CONTRIBUTIONS TO THE GLACIOLOGY OF THE ANTARCTIC

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ABSTRACT. During a winter in Terre Adélie in 1951 (Antarctica) certain glaciological studies were made. These were strongly hampered by the extraordinary strength and persistence of the blizzards from the ice cap. Near the coast the wind dominates the distribution of snow completely. The firn limit on the open ice cap is at a height of 450 m. (1500 ft.). The deposited snow is very tightly packed with a density of 0·4—0·5 gm./cm.^{3}. On the ice cap the mean annual accumulation is 20–30 cm. water. At the coast and particularly on the ice cap measurements and calculations of the radiation balance show a strong loss for most of the time owing to the high albedo of the snow. The snow surface is almost continuously colder then the snow below and the air above. The radiation loss is mainly replaced by the influx of warmer air into the continent. The density of the drifting snow was measured. On a day with heavy blizzard the snow transport across each m. of the coast line is 2·5–3 kg./m.sec. In a year at least 20 million tons pass each km. (30 million tons per mile). In Terre Adélie the drifting snow is an important item in the mass economy of the ice cap.

ZUSAMMENFASSUNG. Glaziologische Studien während einer Überwinterung 1951 in Adélieland (Antarktis) zeigen den entscheidenden Einfluss der überaus starken und anhaltenden Stürme vom Inlandeis (Jahresmittel des Windes 19m/sec) auf die Verteilung des Schnees. Auf dem blankgefegten Abfall des Inlandeises tritt ständig das Eis zutage. In Leelagen liegt festgepackter Schnee von Dichte 0,4–0,5 auch im Sommer. Die Firngrenze liegt auf dem Inlandeis in 450 m Höhe. Im Innern bis 50 km Randabstand beträgt der Jahreszuwachs etwa 20 cm Wasser.

Messungen und Berechnungen der Strahlungsbilanz geben dank der hohen Albedo des Schnees an der Küste einen überwiegenden, im grössten Teil des Inlandeises einen fast ständigen Verlust, der hauptsächlich durch Einströmen wärmerer Luft gedeckt wird. Die Schneeoberfläche ist meistens kälter als die tieferen Schnee- und benachbarten Luftschichten. Die mittleren Firntemperaturen zeigen eine starke Abnahme mit zunehmender Seehöhe der Inlandeisoberfläche.

Die Dichte des Schneefegens wurde gemessen. Während heftiger Schneestürme werden jede Sekunde 25–30 g über jeden cm der Küstenlinie verfrachtet. Die jährliche Gesamtmenge beträgt mindestens 20 Millionen t auf 1 km Küstenlänge. In Adélieland leistet das Schneefegen einen wesentlichen Beitrag zum Massenhaushalt des Inlandeises.

INTRODUCTION

The "Expéditions Polaires Françaises," besides their more extensive and important work in Greenland, maintained between 1950 and 1952 wintering parties in Terre Adélie, the French sector of the Antarctic Continent, 1950 and 1951 at Port Martin (lat. 66° 49′ S., long. 141° 22′ E.), 1952 at Pointe Géologie (lat. 66° 40′ S., long. 141° 0′ E.)[1]. As an observer for ANARE (Australian National Antarctic Research Expedition) the author visited Terre Adélie in the summer of 1950 and wintered at Port Martin in 1951. During this period he had the opportunity of doing some glaciological work, aided in different respects by the French members of the expedition. His results, which are summarised in the following article, will be more fully published through the Expéditions Polaires Françaises.

Terre Adélie, "The Home of the Blizzard"[2, 3], on account of the unparalleled frequency and violence of blizzards, represents the Antarctic climate at its hardest and offers very serious difficulties to scientific work in general and to glaciological studies in particular. These super-storm conditions have been most impressively described by Sir Douglas Mawson[2]. The annual mean wind velocity at Mawson's winter station, Cape Denison, and at Port Martin was about 19 m./s. (42 m.p.h.). The month with the strongest wind, March 1951, had a mean of 29 m./s. (65 m.p.h.): days with a wind mean exceeding 45 m./s. (100 m.p.h.) were experienced. Snow drift existed during more than half of the year; very heavy drift with invisible sky and a horizontal visibility of a few metres occurred during the winter months in over 20 per cent of the time. It is remarkable that at Pointe Géologie, only 70 km. (40 miles) west of Port Martin, the wind was only about half as strong, a fact of which, incidentally, the Emperor Penguins have taken advantage to establish here one of their five hitherto located rookeries[4]. These gales, invariably blowing off the ice cap and generally heavily charged with drifting snow, are of the type of the Bora; their driving force is preponderantly that of gravity acting upon the air near the surface of the ice cap which has been cooled by contact with the cold snow surface[5].

