Hydrometeorological Characteristics of Snow and Ice over Antarctica

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ABSTRACT

This paper deals with hydrometeorological characteristics of snow and ice along with radiation balance and computation of melt rate over the Antarctic continent. Climatic features of the continent were also studied and are presented here. It is observed that a large quantity of solar radiation (0.5 - 0.7 1y/min) is received at the surface but more than 80% of it is reflected back in space. Day light remains continuous round the clock during the peak summer months viz. December and January. The net radiative heat balance for the continent is positive in the months of December and January while negative for other months of the year. The net long wave radiation exchange, convective transfer and exchange of sensible heat contribute negatively to the mechanism of snowmelt during the summer months. The net snowmelt computed by various physical processes is found to be a few centimetres per day even in extreme summer period. The maximum wind speed observed during the expedition period was 80 km/hr. Also the typical phenomena of inversion mirage formed on the snow surface were observed during the expedition.

INTRODUCTION

The continent of Antarctica covers an area of about 14 x 10^{6} sq. km between the Antarctic circle (66.5°S) and the south pole. About 98% of its surface lies under snow and ice cover with an average thickness of about 1.6 km and maximum thickness of about 4.5 km. The total volume of ice is about 3 x 10^{16} m^3 According to an estimate if the whole mass of ice melts the sea level of all the oceans would rise by about 50 m. This ice load has depressed the continent by about 600 m on an average.

To study the climatic and hydrometeorological features of Antarctica, India Meteorological Department actively participated in the 'First Indian Antarctic Expedition' with the following scientific objectives:

(a) To study the tropical and high altitude atmosphere over the Indian Ocean.

(b) To investigate thermal structure of the atmosphere over the different regions enroute viz: trades, roaring forties and Antarctic easterlies.

(c) To study air-sea interaction over the south Indian Ocean particularly in the sub-tropical and Antarctic Convergence zones.

(d) To study airmass modification due to thermal characteristics associated with the convergence zones mentioned above.

(e) To study the radiation and heat balance at sea surface

(f) To study the vertical distribution of radiation fluxes in the troposphere

(g) To study meridional variation of ozone over the Indian Ocean.

(h) Radiation balance over Antarctica.

(i) Mechanism of snow melt and its melt rate.

In order to achieve these objectives, the following meteorological parameters were observed at synoptic hours:

(a) Temperature
(b) Pressure
(e) Humidity
(d) Wind velocity and direction
(e) Surface ozone
(f) Global, diffused, direct and net radiation measurements
(g) Radiosonde and Radiometersonde ascents
(h) Pilot balloon ascents for studying the upper atmosphere

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In the present paper the authors have confined themselves to assess the radiation balance and physical properties of snow and its melt rate. The above observed meteorological parameters (a - f) have been used for its computation.

Antarctic air is free from pollutants. It may serve as a reference for the determination of changes in pollution level and climate. Antarctica is a 'pulsating' continent. The pack ice stretches upto 1100 km from the coast during winter, but this very ice melts and breaks during summer. The recorded temperature during winter is below -80°C and wind blows outward from the high interiors to all directions sloping towards ocean.

TOPOGRAPHY

Antarctica is the remotest continent in the world; about 990 km from the nearest land at Cape Horn.

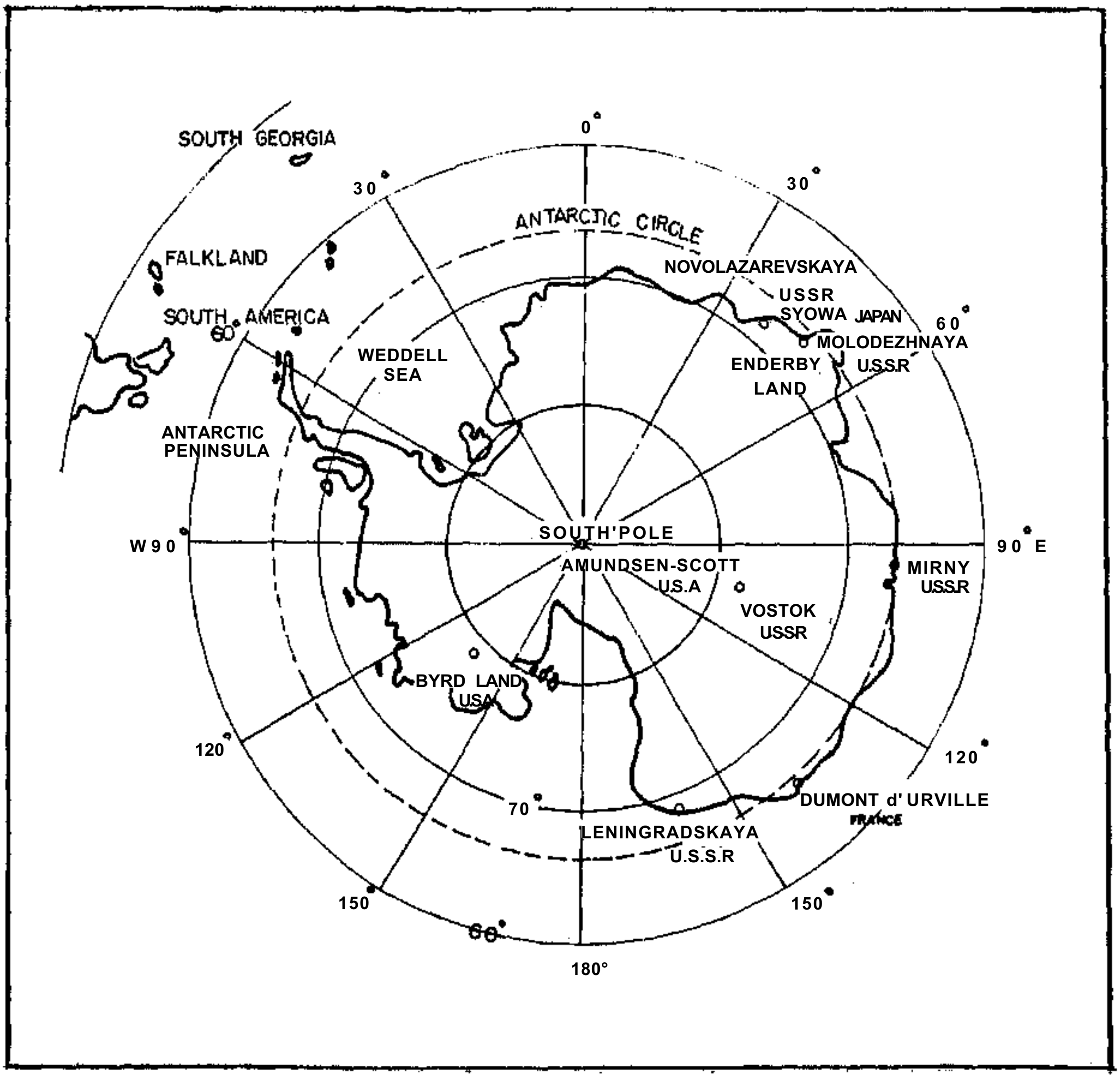

Fig. 1 ; Map of Antarctica and south pole

The transantarctica mountains with N-S orientation roughly divide the continent in two parts: east being larger in size and geologically older. If the Ice of Antarctica melts the west would then be an isolated group of islands and the east would be mountainous. The elevationwise distribution of the area in respect of the entire continent is as follows:

