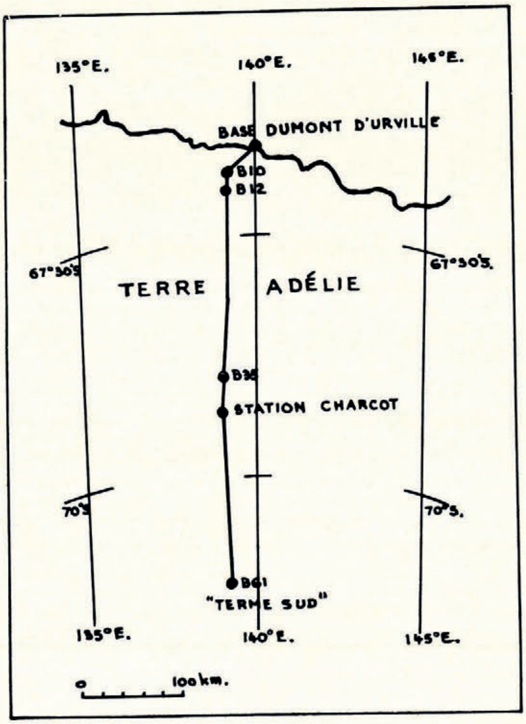

Fig. 1. Terre Adélie. I.G.Y. Traverse route

bedrock depth at 27 of these points (Imbert, 1959). These data then allowed the rock surface profile to be plotted from the gravimetric results (Rouillon, 1960). For a mean bedrock depth of −40 m. (the actual depth varied from −644 m. to +463 m.), the surface profile is expressed by the equation

$$\left(\frac{h}{2\cdot 68}\right)^2+\left(\frac{550-D}{550}\right)^2=1$$

where D is the distance to the coast in kilometres, and h the height of the surface above the mean bedrock level in metres.

Climatic Data: Mean Annual Temperatures

Mean annual temperatures of the air at ground level were measured at fourteen points by lowering thermometers to the bottom of coring holes, the depth of which exceeded 10 m.

Temperature variation plotted against altitude gives a straight line of slope 1·10° C. for

100 m. altitude difference;* this is comparable with the figures published by Mellor (1960). A comparison of our measurements with those of Loewe (1956, p. 114) along a line near long. 142° E., with due allowance for the contour line pattern in Terre Adélie, leads to a correction of 1° C. for 1° of latitude. Figure 3, which includes the results of two American parties to extend the line of our measurements, was plotted from temperature records reduced to lat. 66° 50′ S. The slope of the resulting plot is 1·04° C. per 100 m.

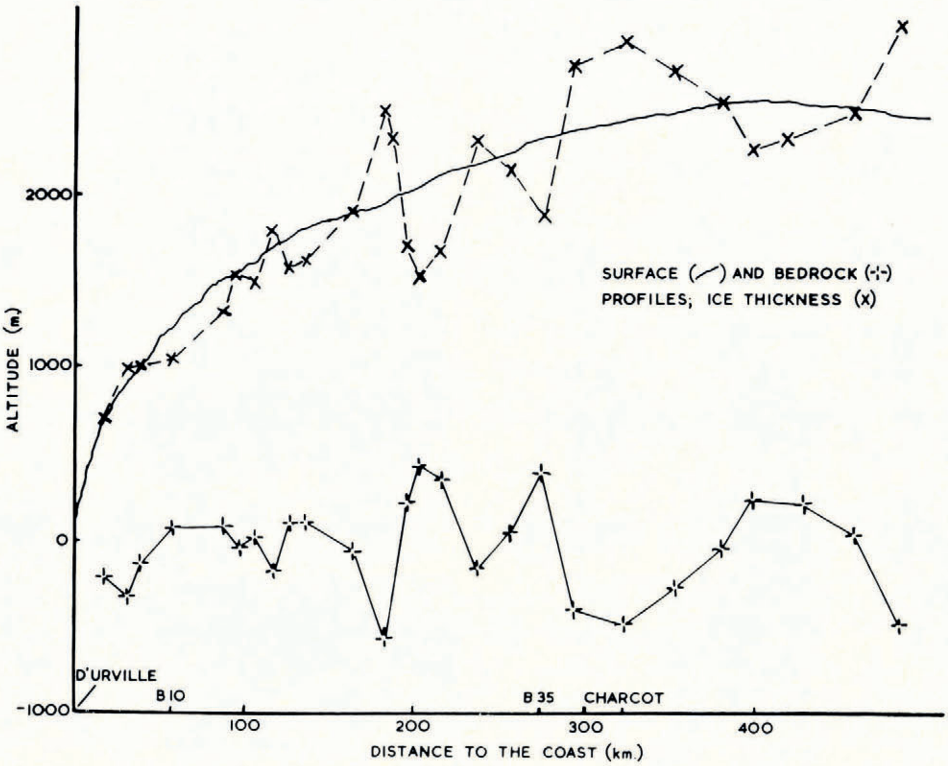

Fig. 2. Elevation and bedrock profiles; ice thickness in Terre Adélie

Snow Accumulation

A study of precipitation types at Station Charcot confirms the predominance of crystals such as prisms, needles and microcrystals usually produced at low temperatures and humidities. Replicas produced by the method developed by Schaefer (1941) are excellent; photomicrographs of originals measuring less than 10^{-2} mm. were obtained with a magnification of 1,000.