THE DISTRIBUTION OF SNOW AND ICE

The gales of Terre Adélie have a profound influence upon the distribution of the snow on the ice cap, on the small rock outcrops along the coast and upon the ice cover of the sea itself. The sea ice conditions along this part of the Antarctic coast, as far as they are known from observations during five years, are very peculiar. During the winters Mawson spent at Cape Denison, 1912 and 1913, no solid sea ice was ever formed; thin ice layers which occasionally occurred near the coast were always driven out to sea with the next gale. In 1950 and 1951 on the other hand solid sea ice off Port Martin lasted from May to November for at least 30 km. (20 miles) and probably even farther out to sea. In both years sledges were able to travel on the sea ice to Cape Denison to the east and to Pointe Géologie to the west[1a, b, 3]. In 1952 too solid ice was formed between Pointe Géologie and Port Martin. But in this year during its coldest part, early in September, a heavy gale drove all winter ice off Pointe Géologie out to sea. It reformed, however, after a few days[1c, 4]. These varying ice conditions must have a great influence upon the movements of the Emperor and Adélie penguins between their rookeries and the pack ice. The reason for the fundamentally different state of the sea ice in different years is unknown. The air temperatures in 1912, 1913, 1950 and 1951 were almost identical[6]. The sea temperatures along the coast are always near the freezing point of the sea water. One would expect that a period of calm weather in autumn would allow the ice cover to consolidate to such a degree that subsequent winter gales would no longer be able to destroy it. But in 1951 the offshore gales in March and April were stronger than in the two years of Mawson's winterings; nevertheless the sea ice formed in 1951, but not in 1912 or 1913.

Wherever a place is sheltered from the wind which pours down from the ice cap in winter almost incessantly and with speeds which exceed frequently 40 m./sec. (90 m.p.h.), permanent snow drifts and snow drift glaciers are formed. At favoured places the snow drifts on the sea ice build up to the height of the terminal face of the ice cap, 20–30 m. (60–100 ft.). The tails of these drifts extend on the sea ice northward to a distance of more than one kilometer. At these and at other places where much drift snow is deposited, the sea ice is depressed under the load and sea water infiltrates between the ice and the snow cover. In this way the ice under a continuous snow cover might become completely rotten[3, 4]. This effect, well-known from other expanses of ice-covered water, represents a serious difficulty for the travels of heavy vehicles on seemingly solid sea ice.

On the other hand at places exposed to the full blast of the katabatic wind no snow will collect even in winter. Thus the last slopes of the ice cap near Port Martin like those at Cape Denison[2] had a nearly permanent surface of bare ice. Ablation stakes showed a slight lowering of the surface even in winter; it could not be established in what proportion this was due to evaporation and to erosion by the incessantly drifting snow.

THE NATURE OF THE SNOW SURFACE

Under the storm conditions of Terre Adélie almost all deposits consist, not of freshly fallen dendritic snow, but of particles that have been carried a long distance before coming to rest. They have been reduced to a size of only 0·1 to 0·2 mm. by continuous collisions with each other and the surface and have been rounded to spherical, ellipsoidal or cylindrical shapes[7]. When they are deposited, the pressure of the wind packs them very tightly. Hence the density of the surface layers exceeds generally 0·4, even without melting effects, and their resistance to the penetration of a disk[8] shows a mean value as high as 20–25 kg./cm.^{2}. This hardening facilitates travelling on the ice cap, but on the other hand since it is combined with considerable unevenness of the surface it puts a big strain on all vehicles.

The drifting snow is generally deposited in whaleback dunes of a height of about 1 m. which extend to different lengths in the direction of the prevailing wind. After a short time these dunes get a harder crust which after some time frequently becomes pockmarked, an initial form of the cuspate surfaces which are so common in snow and ice. We found that this crust was then locally destroyed, and drifting snow started to undercut it at the front and the sides of the dune. In this way typical sastrugi were gradually cut out of the surface. Their varying and ever-changing forms invariably follow a certain pattern. The normal relative height of the sastrugi thus formed was about 30 cm. but would occasionally exceed 1 m. An overhanging lip on the windward side of each sastruga was a typical feature; after some time this would either break off or the tip would be lowered to the lower eroded level.

These sastrugi sometimes made travel with tracked vehicles almost impossible in a direction at right angles to the prevailing wind and to their own extension. As far as 300 km. (200 miles) south of the edge of the ice cap the surface was still strongly cut up and pressed hard, thus proving the prevalence of blizzards during much of the year even at this distance. This is a considerable difference from the state of the surface in Greenland and in other parts of the Antarctic.