Elevation range (m)		Area (10^{fi}sq. km.)	Area Percentage
0—2000	... ...	**6.3**	**45**
2000—3000	... ...	**4.2**	**30**
3000 & above	... ...	**3.5**	**25**
	Total	**14.0**	100

The highest mountain peak of Antarctica is the 5140 m high Vinson Massif (Lat. 78.6°S, Long. 85.4°W). The ice cover has an extension of 3600 km during summer and 5400 km during winter along 0° longitude. The thick ice sheet has an elevation of about 4000 m in the interior of the continent which gradually reduces towards the coast. Permanent ice shelves with thickness varying from 200 to 1300 m have been formed at various places along the coast. The average area of extension of pack ice, around the continent is minimum in March (2.6 x 10^6 km^2) and maximum in September (18x$10^6$$km^2$). It means that the total ice covered surface (sea plus continent) in September is about twice as large as in the month of March. Fig. 1 shows the map of the continent with a few meteorological stations.

CLIMATOLOGY

Antarctica has a short summer during December and January when the sun remains above the horizon all the time. April to September are winter months when practically there is no sunshine. The rest of the months may be regarded as transition period. A brief account of meteorological elements are provided below:

Temperature

The mean air temperature during summer (January) and winter (July) of the continent are presented in Fig. 2. It can be seen that the coastal areas are comparatively warmer and temperature decreases inwards. Peninsular regions have the highest temperature (above freezing point during summer and between -10° to -20° during winter). Central land mass is the coldest (-30° or below during summer and —60°or below during winter). The mean daily temperatures for the two seasons (short summer and winter) alongwith annual mean in respect of few stations are listed in Table 1.

The lowest temperature so far recorded on this continent is -88.3°C on 24th August, 1960 at the Russian station, *Vostok* (Lat. 78.45°N Long. 106.8°E, 3488 m). The maximum and minimum temperatures recorded at the ice shelf during the expedition were +1° and -7°C respectively (Table 2).

Another important feature besides low temperatures of the interior of the continent is surface inversion. The strength of the inversion varies from place to place. The stability of the lower atmosphere caused by this may be one of the factors responsible for low precipitation. Mirage formed due to surface inversion appear to be common. A number of huge icebergs are seen towards the land, which vanished away after a few hours.

Pressure and Wind

No isobars could be drawn on the continent due to abrupt changes in elevation. The average surface pressure in east Antarctica is less than 700 mb and over central high plateau even less than 600 mb,