The surface forms of the snow are basically of aeolian origin and sastrugi are oriented along 165° E., thus making an angle of about 30° to the west of the line of greatest slope (195° E.). This shift agrees with earlier observations (Dolgushin, 1958, map; Hollin and Cameron, 1961, p. 838; Stuart and Heine, 1961, p. 1000) and with the theoretical predictions of Ball [1960]. Snow accumulation measurements (Cornet and others, 1960) at 47 points over annual periods, using stakes regularly spaced along the track, reveal a very irregular distribution due to wind conditions; there is a marked maximum (60·6 cm. water equivalent) at B 12 (altitude 1,104 m.,

* Air temperature recordings at Dumont d'Urville (altitude 40 m.) and Charcot (altitude 2,400 m.) give a gradient of 1·12° C. per 100 m. for 1957 and 1·10° C. per 100 m. for 1958.

distance to the coast 47 km.), followed by a general decrease with distance from the coast. The last two remarks are comparable with, for example, the observations of Vyalov (1958, fig. 6, p. 271). There may be various reasons for this decrease, such as the decrease in the number of atmospheric depressions towards the interior of the Continent, and the sudden rise in altitude in the coastal area, which favours condensation phenomena: the air which penetrates onto the plateau, having lost a certain amount of its vapour content, will generate less

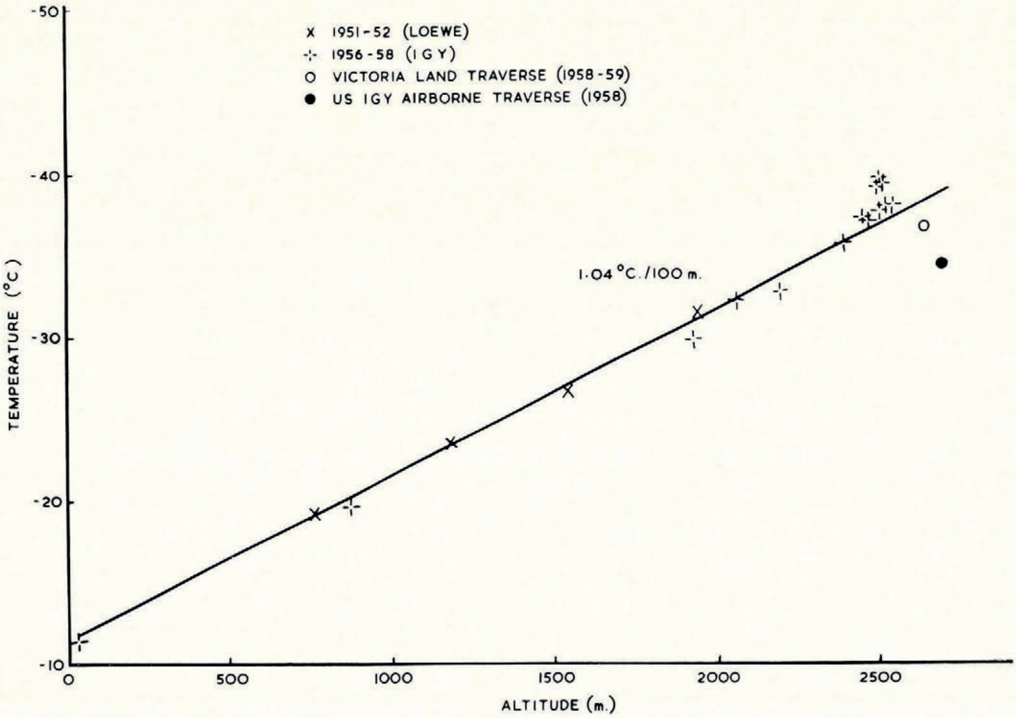

Fig. 3. Variation of temperature as a function of altitude

abundant precipitation. It seems that an altitude slightly above 1,000 m.a.s.l. is a clearly defined condensation level for the predominant air masses during depressions.

Measured accumulations have been grouped for sectors defined by comparatively large differences of mean slope to avoid the individual spread of readings due to local influence of the wind. This computation leads to the following rough equation

$$A = 10 + \frac{1000}{D} + 10p$$

where A is expressed in cm. of water equivalent, D is the distance to the coast in kilometres, and p is the slope expressed as a percentage. Figure 4 shows the good agreement between measurements and the graphical representation of this formula except for the point in the border area, where the rapid drop in altitude is responsible.