The Mass Economy of the Ice Cap

As the deposition and the removal of the snow are almost completely determined by the wind in Terre Adélie, the position of the firn limit where ablation equalises accumulation, varies strongly with the exposure to the wind. In protected places permanent snow drifts extend right down to sea level. But on the slope of the ice cap where almost all deposited snow has again been removed by the wind, ablation exceeds accumulation to a height of about 450 m. (1500 ft.) and to a distance of 8 km. (5 miles) from the border. Towards the end of summer bare ice appeared to that distance. Lower down near the edge of the ice cap the effects of melting were quite marked; unfortunately, owing to the fall of the ablation stakes, no reliable data of its amount have been secured. During the months March to November 12 cm. of ice were removed, half of it in November.

Further inland to a distance of 50 km. (30 miles) from the coast, the accumulation was measured on stakes. On account of the irregular erosion and accumulation by drifting snow the readings on these stakes differ considerably and unsystematically; on the average an annual accumulation of 20–30 cm. of water can be assumed. If these values, and even smaller ones, can be accepted as representative, the accumulation on the ice cap would probably exceed the removal by melting and iceberg formation. During the midsummer period the height of the stakes in the accumulation area increased; this is mainly due to a consolidation of the firn and not to a process of true ablation.

The Radiation Balance at Port Martin

Using Albrecht's "Net radiation recorder" (*Strahlungsbilanzmesser*)[9] studies of the radiation balance of the snow surface were made at Port Martin and to a smaller extent during a sledge journey on the ice cap in December. These observations were very strongly hampered by the blizzard conditions of Terre Adélie. No permanent installation was possible, and the often extremely sudden onset of the gales made even the safeguarding of the instruments precarious. Extended extrapolations had therefore to be made in order to establish the radiation balance.

In view of the great purity and small water vapour content of the Antarctic atmosphere the incoming global (sun and sky) radiation and the emitted radiation passing into space are, for a given height of the sun, rather bigger than in lower latitudes. With the aid of a formula derived by Albrecht[10] and checked by our observations the mean daily heat energies in cal./cm.^{2} were calculated (1 cal./cm.^{2}=3·7 B.Th.U./ft.^{2}). The radiation received on clear days is given in the second line of Table I.

TABLE I. RADIATION AT PORT MARTIN (cal./cm.^{2} day)

Month	*I*	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year* $\times 10^{-3}$
Global radiation, clear sky	675	475	280	95	8	0	2	45	185	400	620	725	106
Global radiation, cloud, drift	525	340	180	65	7	0	2	33	120	305	465	540	76
Absorbed radiation, Port Martin	290	170	90	20	1	0	0	7	20	75	140	270	33
Absorbed radiation, coastal strip of ice cap	155	85	35	15	1	0	0	5	20	60	115	165	20
Effective outgoing radiation	−115	−100	−75	−105	−95	−94	−100	−80	−125	−110	−130	−125	−38
Balance, Port Martin	175	70	15	−85	−95	−95	−100	−75	−105	−35	10	145	−5·3
Balance, coastal strip	40	−15	−40	−90	−95	−95	−100	−75	−105	−50	−15	40	−19

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In Antarctic regions the global radiation remains very considerable even if clouds are present[11]. The clouds are generally thin, have a small water content and transmit a high proportion of the incident solar and sky radiation. Secondly the snow-covered ground has a strong reflecting power for the radiation from the sun and sky shorter than $1\cdot5\mu$, and part of this reflected radiation is in its turn reflected by the atmosphere and particularly by the lower side of clouds[12] (ice blink). Over an unsoiled snow surface the multiple reflection between sky and ground raises the global radiation with clear sky by 1/7, with overcast sky even by 9/5. This multiple reflection between cloud and sky is responsible for the phenomenon of the "whiteout" when all differences in brightness vanish in the completely diffused light, and the traveller is unable to distinguish the inequalities of the ground or to judge any inclination because the reference line of the horizon disappears. This equality of the light fluxes in the upward and downward direction over an unbroken snow surface is even strengthened by the fact that unmodified snow is an almost perfect reflector of light in the visual range[13].

A special difficulty in the establishment of the radiation balance in Port Martin arises from the frequency of dense snow drift which modifies the radiation reaching the surface as well as that emitted from it. No quite satisfactory solution regarding the influence of drifting snow could be reached as no radiation measurements could be taken under blizzard conditions. The most likely values of incoming radiation under the influence of blizzards and clouds are given in line three of Table I.