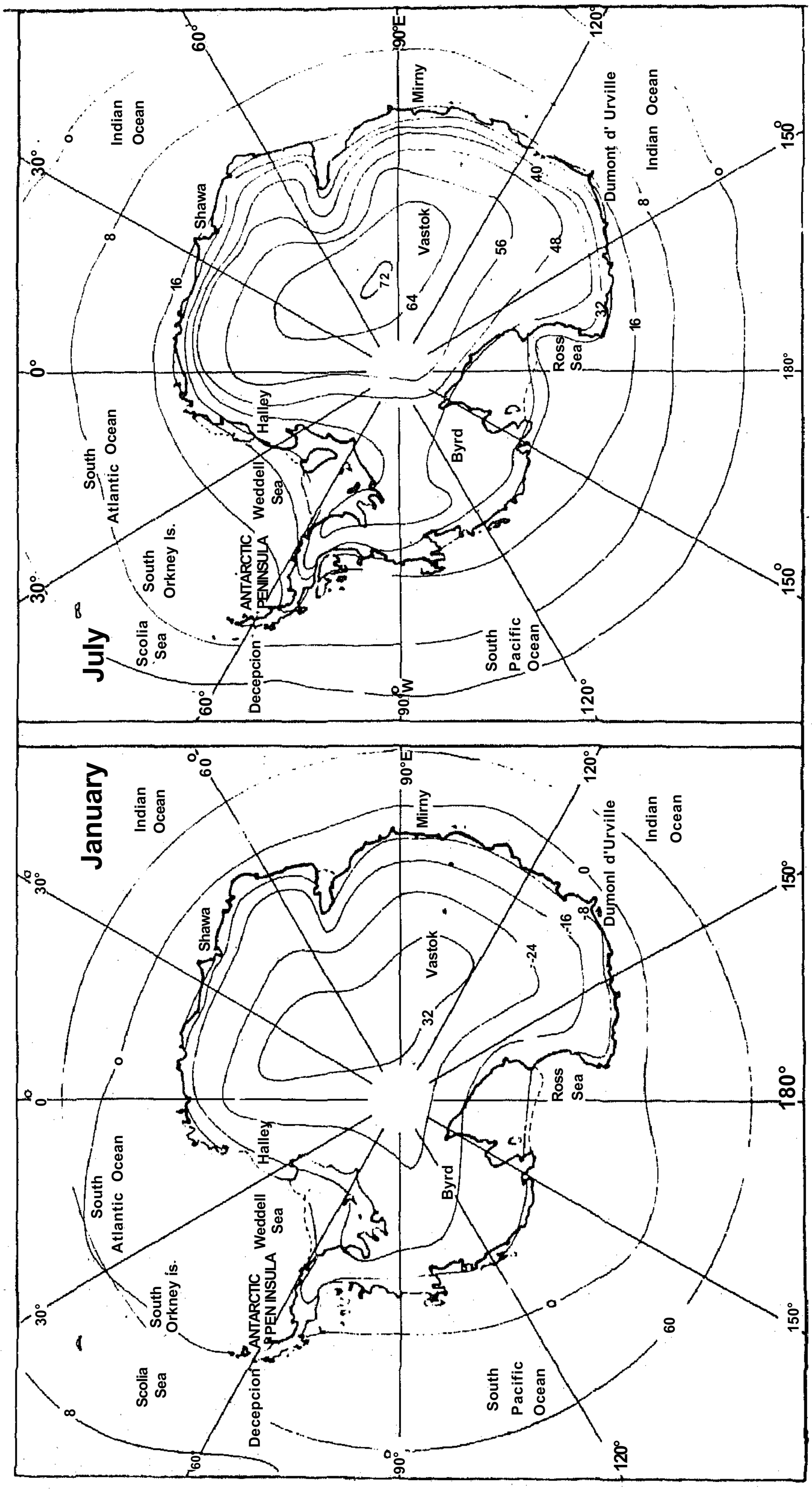

Fig. 2 : **Mean air temperature (°C)**

TABLE I

Climatic Table

S No	Station	Lat (°S)	L (E/°W)	Elevation (mt)	Daily Mean Temperature (°c) 1+XII/2	IV–IX/6	Annual	Daily Mean Wind Speed (km/hr) 1+XII/2	IV–IX/6	Annual	Daily Mean cloudiness (Friction) 1+XII/2	IV–IX/6	Annual	Annual pptn (cm)
1		3	4	5	6	7	8	9	10	11	12	13	14	15
1	South Pole	90°00	—	2800	-28.5	-58.3	-49.3	15.5	25.6	22.3	—	—	—	—
2	Byrd	80°00	120°00 W	1511	-14.9	-34.1	-27.9	22.3	35.0	31.0	—	—	—	15.9
3	Plateau	79°15	040°30 E	3625	-33.1	-67.6	-56.4	12.2	19.8	17.6	—	—	—	—
4	Vostok	78°28	106°48 E	3488	-33.1	-66.4	-55.6	16.2	19.2	18.4	0.33	0.35	0.36	—
5	Little America	78°18	163°00 W	40	-6.5	-28.2	-20.9	16.9	19.6	19.1	0.69	0.57	0.64	265(Snow)
6	Belgrano	77°58	038 48 W	50	-6.0	-31.0	-22.3	13.0	22.8	19.8	0.52	0.65	0.59	—
7	Mcmurdo	77°53	166°44 E	24	-3.6	-24.3	-17.4	21.2	24.0	23.4	0.65	0.56	0.61	17.8
8	Halley Bay	75°30	026 39 W	30	-5.3	-25.9	-18.7	15.8	17.8	17.3	0.73	0.60	0.66	22.5
9	Eights	75°14	077 10 W	421	-10.7	-33.7	-26.0	19.8	19.2	19.4	—	—	—	286 (Snow)
10	Hallett	72 18	170°19 E	5	-1.4	-23.5	-15.3	11.2	12.9	13.0	—	—	—	—
11	Novolazarevskaya	70°46	011 49 E	87	-1.0	-15.7	-10.8	27.0	40.5	37.3	0.61	0.57	0.59	30.3
12	Norway stn & Sanae	70°30 70 19	002 32 W 002°21 W	56 52	-4.8	-24.0	-17.2	22.0	28.2	26.6	0.71	0.60	0.65	—
13	Pioners Kaya	69 44	095 30 E	2740	-23.3	-44.7	-38.0	36.0	38.9	38.2	0.65	0.59	0.60	—
14	Syowa	69°00	039 35 E	15	-1.3	-16.1	-10.7	17.6	22.7	21.2	0.61	0.64	0.66	22.5
15	Davis	68 35	077°58 E	12	-0.3	-15.8	-10.3	18.7	16.6	17.6	0.64	0.63	0.65	—
16	Molodezhnaya	67°40	045 50 E	42	-0.9	-15.7	-10.8	21.2	44.3	37.1	0.64	0.69	0.67	71.2
17	Mawson	67°36	062 53 E	8	-0.3	-16.7	-11.2	32.4	40.9	39.2	0.81	0.66	0.72	—
18	Dumont D Urville	66 42	140°00 E	41	-1.7	-15.9	-11.0	34.9	39.5	39.2	—	—	—	47.5
19	Mirny	66°33	093 01 E	30	-2.3	-16.1	-11.5	29.9	47.9	41.4	0.69	0.63	0.64	62.5
20	Wilkes	66 15	110°35 E	12	-0.8	-14.9	9.4	18.7	26.6	24.8	0.74	0.66	0.69	—
21	Argentine	65 15	064°15 W	11	-0.1	-8.8	-5.2	10.6	15.0	14.0	0.83	0.76	0.80	—
22	Melchior	64°20	062°59 W	8	-0.7	-6.5	-3.7	7.0	13.0	12.2	0.60	0.55	0.58	118.9
23	Hope Bay	63°24	056°59 W	11	-0.1	-8.7	-5.3	19.8	23.4	23.0	0.81	0.70	0.75	—
24	Decepcion	62 59	060 43 W	8	-0.9	-5.5	-2.8	17.3	23.9	22.0	0.89	0.83	0.85	39.8

TABLE 2

Meteriological Observations taken at Antarctica (Snow-cover) during January 1982

Lat. 69° 59' 12"°S, Long. 011°55' 09"°E } From 11th January to 12th January (1730 Hrs.)