Building Up of the Firn Cover at Station Charcot: Annual Accumulation

The determination of annual layers from stratigraphic studies has been dealt with by a number of authors (Benson, 1961; Schytt, 1958; Shumskiy, 1955; Sorge, 1935, to mention but a few). In Terre Adélie the generally accepted methods were used to interpret our measurements of density, grain-size and hardness, for which continuous samples from various cores were available; these determinations were supplemented by ram hardness profiles (rammsonde). The summer layers are characterized by large-grained layers, low density and poor cohesion. The results are tabulated below, and are to be compared with the accumulation measured directly of 10·2 cm. water equivalent for 1957 and 18 cm. for 1958.

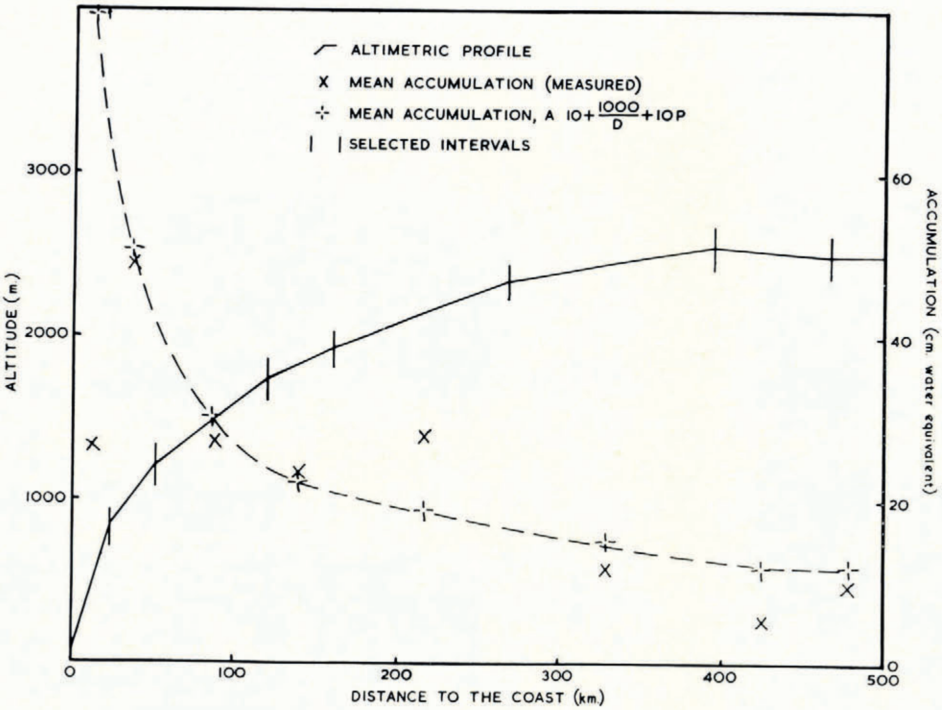

Fig. 4. Annual accumulation (water equivalent, 1957) versus distance to the coast

TABLE I. ACCUMULATION AT STATION CHARCOT DETERMINED FROM CORE STRATIGRAPHY

	Mean annual accumulation cm. water equivalent	*Number of years*
Core 1	22·6	37
Core 2	13·4	10
Core 3	16·6	17
Core 4	18·0	10
Core 5	22·4	23
Core 6	28·1	24

The spread of these figures raises the problem of the accurate determination of accumulation in areas where, as on the plateau of Terre Adélie, temperature is always well below 0° C. and accumulation is small and very irregular. Sastrugi, which are the main feature of the microrelief, may actually remain on the surface for a year or more, and besides this our observations did not enable us to identify a marked development of strongly settled winter layers which had been exposed to air temperature variations and solar radiation during the summer. Hence, in cases such as this, the counting of years will necessarily be inaccurate.

A seasonal study of firn layers was conducted on profiles of 20 m. length using coloured nylon threads as reference marks, over a one-year period, during which the mean accumulation was 10·2 cm. of water equivalent, seasonal deposits of comparable size show a marked difference as regards density: 0·375 g./cm.^{3} in summer as against 0·426 in winter, the grain-size remaining however practically the same. This difference can be attributed to wind con-