The fraction of the incoming radiation that is actually absorbed by the surface is determined by its albedo. In Terre Adélie, as in all polar regions, the albedo is high on account of the prevalence of ice and particularly of snow at the surface. The hard-packed snow of Terre Adélie has a high density which in most regions is connected with a marked decrease of its reflective power[14]. But in the Antarctic the snow remains completely free of dust and is not modified by melting except during a short time over a small part of its surface; it therefore retains the high albedo which at other places characterises only loose freshly fallen snow. On the ice cap an albedo of 6/7 is certainly not overestimated. At Port Martin where the melting in summer is substantial, the albedo falls to about 0·5. This low albedo applies, however, only to the snow-free region nearest to the coast; even the bulk of the border regions of the ice cap remains snow-covered in summer and keeps an albedo of the order of 0·7. Under these assumptions the absorbed energies at Port Martin and in a coastal strip of the ice cap are given in Table I.

The effective outgoing radiation from the surface is determined by the emission of the snow surface that radiates almost like a black body and the back radiation from the atmosphere. In polar regions the proportion of the energy lost to that emitted from the surface is high because the atmosphere contains little of the absorbing water vapour and because the clouds are frequently so thin that a not negligible fraction of the long wave radiation coming from below passes through them. This effective outgoing radiation of the snow surface depends only to a small degree upon the temperature of the snow and varies mainly with cloudiness and the frequency of snow drift which, if heavy and spreading high aloft, influences the emitted radiation like a low cloud cover. In darkness the measurements of the radiation balance are at the same time those of the effective loss of radiative energy from the surface. At night, with a clear sky, the measurements of the radiation balance at Port Martin give an average of $-0\cdot118$ cal./cm.^{2} min. The effective outgoing radiation diminishes with increasing cloudiness, and with heavy low cloud cover the measured radiation balance becomes almost zero.

The differences of the absorbed and lost radiation at Port Martin and on the coastal strip of the ice cap, insofar as it remains snow-covered throughout the year, give the radiation balances of the last lines of Table I. The observations of the radiation balance made at Port Martin and on the ice cap agree satisfactorily with the calculated values.

As the snow surface absorbs only a small fraction of the incident radiation and the effective outgoing radiation is substantial, a strongly negative radiation balance of the surface on the ice cap and in the coastal regions results. According to the measurements at Port Martin with a clear

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sky the radiation balance is negative to a height of the sun of 27°. This is in good agreement with the calculated values. The observations on the ice cap itself indicate that in order to make the radiation balance of the snow surface positive with a clear sky, the sun has to reach a height of about 40°, which is never attained over most of the Antarctic Ice Cap. To a height of the sun of about 25° the radiation balance of the surface becomes less negative with increasing cloud cover. As for most of the time the sun is below that height, a clearing sky leads to a cooling of the snow surfaces on and near the ice cap; in consequence disappearance of clouds on the Antarctic Ice Cap and at its borders is accompanied by a lowering of the mean air temperature almost throughout the year. For instance the mean temperatures with different degrees of cloudiness over the snow surface at Port Martin are given in Table II.

TABLE II. MEAN TEMPERATURES WITH DIFFERENT CLOUDINESS (°C)

Cloudiness (/8)	0–1	2–3	4–5	6–8
May, June, July	−22	−20·5	−18·5	−16
Year	−15	−14	−12	−10

THE RADIATION BALANCE OF THE ICE CAP

As only few observations of the radiation balance of the ice cap were made in December–January 1951/52, during a sledge journey from the coast to lat. 69 1/4° S. and a height of 1950 m., we have to rely almost completely on extrapolation. The extremely high albedo throughout the year is the decisive factor in the radiation balance of the ice cap. It leads to a very small intake of the incoming short wave radiation from sun and sky and, with the exception of midsummer days at latitudes north of lat. 75° S. and a few days with low cloud and a particularly strong inversion of temperature in the atmosphere, to a loss of net radiation. Considering a position at lat. 80° S. and at a height of 1800 m. (6000 ft.) as typical for ice cap conditions one gets the radiation values of Table III.

TABLE III. RADIATION FLUXES AT LAT. 80° S., 1800 m. (cal./cm.^{2}day)

	I	*II*	*III*	*IV*	*V*	*VI*	*VII*	*VIII*	*IX*	*X*	*XI*	*XII*	*Year* $\times 10^{-3}$
Global radiation, clear sky	885	525	195	1	—	—	—	0	55	315	740	975	112
Global radiation, cloud, drift	790	460	170	1	—	—	—	0	45	275	640	855	98
Absorbed radiation	130	75	30	0	—	—	—	0	10	45	105	145	16
Effective outgoing radiation	−150	−135	−150	−150	−150	−145	−145	−145	−145	−155	−150	−145	−55
Radiation balance	−20	−60	−120	−150	−150	−145	−145	−145	−135	−110	−45	0	−38
Balance, whole ice cap	−15	−55	−110	−145	−145	−140	−140	−140	−130	−105	−40	5	−36

Supposing that the radiation on the ice cap is given as 9/10 of that at lat. 80° S. (Table III) and 1/10 of that in the border region (Table I), one gets the monthly radiation balances of the last line of Table III. Admitting that these calculations are very tentative, the radiation balance of the ice cap becomes continuously negative with the exception of a few weeks in midsummer. The ice cap loses by radiation heat at the rate of 100 cal./cm.^{2} day: this loss would cool a firn layer of 4 m. by 1° C. each day.