From 12th January (2200 Hrs.) onward { Lat. 69° 59' 07"°S, Long. 011°55' 19"°E

Date	Hours ISTA	Surface Pressure (mb)	Temperature (°C) D.B	W.B.	Surface Tem. (°C)	Wind Speed km/hr	Direction (Deg.)	Visibility (Code)	Precipitation (m)	Clouds/Remarks Amount and Type: Total amount	Low	Medium	High
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
11th January 1982	0830	983.7	−6.2	—	—	05	145	97	000	1			1 ci
	1130	984.5	−3.8	−1.8 (W.F.)*	—	10	120	97	000	2		1 Ac	1 ci
	1430	986.2	0.0	+0.5 (W.F.)	—	18	120	98	000	2		1 Ac	1 ci
	1730	986.0	−1.7	0.2 (W.F.)	—	24	120	98	000	1		1 Ac	1 ci
	1930	—	−0.5	0.0 (W.F.)	—	25	110	98	000	1		1 Ac	1 ci
12th January 1982	1130	990.7	−1.5	0.5 (W.F.)	−1.3	08	135	97	000	7	1st	5 As, 2 Ac	
	1430	991.2	−0.9	−1.4 (W.F.)	—	10	120	96	000	7		2 As, 5 Ac	
	1730	992.0	−0.8	−1.2 (W.F.)	—	10	120	97	000	6		1 As, 5 Ac	
	2210	990.8	1.0	0.4	—	00	000	96	000	7		7 Ac	
13th January 1982	1200	992.0	−2.7	−2.4	−2.0	00	000	98	000	1		1 Ac	1 ci
	1430	991.6	−0.7	0.5 (W.F.)	−1.2	00	000	98	000	1		1 Ac	1 ci
	1730	991.2	−0.1	0.5 (W.F.)	−0.9	00	000	98	000	1		1 Ac	1 ci
	2030	990.1	0.5	0.3	—	08	260	98	000	2		2 Ac	1 ci
14th January 1982	1030	987.2	−2.7	+0.5 (W.F.)	—	06	330	96	020	7	2st	5 As	0.2 m water equivalent
	1200	987.8	−3.1	−2.8 (W.F.)	−2.7	06	030	96 95 N & NNW	000	8	5st	3 As	
	1430	988.0	−2.1	−1.8 (W.F.)	−1.8	08	070	97 W-S-E 96 W-N-E	000	8	5st	3 As	
	1730	988.3	−2.5	−1.7 (W.F.)	−2.0	18	090	96	000	8	5st	3 As	
	2030	988.3	−2.2	0.5 (W.F.)	—	14	090	96	000	7	7st	1 Ac	
15th January 1982	1130	992.7	−3.8	0.5 (W.F.)	—	12	120	97	000	7	4st	2 Ac, 2 As	
	1430	992.5	−2.8	−0.5 (W.F.)	−0.3	12	120	96	000	7	3st	3 Ac, 2 As	
	1730	992.8	−1.2	−0.2 (W.F.)	0.0	14	120	96	000	7	3st	3 Ac, 2 As	
	2030	992.2	−0.5	−0.7 (W.F.)	0.2	18	135	96	000	7	4st	3 As, 1 Ac	
16th January 1982	1530	991.0	0.8	0.5	00.8	00	000	97	Tr. (snow)	6		6 Ac	
	1730	991.5	2.5	1.2	00.8	08	250	97	000	6		6 Ac	1 ci
	2030	991.4	00.0	−1.2	00.7	05	260	97	000	5		4 Ac	1 ci
	2330	991.7	−2.2	−2.4	—	00	000	97	000	3		2 Ac	1 cc
17th January 1982	0830	994.7	−5.5	−5.8	−5.2	00	000	97	000	6		6 Ac	
	1130	994.8	−2.8	−3.0	−2.3	00	000	96	000	6		6 Ac	
	1430	996.3	0.0	−1.7	—	00	000	97	000	7		7 Ac	
	1730	997.2	1.0	−0.7	—	00	000	97	000	6		6 Ac	
	2030	997.6	0.5	−0.8	—	04	260	97	000	6		6 Ac	1 ci
	2330	997.8	−2.0	−2.6	—	04	225	98	000	1		1 Ac	1 cc
18th January 1982	0515	997.8	−7.2	−6.2 (W.F.)	—	10	250	98	000	1		1 Ac	
	0830	997.8	−1.0	−1.2 (W.F.)	—	18	260	96	000	5		4 Ac	1 cc
	1130	997.8	−1.5	−2.1	—	18	260	96	000	5		5 Ac	1 ci 1 ci
	1400	999.1	−0.1	−1.2	—	18	250	97	000	3		3 Ac	1 ci

* W. F. -- Water freezed

TABLE 3

Radiations recorded at the base Camp at Antarctica (Snow Cover)