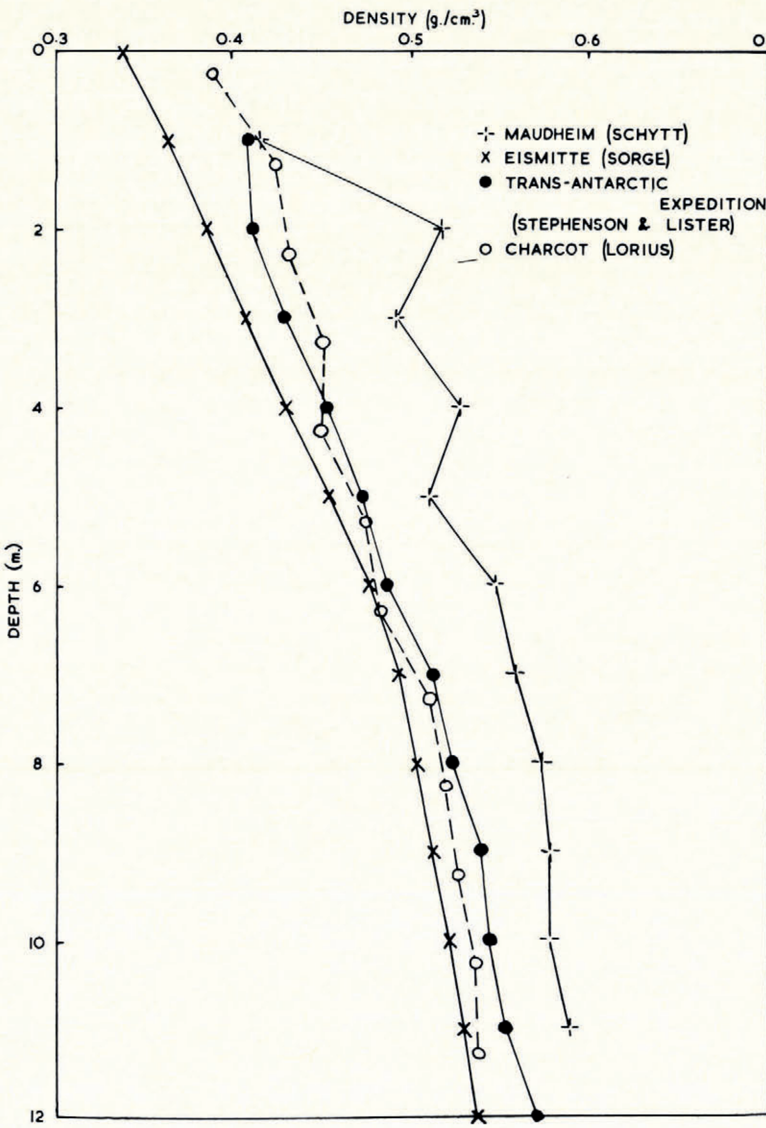

Fig. 5. Relationship between density and depth from various polar stations

ditions; the maximum and mean velocities are higher in winter (10·5 m./sec.) than in summer (9·1 m./sec.). This effect of wind velocity has been further assessed by a thorough investigation of the evolution of superficial deposits.

Porosity plays an important part in water-vapour transfer but, although we know that the density of winter deposits was 12 per cent above those of summer deposits, this is true only on

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the average, and individual deposits may have atypical characteristics which could lead to an erroneous analysis of layers.

For all these reasons, stratigraphic interpretation of layers is not an accurate method of determining the mean accumulation in Terre Adélie. It therefore seems necessary to supplement the conventional methods of observation with some recently developed dating procedures (Botter and others, 1961) based on deuterium and ^{18}O concentration. The simultaneous use of various techniques such as stratigraphy, dating, and measurement of electrical properties, is required to reach a high degree of accuracy.