If the heat content of the ice cap is supposed not to vary from year to year this loss must be replaced. The contribution from below, from the internal heat of the earth and from the frictional heat produced by the motion of the ice, is insignificant amounting in a year to the radiation loss of only one day; and the heat must be supplied from the air. The seasonal storage of heat in the snow, too, involves only amounts which are small compared with the mean radiation loss and which even at the time of the biggest intake and loss reach less than 10 cal./cm.^{2} day[17]. As the water vapour content of the Antarctic atmosphere is small and the mean precipitation is probably equivalent to less than 10 cm. of water a year, only a fraction of this heat will be supplied by the heat of crystallisation. The bulk of the heat comes from the convectional cooling of warmer air that enters the Antarctic Continent from the surrounding seas. This seems fundamentally different from the energy balance of the Greenland ice cap where the loss of radiative energy can be largely replaced by the heat of crystallisation of the stronger precipitation[17].

The Temperatures near the Surface

To study the heat fluxes to the snow surface, observations of temperature in the uppermost snow layers and at different small heights above the surface were taken simultaneously with the measurements of the radiation economy. Here again the weather conditions of Terre Adélie made permanent installations impossible. Generally the temperatures near the surface were lower than those at a depth of 5 cm.; only with a height of the sun exceeding 20° did the temperatures at the surface become higher than lower down. The clearer the sky the colder is the surface layer compared with the lower snow layers. This shows again the predominant importance of the outgoing radiation for the heat economy of the surface layers of the snow. The same relation prevails for the temperatures at the depths of 5 cm. and 20 cm.; here again the temperatures at the higher level are lower than those deeper down in the snow except with high position of the sun or a high degree of cloudiness. The mean temperature differences between the depths of 1 cm. and 20 cm. are shown in Table IV.

Table IV. Temperature difference in snow, 20 cm. minus 1 cm., °C, at Port Martin, depending on height of the sun and cloudiness. (March–November)

Cloudiness (/8)	0–1	2–6	7–8	*Mean*
Height of sun:				
< −2°	4·6	3·5	1·4	3·3
−2° to 9°	3·8	3·7	0·2	3·1
10° to 19°	2·4	3·2	−1·1	1·9
>19°	−1·3	−1·0	−2·5	−1·3

On the ice cap itself the same coldness of the surface layer was revealed by a small number of temperature observations of the snow even in midsummer.

Supposing an unchanging temperature of the snow and firn from year to year, the heat conducted towards the colder snow surface must be replaced. As the internal heat of the earth and the frictional heat of the motion of the ice make only insignificant contributions, the heat is brought beyond the depth of 20 cm. mainly by the penetration of and absorption by solar radiation into the partly transparent snow[18], and near the coast by the infiltration and refreezing of melt water in summer.

The temperatures of the snow surface at Port Martin as represented by those at a depth of ½ to 1 cm. are not only lower than those in the snow deeper down but also on the average lower than those of the neighbouring air layer. The mean temperature difference between −1 cm. and + 1 cm. is 1° C.; it is again bigger with clear than with overcast sky, corresponding to the strong variation of the effective outgoing radiation from the snow with varying cloudiness.

Structure and Temperature of the Firn

Several pits dug on the ice cap facilitated the study of the temperatures and firn structure to a depth of 3½ m. In general the firn is very hard; but at all depths occasional soft layers were encountered, generally below a particularly hard crust. The firn particles in these soft layers have sometimes so little cohesion that they start to roll out as "sago snow" (depth hoar or *Schwimmschnee*) if the layer is cut. Owing to the initial hardness of the deposited layers the rate of compression with time is smaller than under similar conditions on the Greenland ice cap[19]. At a height of 860 m. (2800 ft.) and a distance of 28 km. (18 miles) from the coast a layer which extended on the mean from 75 cm. to 250 cm. below the surface, showed an annual compression of slightly over 2 per cent. Neither the observations of the structure nor those of the density in the pits, which were frequently hampered by snow drift, revealed any regular annual or seasonal stratification of the firn. This is not surprising in view of the frequent changes between accumulation and ablation caused by the blizzards. As an example of the firn structure Fig. 1 (below) gives the observations in a pit at Point S_4 (lat. 69¼° S., 1950 m.).