Date	Lat (°S)	Long (°E)	Pressure (mb)	Time 1st	Global mV	Global Watt/m²	Diffuse mV	Diffuse Watt/m²	Reflected mV	Reflected Watt/m²	Albedo %	Soil and Colour	Weather Remarks
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
11th January 1982	69 59' 12"	011 55' 09"	983.7	0830	1.00	134.59	0.60	80.75	0.90	121.13	90	Snow cover White	1 Octa Cloud, VV97 Sun, free from cloud
	69 59' 12"	011 55' 09"	984.5	1130	2.70	363.39	2.00	269.18	2.25	302.83	83	Do	2 Octa Clouds, VV 97
	69 59' 12"	011 55' 09"	986.2	1430	3.75	504.71	1.60	215.34	2.90	390.31	77	Do	2 Octa Clouds, VV 98
	69 59' 12"	011 55' 09"	986.0	1730	4.00	538.36	3.00	403.77	3.40	457.60	85	Do	1 Octa Cloud, VV 98
	69 59' 12"	011 55' 09"	—	1930	3.60	484.52	1.40	188.43	2.50	336.47	69	Do	l Octa Cloud, VV 98
12th January 1982	69 59' 12"	011 55' 09"	990.7	1130	1.60	215.34	1.60	215.34	1.50	201.88	94	Do	7 Octa Clouds, VV 97 Sun, behind the clouds
	69 59' 12"	011 55' 09"	991.2	1430	2.80	376.85	2.80	376.85	2.40	323.01	86	Do	Do
	69 59' 12"	011 55' 09"	992.0	1730	3.20	430.69	3.20	430.69	2.60	349.93	81	Do	6 Octa Clouds. VV 97 Sun behind the clouds
	69 59' 07"	011 55' 19"	990.8	2210	1.40	188.43	1.40	188.43	1.20	161.51	86	Do	7 Octa Clouds, VV-96 Sun, behind the clouds
13th January 1982	69 59' 07"	011 55' 19"	992.0	1200	2.40	323.01	1.05	141.32	2.30 * 1.15	309.55 * 154.78	96	Do	1 Octa Cloud, VV 98 Sun. free from clouds.
	69 59' 07"	011 55' 19"	991.6	1430	3.65	491.25	0.90	121.13	2.75 *1.55	370.12 * 208.61	75	Do	1 Octa Cloud, VV-98 Sun, free from clouds.
	69 59' 07"	011 55' 19"	991.2	1730	3.35	450.87	1.00	134.59	2.85 * 1.35	383.58 * 181.70	85	Do	1 Octa Cloud, VV-98 Sun. free from clouds.
	69 5' 07"	011 55' 19"	990.1	2030	2.95	397.04	0.80	107.67	2.00 1.30	269.18 174.97	68	Do	2 Octa Clouds, VV-98, Sun, free from clouds.
14th January 1982	69 59' 07"	011 55' 19"	987.2	1030	0.80	107.67	0.80	107.67	0.70 *0.60	94.21 * 80.75	87	Fresh snow fall ocurred	7 Octa Clouds, VV-96, Snow fall
	69 59' 07"	011 55' 19"	987.8	1200	1.40	188.43	1.40	188.43	1.10 *0.90	148.05 * 121.13	79	Snowcover (White)	8 Octa Cloud, VV-97 Sun, behind the clouds.
	69 59' 07"	011 55' 19"	988.0	1430	2.20	296.10	2.20	296.10	1.70 *1.25	228.1H, * 168.24	77	Do	8 Octa' Clouds, VV-96 Sun, behind the clouds.
	69 59' 07"	011 55' 19"	—	1600	2.40	323.01	2.40	323.01	1.90 * 1.50	225.72 *201.88	70	Do	8 Octa Clouds, VV-96 Sun, behind the clouds.
	69 59' 07"	011 55' 19"	988.3	1730	2.30	309.55	2.30	309.55	1.85 * 1.30	248.99 * 174.97	80	Snowcover (white)	8 Octa Cloud, VV96, Sun, behind the cloud.
	69 59' 07"	011 55" 19"	988.3	2030	1.15	154.78	1.15	154.78	0.95 * 0.70	127.86 94.21	83	Do	7 Octa Clouds, VV-96, Sun, behind the clouds.
15th January 1982	69 59' 07"	011 55" 19"	992.7	1130	1.10	148.05	1.10	148.05	0.85 * 0.70	114.40 * 94.21	77	Do	7 Octa Clouds, VV-97, Sun, behind the clouds.
	69 59' 07"	011 55' 19"	—	1230	1.20	161.51	1.20	161.51	0.95 * 0.60	127.86 * 80.75	79	Do	Do
	69 59' 07"	011 55' 19"	992.5	1430	1.80	242.26	1.80	242.26	1.40 * 1.00	188.43 * 134.59	78	Do	7 Octa Clouds, VV-96, Sun, behind the clouds.
	69 59' 07"	011 55' 19"	—	1530	2.05	275.91	2.05	275.91	1.75 * 1.05	235.53 * 141.32	85	Do	Do
	69 59' 07"	011 55' 19"	992.8	1730	2.45	329.74	2.45	329.74	1.95 * 1.20	262.45 *161.51	80	Do	Do
	69 59' 07"	011 55' 19"	—	1830	2.80	376.85	2.80	376.85	2.25 * 1.45	302.83 * 195.15	80	Do	Do
	69 59' 07"	011 55' 19"	—	1930	2.35	316.29	2.35	316.29	1.85 * 1.05	248.99 *141.32	79	Do	Do
	69 59' 07"	011 55' 19"	992.2	2030	1.25	168.24	1.25	168.24	1.05 * 0.60	141.32 * 80.75	84	Do	Do Snowfall trace
16th January 1982	69 59' 07"	011 55' 19"	991.0	1530	3.30	444.14	2.10	282.64	2.55 * 1.35	343.20 * 181.70	77	Do	6Octa Clouds, VV -97,Sun, partial behind the clouds.
	69 59' 07"	011 55' 19"	991.5	1730	2.50	336.47	2.20	296. 10	2.10 * 1.30	282.64 * 174.97	85	Do	6 Octal Clouds,VV-97, Sun,
	69 59' 07"	011 55' 19"	—	1850	2.50	336.47	2.10	282.64	2.00 * 1.30	269.18 *174.97	80	Do	Do
	69 59' 07"	011 55' 19"	991.4	2030	1.80	242.26	1.40	188.43	1.20 * 0.70	161.51 * 94.21	67	Do	5 Octa Clouds,VV-97, Sun behind the cloud.
	69 59' 07"	011 55' 19"	—	2200	1.30	174.97	0.90	121.13	1.00 * 0.70	134.59 * 94.21	77	Do	4 Octa Clouds,VV-97, Sun, partial behind the clouds.
	69 59' 07"	011 55' 19"	991.7	2330	1.20	161.51	0.60	80.75	0.95 * 0.55	127.86 * 74.02	79	Do	Do
17th January 1982	69 59' 07"	011 55' 19"	—	0100	1.05	141.32	0.40	52.83	0.70 * 0.45	94.21 *60.57	67	Do	3 Octa Clouds, VV-98 Sun, free from clouds
	69 59' 07"	011 55' 19"	994.7	0830	0.60	80.75	0.50	67.29	0.55 *0.30	74.02 * 40.38	92	Do	6 Octa Clouds, VV-97 Sun, behind the clouds
	69 59' 07"	011 55' 19"	994.8	1130	1.10	148.05	1.00	134.59	0.85 * 0.65	114.40 * 87.48	77	Do	6 Octa Clouds, stratified VV-96, Sun, behind the clouds.
	69 59' 07	011 55' 19"	—	1230	1.40	188.43	1.40	188.43	1.25 * 0.80	168.24 * 107.67	89	Do	7 Octa Clouds.Cumti form AC, W-96. Sun behind the clouds.
	69 59' 07"	011 55' 19"	996.3	1430	2.50	336.47	1.60	215.34	2.10 * 1.20	282.64 * 161.51	84	Do	7 Octa Clouds, cumti form Sun. behind the clouds.
	69 59' 07"	011 55' 19"	997.2	1730	3.15	423.96	2.20	296.10	2.25 *1.50	302.83 *201.89	71	Do	6 Octa Clouds, VV-97, Sun. partially behind the clouds.
	69 59' 07"	011 55' 19"	997.6	2030	2.20	296.10	1.50	201.88	1.80 * 1.00	242.26 *134.59	82	Do	Do
	69 59' 07"	011 55' 19"	—	2200	2.10	309.55	1.00	134.59	1.75 * 1.00	235.53 * 134.59	76	Do	5 Octa Clouds, VV- 97. Sun, free from clouds.
	69 59' 07	011 55' 19"	997.8	2330	1.15	154.78	0.40	53.83	0.95 * 0.55	127.86 * 74.02	83	Do	1 Octa Cloud, VV-98. Sun. free from clouds.
18th January 1982	69 59' 07"	011 55' 19"	997.8	0515	0.20	26.92	0.10	13.46	0.15 * 0.10	20.19 *13.46	75	Do	1 Octa Cloud, VV-98. Mid night sun seen at 0442 hrs 1ST
	69 59' 07"	011 55' 19"	997.8	0830	1.30	174.97	0.90	121.13	1.20 * 0.80	161.51 * 107.67	92	Do	5 Octa Clouds, VV-96 sun. partial behind the thin clouds.
	69 59' 07"	011 55' 19"	997.8	1130	1.20	161.51	1.20	161.51	0 90 *0.60	121.13 *80.75	75	Do	5 Octa Clouds, VV-96 Sun. behind the clouds.
	69 59' 07"	011 55' 19"	—	1300	3.00	403.77	1.30	174.97	2.35 *1.30	316.19 *174.97	78	Do	4 Octa Clouds, VV-97 Sun. partial behind me clouds (Very thin clouds)
	69 59' 07"	011 55' 19"	999.1	1400	3.05	410.50	1.25	168.24	2.60 * 1.65	349.93 *222.07	85	Do	3 Octa Clouds, VV-97. Sun. free from clouds.