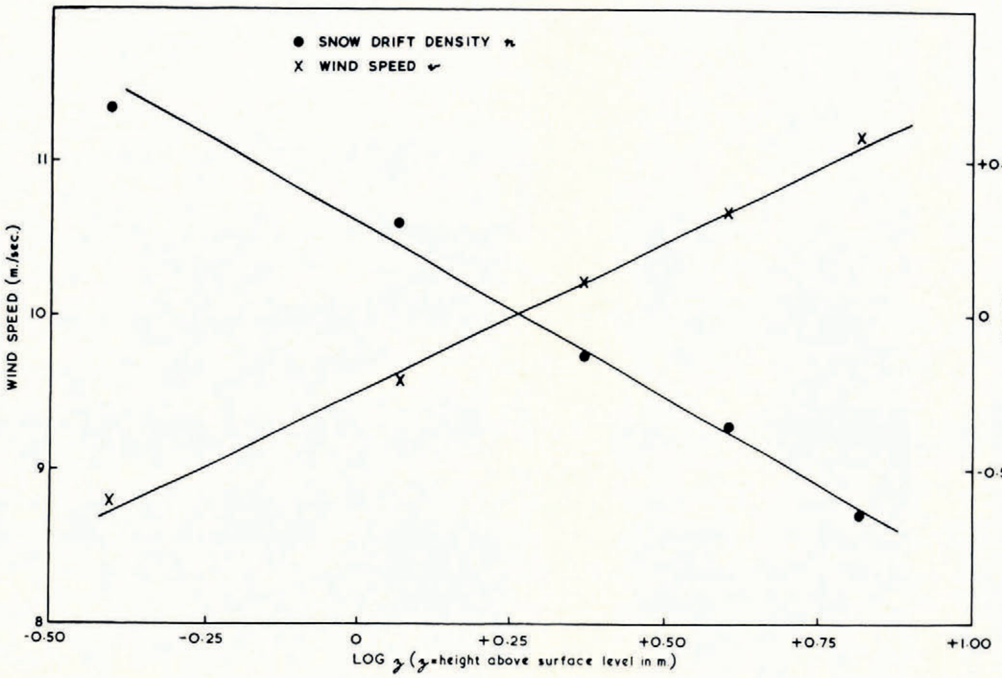

Fig. 6. Variation of windspeed and snow-drift density with the height above surface level, 14 November 1957, 10.00–12.30 hr.

The variation of density d with depth h is represented from 0 to 20 m. by a formula derived from the mean of several corings by the method of least squares (previously used for this purpose by Bader).

$$d = 0{\cdot}017h - 0{\cdot}0004h^2 + 0{\cdot}4$$

where d is measured in grams per cubic centimetre and h in metres. This curve, found for Station Charcot, is compared with the results of other authors in Figure 5.

Drifting Snow

In 1956, snow collected at Dumont d'Urville base* between 0 and 21 m. altitude, corresponded to a transfer of about 400,000 kg. per metre of coast per year for a mean wind velocity of 10·4 m./sec., ignoring any efficiency factor which should be applied to allow for the use of improvised traps. In 1957 twenty-two series of measurements were made at five levels at Station Charcot, with simultaneous wind velocity recordings. A study of the results, based on

* Dumont d'Urville base is located on a rocky islet bordering the Continent.

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theoretical considerations of Loewe (1956, p. 125) and Dingle and Radok (1961) leads to the following conclusions: (a) wind velocity varies logarithmically with height above the ground, and (b) there is a linear relationship between the logarithms of density of drifting snow and altitude above the ground. A typical illustration of these relationships is given in Figure 6. Furthermore, the transported amount of snow, determined by integration of the curve representing the weight of collected snow as a function of height (Fig. 7), is roughly proportional to the quantity of snow drifting across the 0·5 m. level.

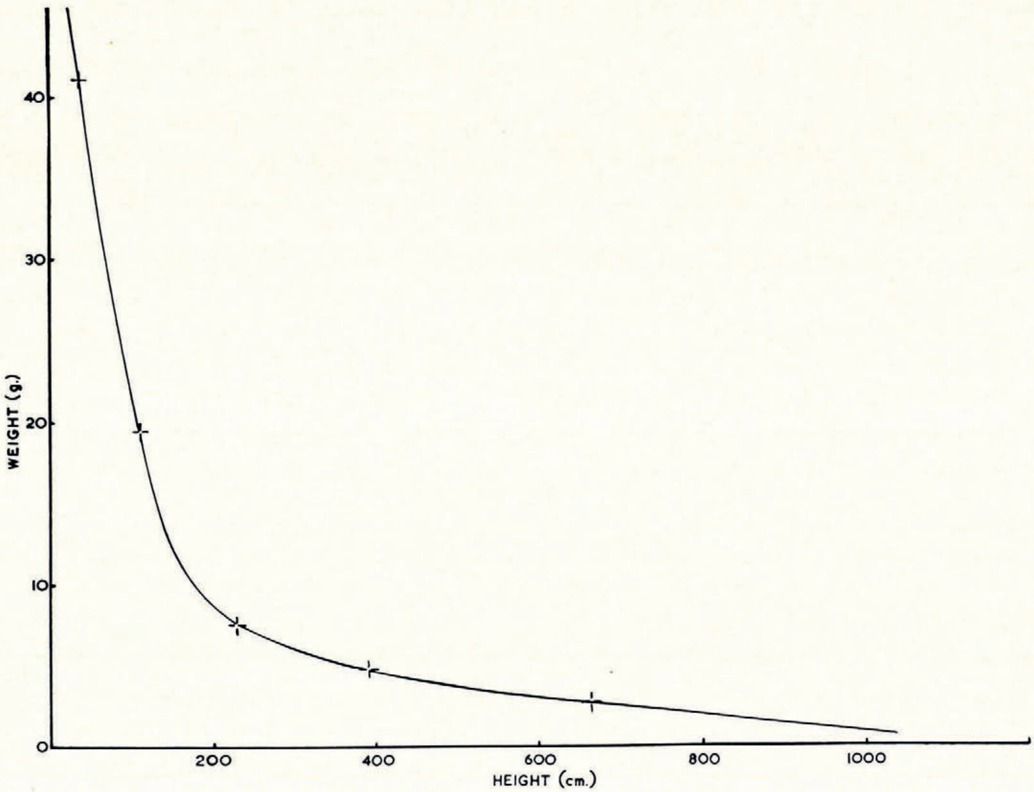

Fig. 7. Weight of snow drift versus height above surface level, 14 November 1957, 10.00–12.30 hr.