Where the infiltration of melt water becomes insignificant, *i.e.* everywhere outside the outermost border region of the ice cap, the temperatures, as measured in pits and bore holes to a depth of 10 m., agree satisfactorily with the theorems of heat conduction. At a depth of 7 m. the annual temperature variation would be less than one tenth of that at the surface, at 9 m. only 3 per cent. The temperature at this depth therefore gives the mean annual temperature of the snow at any time with great accuracy. These snow temperatures will not differ much from the mean air temperature above the snow. In this way the following mean temperatures on the ice cap have been found.

TABLE V. MEAN ANNUAL TEMPERATURES ON THE ICE CAP

Height	0	500	1000	1500	2000 m.
	0	1600	3200	4800	6400 ft.
Lat. S.	66¾°	67°	67¼°	68¼°	69¼°
Temperature	−12	−17	−21	−27½	−34½° C.
	10	1	−6	−18	−30° F.

The corrections due to the accumulation of snow during the downward progress of the temperature wave are rather insignificant[20]. The temperature decreases very rapidly as one ascends the ice cap; only a small fraction of this decrease can be attributed to the increase in latitude. The surface of the ice cap at a height of 1000 m. (3300 ft.) is 6° C. and at a height of 2000 m. (6600 ft.) 15° C. colder than the air at the same level at the coast. This big difference of temperature and density of the air at the same height tends to set up a vigorous circulation between ice cap and ocean which is reflected in the strength and persistence of the katabatic winds off the ice cap of Terre Adélie[5].

If the mean temperature of the firn near the surface and the depth of the ice are known, conclusions can be drawn about the state of the ground below the ice cap, whether frozen or unfrozen. It is found that under the relatively shallow ice in Terre Adélie where depths of 200 and 500 m. (600 and 1600 ft.) have been measured, the ground is likely to be frozen; the temperature at the bottom of the faster moving glaciers is probably at the melting point of the ice.

THE SNOW DRIFT

Owing to the high wind velocities drifting snow was a very frequent phenomenon at Port Martin and on the adjoining ice cap. Table VI contains the seasonal frequencies of the different degrees of snow drift at Port Martin.

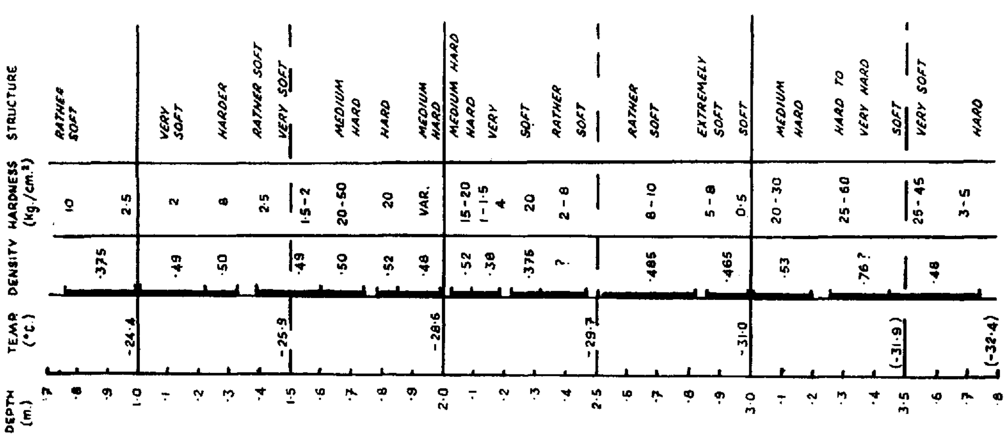

Fig. 1

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TABLE VI. PERCENTAGE OF TIME WITH DRIFTING SNOW, PORT MARTIN 1951

	Spring	*Summer*	*Autumn*	*Winter*	*Year*
Low, weak and moderate	13	7	16	12	12
Low, strong	6	4	16	9	9
High, weak and moderate	22	3	17	26	17
High, strong	10	4	23	21	15
All drifts	51	18	72	68	53

In 1950 and 1951 efforts were made to determine the amount of drift snow transported by the wind. A collector box [1a] similar to that used by Mawson at Cape Denison [21] was in operation in both years. The air carrying the snow enters the box through a small opening at a height of 50 cm. above the ice surface, drops its snow load in the box and leaves through a wider opening at the back. Owing to the distortion of the stream lines by the square box the air and the snow which enter it are only a fraction of that actually passing the cross section of the entrance. This was shown by the simultaneous use in 1951 of a more streamlined box with the opening at the same height, which collected nearly twice as much drift snow as the square box. The observations of the boxes give a mean transport of about 50 gm./cm.^{2} hour or a layer of 4300 m. of water per year.