Radiations taken on a surface of carbon dust spread uniformly over the snowcover.

Antarctica is known as the home of blizzards. Severe blizzards occur under the influence of cyclonic storms/depressions originating in the Southern Ocean between 40° and the Antarctic circle. These affect mainly the coastal areas. In the interior, strong katabatic winds generally prevail which originate from the central highland and blow down the inclined slopes towards the coast. These winds onset suddenly with speed jumping to 30-40 knots. It also falls suddenly. Winds are more pronounced the months with daylight. However, occasionally under the influence of cyclonic storms, the prevailing circulation is disturbed and violent blizzards (severe storms laden with snow, wind speed exceeding 200 km/hr.) may occur. On 9th January 1982 the maximum surface wind recorded (80 km/hr. between 9—12 hrs. GMT) reduced the visibility to zero due to blowing snow. Surface winds recorded during the expedition are presented in Table 2 while the average daily surface wind during different seasons of the year have been listed in the climatic Table 1.

Cloudiness and Precipitation

Mist, blowing snow and lack of light cause considerable difficulty for cloud observations. Average cloudiness (fraction) based on available observations during different seasons in accordance with latitude are as follows:

Lat. (°S)	Records (Yrs.)	Summer	Fall	Winter	Spring	Year
66 — 69	7 —10	0.69	0.69	0.64	0.67	0.67
70 — 75	5 —10	0.68	0.62	0.56	0.62	0.62
78	7 —11	0.69	0.63	0.51	0.64	0.62
69.5 (Plateau stations)	2	0.55	0.60	0.46	0.50	0.53
79 (Plateau stations)	3 — 9	0.38	0.34	0.33	0.39	0.36

Seasonal and annual mean cloudiness in respect of few stations of Antarctica are listed in Table 1. The type and amount of clouds observed during the expedition period at Antarctica are shown in Table 2.

The annual snowfall (water equivalent) ranges from about 50-60 cm in the coastal areas to 5 cm or less in the interior of the continent. This has a very high degree of spatial variability. The redistribution of fallen snow due to wind drift is very frequent. Antarctic blizzards are mainly snow being blown from one place to another without fresh snowfall. Average annual precipitations at few stations are shown in Table 1.

Evaporation is estimated to be about 1 mm/month in the two summer months of December and January.

The meteorological data recorded during the Indian expedition to Antarctica (January 1982) are presented in Table 2.

RADIATION BALANCE

Antarctica receives tremendous amount of sunlight. During summer more solar radiation reaches the surface of the south pole than that received at the equator during equivalent period. The total annual radiation at south pole is about equal to that received in the equatorial regions, despite there being six months ofdarkness. However, about 60-80% of it is reflected back in space without being absorbed by the ice-surface. Radiations recorded at the base camp of Antarctica are presented in Table 3.

For long wave radiation, the snow surface acts almost as a black body. Though during summer, the sun shines throughout the day, it can be seen from Table 4, that the intensity of solar radiation has

TABLE 4
Mean radiation during the observation period.

Date	Period (GMT)	Qs 1y/min	Albedo (a)%	Mean T_a(°K)	Mean T_S(°K)	Mean N (fraction)	Mean P (mb)	Mean Wind Speed km/hr
11th. January 1982	03-06	0.356	85	268.0	273.0	0.19	984.1	7.5
	06-09	0.620	80	271.1	273.0	0.25	985.3	14.0
	09-12	0.745	81	272.1	273.0	0.19	986.1	21.0
	12-15	0.131	78	271.9	273.0	0.13	986.0	24.5
12th January 1982	06-09	0.423	89	271.8	271.7	0.89	990.9	9.0
	09-12	0.575	84	272.1	273.0	0.89	991.6	10.0
	12-15	0.529	82	272.6	273.0	0.75	991.7	10.0
	15-18	0.356	84	273.5	273.0	0.89	991.1	0.0
13th January 1982	06-09	0.582	82	271.3	271.4	0.13	991.8	0.0
	09-12	0.673	80	272.6	271.9	0.13	991.4	0.0
	12-15	0.606	77	273.2	272.1	0.19	990.7	4.0
14th January 1982	03-06	0.211	64	270.1	270.3	0.94	987.5	6.0
	06-09	0.303	89	270.5	271.7	1.0	987.9	7.0
	09-12	0.442	76	270.7	271.1	1.0	988.1	13.0
	12-15	0.332	81	270.7	271.0	0.94	988.3	16.0
15th January 1982	06-09	0.267	77	269.7	272.7	0.87	992.6	12.0
	09-12	0.394	83	271.0	272.9	0.87	992.7	12.0
	12-15	0.404	84	272.1	273.1	0.87	992.5	13.0
16th January 1982	09-12	0.558	80	274.7	273.8	0.75	991.3	4.0
	12.15	0.436	78	274.3	273.7	0.69	991.5	6.5
	15-18	0.276	73	271.9	273.7	0.50	991.5	2.5
	18-21	0.216	74	270.8	273.0	0.37	991.7	0.0
17th January 1982	03-06	0.163	74	268.9	269.3	0.75	994.7	0.0
	06-09	0.320	84	271.6	272.9	0.81	995.5	0.0
	09-12	0.543	78	273.5	273.0	0.81	996.7	0.0
	12-15	0.514	76	273.7	273.0	0.75	997.4	2.0
	15-18	0.362	79	272.3	273.0	0.44	997.7	4.0
18th January 1982	00-03	0.144	90	268.9	269.3	0.37	997.8	14.0
	03-06	0.240	84	271.7	272.9	0.63	997.8	18.0
	06-09	0.465	81	272.2	273.0	0.37	998.5	18.0

considerable diurnal variation. The maximum intensity is observed between 09-12 hrs GMT (about 100 1y/3hrs) and lowest between 00-03 hrs GMT (about 20 1y/3 hrs) when the sun shines at the lowest angle of elevation. The histogram showing 3-hourly mean radiation during the period of expedition is shown in Fig. 3.