Use was made of 86 complete investigations carried out in 1958 on three levels at Station Charcot (Garcia, 1960), and of the full set of micrometeorological observations concerned with drifting snow. For an average annual wind velocity of 9·2 m./sec., the annual transfer was about 290,000 kg. for each vertical section of 1 m. width perpendicular to the wind. Again this figure ignores any efficiency factor. The quantity Q of transported snow increases, as a first approximation, according to an exponential law as a function of wind velocity at 10 m. Figure 8, plotted from averages derived for velocity intervals of 1 m./sec., corresponds to the equation

$$\Delta \log Q = \Delta v / 4 \cdot 6.$$

In this connection, the results of Dingle and Radok (1961) should be recalled; they found that

$$\Delta \log Q = \Delta v / 10 \cdot 5 \qquad \text{for } 15 < v < 29 \text{ m./sec.}$$

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Results obtained by various authors are tabulated below.

TABLE II. RESULTS OBTAINED BY VARIOUS AUTHORS FOR QUANTITY OF DRIFTING SNOW

Authors	*Wind velocity at 10 m.* m./sec.	*Quantity of drifting snow* kg./m./hr.
Loewe (1956, p. 131)	35	10,080
Stephenson and Lister (1959, p. 431)	10·3	250
Mellor and Radok [1960]	28	55,080
Dingle and Radok (1961, see fig. 4)	8·9	720
	16·2	3,600
	28	33,840
	36	200,880
Lorius (present work)*	8·9	3·6
	10·3	7·2
	16·2	115

* The drifting snow measurements ignore an efficiency factor which could well double them.

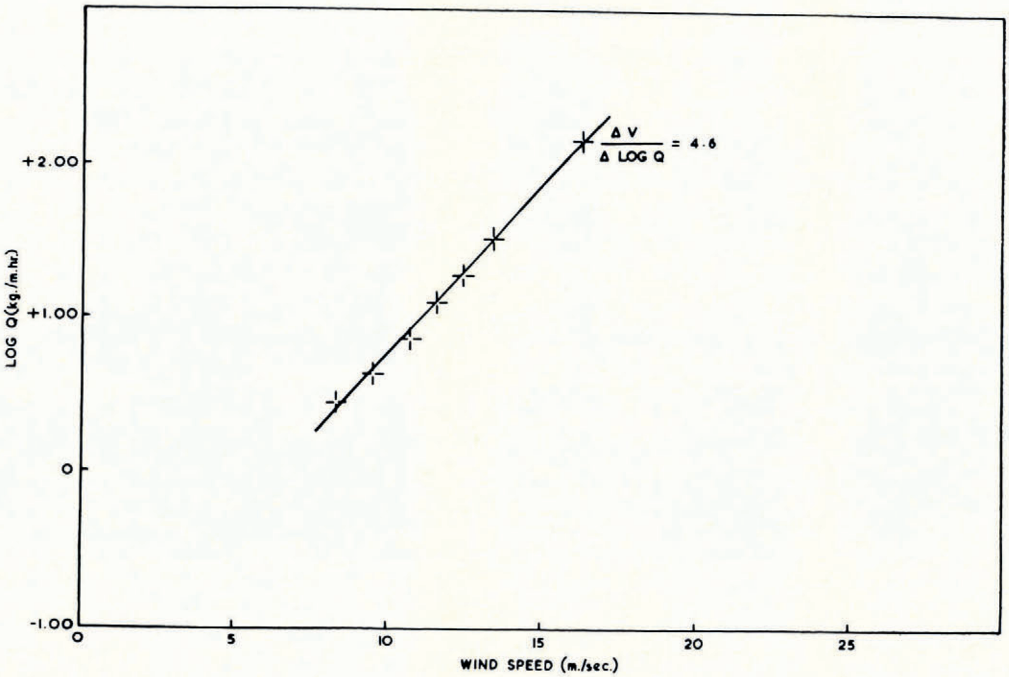

Fig. 8. Total weight of snow drift related to the windspeed

The fact that investigations were conducted at various points and dates, and hence did not have comparable surface conditions, accounts to some extent for the spread of the figures. The variety of recording instruments used is no doubt also largely responsible for the discrepancies. It is interesting to note the agreement between the present observations and the computations made by Vickers (1959) from theoretical considerations using wind profiles found by several authors. These are shown in Table III.

TABLE III. QUANTITY OF DRIFTING SNOW CALCULATED BY VICKERS USING VARIOUS WIND PROFILES COMPARED WITH QUANTITY OBSERVED

Wind velocity at 10 m. and author of profile m./sec.	*Calculated quantity of drifting snow* kg./m. hr.	*Measured quantity of drifting snow* kg./m. hr.
14·7 (Vickers)	54	55
12·4 (Liljequist)	18	19·1
14·3 (Bagnold)	43	45·7

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In this Table the wind velocities have been extrapolated from those at 1 m. using roughness factors given by Vickers.