These boxes give the densities of the snow at one height only. To evaluate the total amount of drifting snow, its vertical distribution must be known. Some observations concerning the density of the drift snow at different heights between 5 cm. and 2 m. were made by Barré[22]. His results are in good agreement with the catches in the trap boxes. In strong blizzards which, however, having a visibility of 10–20 m., were not among the heaviest, Barré found at a height of 1 m. a density of drifting snow of 7 gm./m.^{3}, at 5 cm. about 32 gm./m.^{3}. Extrapolation of these densities which are by no means excessive, gives on blizzard days between the surface and a height of 10 m. a transport of 12 gm./cm. sec. Further extrapolation with regard to the theorems of atmospheric turbulence [23] shows a transport of 13–14 gm./cm. sec. between the heights of 10 m. and 150 m., and of a further 2·5 gm./cm. sec. between 150 m. and the upper limit of the layer of drifting snow. We get then on a typical blizzard day a transport of altogether about 28 gm./cm. sec. On each blizzard day 240,000 tons of drifting snow pass each km. (380,000 tons each mile) of the coast line.

These amounts may appear excessive; but the basic data for the density and height of the drifting snow can be independently corroborated. The range of visibility is dependent upon the size and number of the obscuring snow particles[24]. The actual horizontal visibility at the height of the eye in blizzards is frequently restricted to 2–5 m.; occasionally, seen from the height of the eye, the ground disappears. This suggests drift snow contents of the air several times bigger than those used in our calculations.

The height of the drifting snow cannot generally be measured; the strongly reduced illumination, even with cloudless sky above, the "blizzard gloom" [2], suggests a considerable height of the drift-filled layer. Occasionally the blizzard ceased locally whilst continuing a short distance east or west of the base. In such cases the cloud of snowdrift, sometimes well defined, could be compared with the known heights on the ice cap and seemed to have a height of about 300 m.

Heavy blizzards, with a horizontal visibility of less than 10 m. and sun and sky obscured, occurred at Port Martin during one tenth of the year, giving a transport of 9 million tons over each kilometre (14 million tons per mile) of the coast line. Weaker, but frequently still very strong drift prevailed during a further 43 per cent of the year. If we suppose that during these 160 days the transport is the same as during the 36 days of heaviest drift, we get an annual transport of 18 million tons across each kilometre (30 million tons per mile) of coast line. It may be stressed that our assumptions and extrapolations have been such as to make the transport a minimum; a figure double ours seems well possible.

This transport of drifting snow removes to a distance of 200 km. (125 miles) inland one half of an assumed accumulation of snow corresponding to 20 cm. of water. In Terre Adélie the loss of snow from the ice cap by drift is more important in the mass balance than evaporation, melting or iceberg formation.

It is well known that the katabatic winds do not extend far out to sea[25]; consequently the drifting snow is dropped either into the water or on the ice near the coast. If all drift falls out within a strip of 20 km. (12 miles) along the coast, the water level would be raised 3 mm. per day, a rather important addition. For each cm. of the coast line the melting of this drift snow needs $1{\cdot}7\times10^{10}$ cal. (7×10^{7} B.Th.U.) per annum, or in a belt 20 km. (12 miles) wide along the coast $0{\cdot}016$ cal./cm.^{2} min. This loss of heat of the sea water is of the same order of magnitude as the loss by outgoing radiation [26]; on the continental shelf of Terre Adélie the drift snow carried by the gales off the coast contributes appreciably to the formation of the cold Antarctic water body.