If Q_O is the incoming shortwave solar radiation received at the top of the atmosphere, a fraction of it is absorbed or scattered by the air and water molecules present in the atmosphere. This fraction has been estimated to be between 0.15 to 0.20. Thus, in clear skies, the incident radiation (Q_i) at the surface is:

$$Q_i = 0.8 Q_o$$

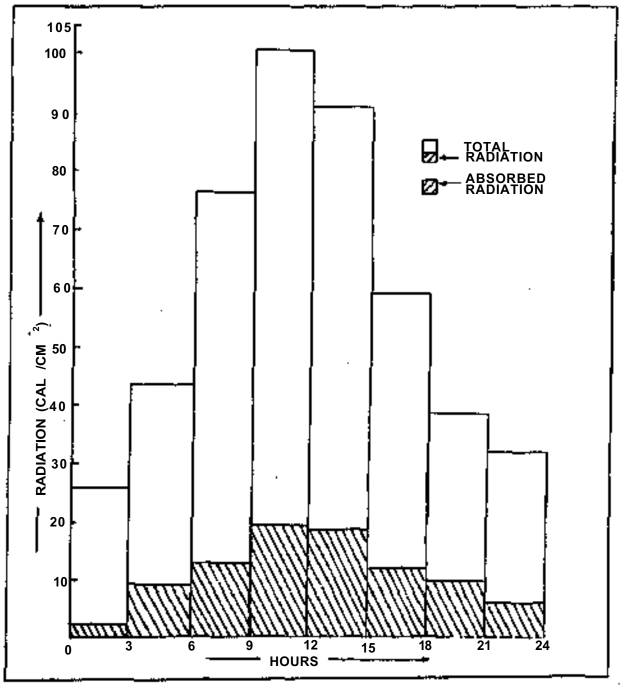

Fig. 3 : Histogram of radiation.

If cloudiness fraction present is N, then the radiation received at the surface (Q_s) is

$$Q_s = Q_i[K+(1-K)(1-N)] \quad .. \quad .. \quad .. \quad (1)$$

where K=0.22 as suggested by Kimball.

If 'a' is albedo of ice surface the net shortwave radiation absorbed (Q_a) is

$$Q_a = Q_s(1-a) \quad .. \quad .. \quad .. \quad (2)$$

The longwave radiation exchange between air and ice surface may be given as

$$Q_t = \epsilon\sigma Ta^4 - \sigma T_s^4 \quad .. \quad .. \quad .. \quad .. \quad (3)$$

where T_a & T_s are temperatures (°K) of ambient air and ice surface respectively,
and $\sigma = 8.17X10^{-11}$ ly/min./°K4
the emissivity, ϵ for air has been suggested as 0.757 whereas snow has been considered as black body in respect of emissivity. Positive values of Q_i are taken as input to the ice pack.

In cloudy skies the equation (3) becomes

$$Q_1 = \sigma \quad (\epsilon T_a^4 - T_s^4)(1-K'N) \quad .. \quad .. \quad .. \quad (4)$$

where K' = 0.76 for low clouds
= 0.52 for medium clouds
= 0.26 for high clouds.

The net radiation input (Q_r) for snowmelt is given by

$$Q_r = Q_a + Q_e \quad .. \quad .. \quad .. \quad (5)$$

The computed values of short wave radiation incident on the snow surface may be given

$$Q_S = Q_o\ (0.8-0.62\ N) \quad .. \quad .. \quad .. \quad \text{(From Eqn. 1)}$$

During the period of expedition (Jan. 11—18,1982) the mean cloudiness, N=0.61; Q_o= 0.662. Hence mean computed radiation

$$Q_s = 0.662\ (0.8-0.62x0.61)$$
$$= 0.279 \text{ ly/min.}$$

But, mean observed radiation (Q_s') recorded is

$Q_s' = 0.326$ ly/min.

While testing the significance of the difference between computed and observed mean radiation, we get

$$t = \frac{(0.326 - 0.279)\sqrt{8}}{0.120} = 1.108$$

where n=8, S. D. = 0.120
At 7 d.f.,t. 05=2.365

Therefore, the difference between observed and computed values of radiation is insignificant. Three hourly mean global and absorbed radiation for the period of expedition is as follows:—

Period (GMT)	Mean Global Radiation (ly/3 hrs.)	Mean Absorbed Radiation (ly/3hrs.)	Period (GMT)	Mean Global Radiation (ly/3 hrs.)	Mean Absorbed Radiation (ly/3 hrs.)
00—03	25.92	2.52	12—15	91.26	19.08
03—06	43.74	9.54	15—18	59.58	12.42
06—09	76.68	13.14	18—21	38.88	10.26
09—12	100.98	19.80	21—24	32.40	6.30

The net 3-hourly daily radiation input has been presented in Table 5.

TABLE 5

3 hourly net radiation balance

Date	Period (Hrs GMT)	Qa (ly/min)	Ql (ly/min)	Qr = Qa+Ql (ly/min)
11th January 1982	03-06	0.0534	- 0.0307	0.0227
	06-09	0.1250	- 0.0109	0.1141
	09-12	0.1415	- 0.057	0.1358
	12-15	0.1608	- 0.071	0.1537
12th January 1982	06-09	0.0465	+ 0.0003	0.0468
	09-12	0.0920	-0.0032	0.0888
	12-15	0.952	- 0.016	0.0936
	15-18	0.0570	+ 0.0018	0.0588
13th January 1982	06-09	0.1048	-0.0006	0.1042
	09-12	0.1346	+ 0.0045	0.1391
	12-15	0.1394	+ 0.0039	0.1433
14th January 1982	03-06		0.0760	-0.0004
	06-09	0.0756	0.0333	- 0.0019
	09-12	0.314	0.1061	-0.0006
	12-15	0.1055	0.0631	- 0.0006
		0.0625		
15th January 1982	06-09	0.614	- 0.0086	0.528
	09-12	0.670	- 0.0055	0.0615
	12-15	0.0646	- 0.0029	0.0617

Table 5— Contd.