Glacier Flow

As a result of measurements made on the Glacier de l'Astrolabe (Cornet, 1960), its mean annual velocity can be taken as 500 m./yr.; its mean thickness is estimated at about 400 m. In 1951, Perroud (1955) recorded an average daily displacement of 0·55 m. over a two month period using a reference mark located 1 km. from the margin of the Glacier de la Zélée (approximate width 11 km.); the velocity of the most conspicuous point of the cliff near this glacier was 9 m. over a ten-month period, that is to say an annual velocity of 11 m./yr. for an ice thickness of about 200 m.

Mass Balance in Terre Adélie

All the above results can be used as a basis for a study of the mass balance in Terre Adélie. Wexler (1961) has shown the difficulty of such a study for the whole of Antarctica; seven different balances show a large spread (from $-0{\cdot}95$ to $+1{\cdot}32 \times 10^{18}$ g./yr.).

Determination of accumulation. This balance has been taken for the sector whose edge is the coast of Terre Adélie, i.e. between long. 136° E. and long. 142° E. If we assume as a first approximation that the ice flows along the lines of greatest slope, we can determine graphically the accumulation area which corresponds to flow through the Terre Adélie coast (see Fig. 9). This area has then been divided into regions so that the data from Figure 4 can be used to calculate the net total accumulation. For 1957 this gave a net accumulation of 15·6 km.^{3} water equivalent for a total surface area of 58,000 km.^{2}.

Determination of ablation. Ablation can take place in the following ways:

surface melting
drifting snow
evaporation
oceanic melting
calving
subglacial melting.

We are not concerned here with surface melting, blowing snow and evaporation, because they have already been subtracted from precipitation before our determination of net accumulation. Let us examine the other factors.

Oceanic melting. This has not been studied experimentally in our case, and, having only a few measurements of sea temperature and salinity, this factor has been estimated from the calculations of Wexler (1960). Using $\Delta T = 1°$ C. for "the initial deviation of the water temperature above its freezing point as the water first comes in contact with the ice bottom", and an eddy conductivity of sea-water $A = 10$ g./cm. sec., and assuming the sea penetrates under the cliff for a distance of about 100 m., we get a melting of the order of 0·8 km.^{3}/yr. (water equivalent).

Calving. The results on glacier flow lead us to the following conclusions:

Table IV. Loss of Ice by Calving in Terre Adélie

Formation	*Width* km.	*Thickness* km.	*Ice velocity* km./yr.	*Calving* km.^{3}/yr.
Important glaciers	34	0·4	0·5	6·8
Secondary glaciers	10	0·3	0·25	0·75
Ice cliff	265	0·2	0·011	0·6
Rock outcrops	30	—	—	0
Total				8·15

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Assuming an ice density of 0·9 g./cm.^{3}, there is thus a net loss of 7·3 km.^{3} of water equivalent. The mean of the results for the calving from the whole of Antarctica given by Wexler (1960), ignoring the three extreme values, and scaled down to the length of the coast-line of Terre Adélie gives the very similar value of 8 km.^{3}.

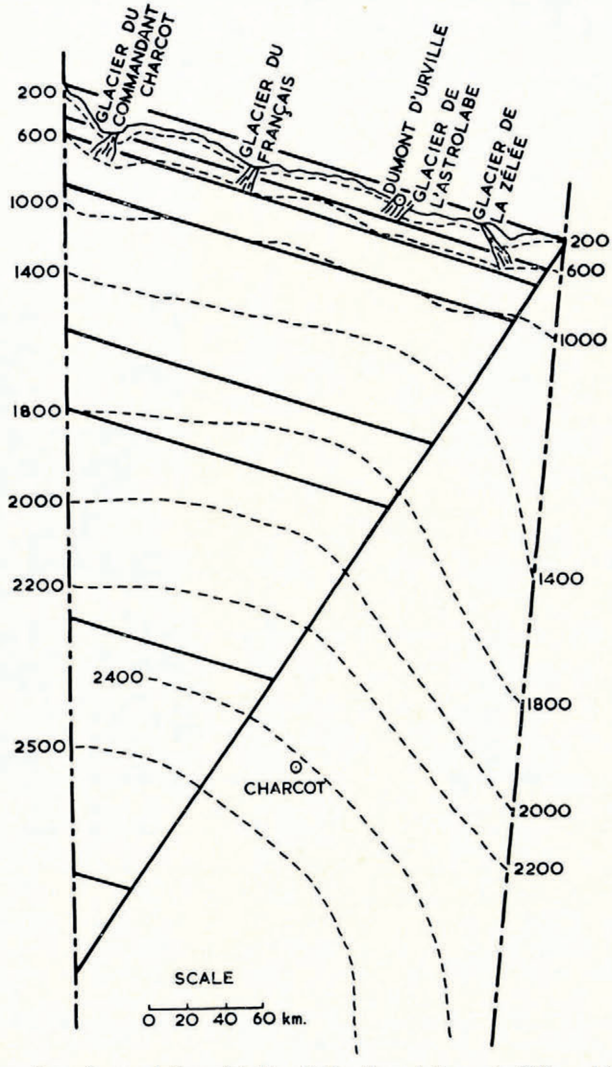

Fig. 9. Area of accumulation related to ablation through the coast of Terre Adélie