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REFERENCES

1. (*a*) Liotard, A.-F., *and others*. Expédition en Terre Adélie, 1949–1951. *Expéditions Polaires Françaises. Publications Préliminaires*, No. 14, [1952].
   (*b*) Barré, M., *and others*. Expédition en Terre Adélie, 1950–1952. *Expéditions Polaires Françaises. Publications Préliminaires*, No. 20, [1952].
   (*c*) Marret, M., *and others*. Expédition en Terre Adélie, 1951–1953. *Expéditions Polaires Françaises. Publications Préliminaires*, No. 24, 1954.
2. Mawson, *Sir* D. *The home of the blizzard; being the story of the Australasian Antarctic Expedition, 1911–1914*. London, William Heinemann, 1915. 2 vols.
3. Barré, M. *Blizzard—Terre Adélie 1951*. Paris, René Julliard, [c1953]. 2 vols.
4. Marret, M. *Sept hommes chez les penguins*. Paris, 1954.
5. Prudhomme, A., *and* Boujon, A. H. Sur les tempêtes observées en Terre Adélie. *La Météorologie*, No. 21, 1952, p. 132.
6. Loewe, F. Beiträge zur Kenntnis der Antarktis. *Erdkunde*, Bd. 8, Ht. 1, 1954, p. 1–15.
7. Koch, J. P., *and* Wegener, A. Wissenschaftliche Ergebnisse der dänischen Expedition nach Dronning Louises-Land und quer über das Inlandeis von Nordgrönland, 1912–13, unter Leitung von Hauptmann J. P. Koch. *Meddelelser om Grønland*, Bd. 75, 1930, p. 590.
8. Klein, G. J. Canadian survey of physical characteristics of snow-covers. *Geografiska Annaler*, Årg. 31, Ht. 1–4, 1949, p. 106–24.
9. Albrecht, F. Ein Strahlungsbilanzmesser zur Messung des Strahlungshaushaltes von Oberflächen. *Meteorologische Zeitschrift*, Bd. 50, Ht. 2, 1933, p. 62–65.
10. Albrecht, F. Intensität und Spektralverteilung der Globalstrahlung bei klarem Himmel. *Archiv für Meteorologie, Geophysik und Bioklimatologie*, Ser. B, Bd. 3, 1951, p. 220.
11. [Peterson, H.-C.] *Results of the solar radiation project of the Ronne Antarctic Research Expedition*. Washington, D.C., Office of Naval Research [1948]. (Navexos P-566. Ronne Antarctic Research Expedition. Technical Report No. 3.)
12. Ångström, A., *and* Tryselius, O. Total radiation from sun and sky at Abisko. *Geografiska Annaler*, Årg. 16, 1934, p. 53–69.
13. Devaux, J. Étude de l'albédo de la neige dans le spectre infrarouge. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* (Paris), Tom. 200, No. 1, 1935, p. 80–81.
14. Eckel, O., *and* Thams, C. Untersuchungen über Dichte-, Temperatur- und Strahlungsverhältnisse der Schneedecke in Davos. *Beiträge zur Geologie der Schweiz. Geotechnische Serie. Hydrologie*, Lief. 3, 1939.
15. Bolz, H. M., *and* Fritz, H. Tabellen und Diagramme zur Berechnung der Gegenstrahlung und Ausstrahlung. *Zeitschrift für Meteorologie* (Potsdam), Bd. 3, 1950, p. 314.
16. Loewe, F. Das Klima des grönländischen Inlandeises. (*In* Köppen, W., *and* Geiger, R., *ed. Handbuch der Klimatologie*. Bd. 2, Teil K. Berlin, Borntraeger, 1935, p. 67–101.)
17. Albrecht, F. Untersuchungen über den Wärmehaushalt der Erdoberfläche in verschiedenen Klimagebieten. *Wissenschaftliche Abhandlungen. Reichsamt für Wetterdienst*, Bd. 8, Nr. 2, 1940.
18. Reuter, H. Über die Theorie des Wärmehaushalts einer Schneedecke. *Archiv für Meteorologie, Geophysik und Bioklimatologie*, Ser. A, Bd. 1, 1948, p. 62.
19. Sorge, E. Glaziologische Untersuchungen in Eismitte. (*In* Brockamp, B., *and others*. *Glaziologie*. Leipzig, F.A. Brockhaus, 1935, p. 62–270. (Wissenschaftliche Ergebnisse der deutschen Grönland-Expedition Alfred Wegener 1929 und 1930/1931, Bd. 3.))
20. Benfield, A. E. The effect of accumulation on temperatures within a snowfield. *Journal of Glaciology*, Vol. 2, No. 14, 1953, p. 250–54.
21. Madigan. C. T. *Tabulated and reduced records of the Cape Denison station, Adelie Land*. Sydney, Government Printer, 1929. (Australasian Antarctic Expedition, 1911–14. Scientific Reports, Ser. B, Vol. 4.)
22. Barré, M. Propriétés électriques du blizzard. *Annales de Géophysique*, Tom. 9, Fasc. 2, 1953, p. 164–83.
23. Lettau, H. *Atmosphärische Turbulenz*. Leipzig, Akademische Verlagsgesellschaft M.B.H., 1939.
24. Middleton, W. E. K. *Visibility in meteorology. Second edition*. Toronto, University Press, 1941.
25. Davis, J. K. *With the "Aurora" in the Antarctic, 1911–1914*. London, Andrew Melrose, Ltd., [1919].
26. Kimball, H. H. Solar radiation and its rôle. *Bulletin of the* [*U.S.*] *National Research Council*, No. 79, 1931, p. 35–66. (Physics of the earth, 3. Meteorology.)