Subglacial melting. Two sources of heat must be taken into account. (a) Geothermal heat, for which we can use a value of 38 cal./cm.^{2} sec. (Jeffreys, 1952, p. 282). This provides 22×10^{15} cal./yr. for the whole area. (b) Transformation of potential energy in the ice, for which we can assume, as a first approximation, that the Antarctic Ice Sheet is in a steady state as regards its mass and shape; this means that each year energy is liberated equivalent to the work each snow accumulation does in descending to sea-level. Calculations for our eight regions (see Fig. 9) give a total value of 58×10^{15} cal./yr.

The maximum heat flux which could be conducted to the surface through the firn is calculated from the equation

$$Q = \lambda \frac{T_2 - T_1}{h}$$

where Q is the heat flux in cal./cm.^{2} sec., λ is the thermal conductivity (5×10^{-3} cal./cm. sec. ° C.), T_2 is the mean temperature at the surface and T_1 the melting temperature of ice under the overlying pressure, both in ° C., and h is the ice thickness in cm. This calculation gives a value of $17 \cdot 5 \times 10^{15}$ cal./yr.; only about one fifth of the total energy due to geothermal heat and potential energy transformation (80×10^{15} cal./yr.).

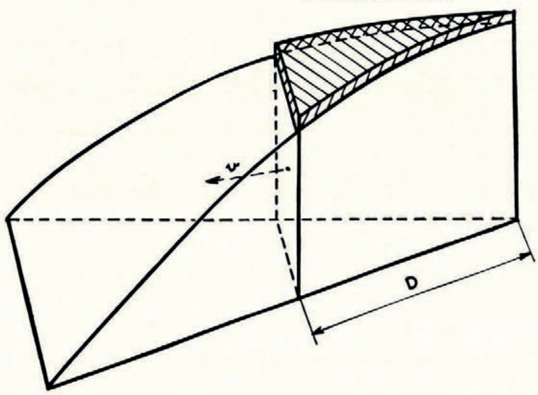

Fig. 10. Theoretical mean rate of outward movement

If we accept Nye's view (1951), all this energy is liberated in the ice at the ice-rock interface; so it seems that the bottom of the ice sheet should be at the melting point. The available energy would then melt $64 \times 10^{15}/80$ or $0 \cdot 8 \times 10^{15}$ g. of ice ($0 \cdot 8$ km.^{3} water equivalent). From Nye's hypothesis, Robin (1955, p. 525) calculates the work done in unit time at the ice-rock interface

$$W = 0 \cdot 88v$$

if W is in kg.m. and v is in m./sec. Determination of the rate of outward movement v_D through a section D is found as the integral of accumulation above that section divided by the area of section through which it flows, as shown diagrammatically in Figure 10.

Integration of the total energy from our eight sectors gives a value of 58×10^{15} cal./yr., and this together with 22×10^{15} cal./yr. of geothermal heat, makes a total of 80×10^{15} cal./yr. which, taking conduction into account, would melt $0 \cdot 8$ km.^{3} water equivalent. Thus these two different methods lead to the same result.

All these data for the mass balance in Terre Adélie are summarized in Table V.

TABLE V. MASS BALANCE FOR AREA DISCHARGING ICE THROUGH THE TERRE ADÉLIE COAST

Area: 58,000 km.^{2}	Ice volume: 100,000 km.^{3}
	km.^{3} water equivalent
Net accumulation	15·6
Ablation by calving	−7·3
Ablation by oceanic melting	−0·9
Ablation by subglacial melting	−0·8
Mass balance	+6·6

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Visual observations during the last three years nevertheless show a retreat of the ice wall in Terre Adélie with the appearance of rock. This retreat can perhaps be explained in one of the following ways; (a) due to movement at depth some ice included in the accumulation area is not calving through the coast of Terre Adélie; (b) current retreat results from past conditions, the time lag could be considerable as can be seen by comparing the mass balance, 6·6 km.^{3} with the ice volume, 100,000 km.^{3}; (c) some ablation processes may have been underestimated; the calculations are of course only very rough because they have to be based on only a few scattered surface measurements made over a very short time interval compared with the times involved in so complicated a phenomenon.

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