Date	Period	Qa (ly/min)	Ql(ly/min)	Qr=Qa + Ql (ly/min)
16th January 1982	09-12	0.1116	+ 0.0037	0.1153
	12-15	0.0959	+ 0.0026	0.985
	15-18	0.0745	- 0.0069	0.0676
	18-21	0.570	- 0.0192	0.0378
17th January 1982	03-06	0.0434	- 0.0015	0.0419
	06-09	0.0512	- 0.0050	0.0462
	09-12	0.1195	+ 0.0019	0.1214
	12-15	0.1234	+ 0.0029	0.1263
	15-18	0.760	- 0.0036	0.0724
18th January 1982	00-03	0.0144	- 0.0021	0.0123
	03-06	0.384	- 0.0053	0.0331
	06-09	0.0883	- 0.0043	0.0840

The net estimated radiation balance (K cal/cm^2/month) of different seasons of Antarctica, over the continent and adjacent ocean is given below:

Latitude (°S)	January	April	July	October
80	1.2	-1.7	-1.4	-0.8
70	3.1	-1.8	-1.9	-0.1
60	4.8	-0.8	-2.3	+ 1.1

In January, the entire continent receives positive radiative heat, though values are not large. The net gain becomes negative when the sun starts going below the horizon in the month of March. In July, the net radiative heat loss increases as the winter becomes intense in the continent. Due to low clouds over plateau and intense surface inversion, long wave radiation loss is suppressed. In October, the sun starts rising above the horizon but still the net radiative heat gain remains negative. At the coastal areas, the net heat gain becomes nearly zero. The net annual radiation balance for the entire continent is negative.

PHYSICAL PROPERTIES OF SNOW COVER

Albedo

Unlike the snowcover in the Himalayas, the Antarctic snowcover exhibits very small variation of albedo with time. This may be attributed to constant freewater content of pack ice and absence of debris and soil. It remains normally high (above 80%) in the interior of the continent. During winter, it increases slightly and becomes more than 90%. However, over the rocky areas having sporadic snowcover it may reduce to 20 to 40%. The observed value of the albedo for the period of expedition is presented in Table 3. It has a mean value of 80.2% with a co-efficient of variation of about 8.4%.

Density of the Snowpack

A sample of snow consists of ice, air and water. The water content of the snow varies with temperature and mainly determines the density of snow sample. It may range from 0.05 gm/cc for dry snow to 0.834 gm/cc for soft ice.

From experiments conducted during the expedition, average density at various depths of snowpack were observed as follows:—

Depth (from snow surface in cm)	Density (gm/cc)
00 — 15.0	0.65
15.0 — 30.0	0.53
30.0 — 50.0	0.51
50.0 — 75.0	0.46
75.0 — 90.0	0.46
90.0 — 100.0	0.46

The higher density at the top of the snow surface occurs due to formation of wind crust. It decreases towards deeper layers and becomes constant after a depth of about 50 cm. However, after a fresh snowfall, density of the top layer may be even less than 0.1 gm/cc.

Penetration of Shortwave Radiation

The radiation absorbed at the surface of ice penetrates in snowcover under the exponential law,

$$Q_x = Q_a e^{-\mu x} \quad (6)$$

where Q_a and Q_x are the intensities of effective shortwave variation absorbed at the surface and at depth x (cm) respectively. μ is the extinction coefficient which depends mainly upon density. It has been computed experimentally that the value of μ varies with density.

Density (gm/cc)	Extinction Co-eff. (μ)
0.261	0.280
0.350	0.184
0.448	0.106

A graph showing the intensity absorbed at various depths is given in Fig. 4. It can be seen that the penetration becomes insignificant after 25 cm.

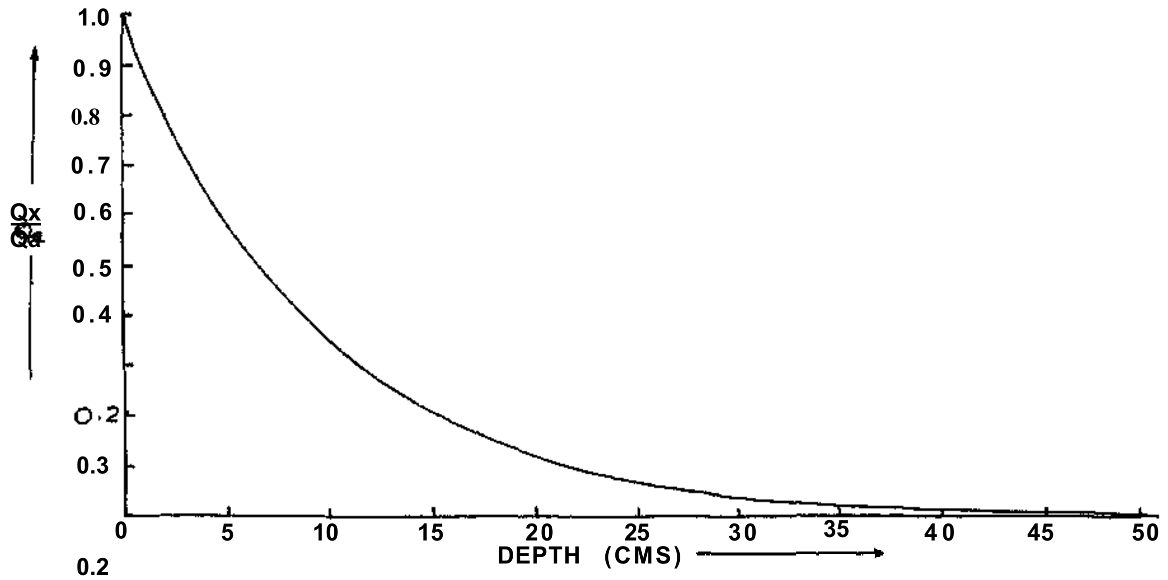

Fig. 4 : Depthwise absorption of radiation

Drifting and Blowing of Snow

Drifting of snow starts near the surface when the wind speed exceeds 30 km/hr at 10 m height. During strong wind, the phenomenon of blowing snow extends to several hundred metres above the surface, causing danger for surface travel and is hazardous for landing of aircraft. The visibility in such cases reduces to zero. The frequency of occurrence of blowing snow remains continuously large throughout the year except in the summer months, when it reduces appreciably.

The mean annual drift of snow transport estimated for a few stations of Antarctica is as follows:

Stations	Annual snow transport (10^6 kg/year)
Wilkes	2.1
Byrd	3.2
Mirnyy	3.5
Mawson	20
Port Martin	50
Cape Denison	60

From the above values, it is clear that the huge amounts of snow drifts towards the coastal stations every year.

MECHANISM OF SNOWMELT

The snowmelt under the processes of radiation, convection and condensation have been computed by using the following equations:

Radiation Melt

From equation (5) the net effective radiations 'Q_r' is

$$Q_r = Q_a + Q_1$$

If Q_t is thermal quality of snowcover then the melt (cm) due to radiations can be given by

$$M_r = \frac{Q_a + Q_1}{80Q_1}$$

Snowmelt for 3 hours will be

$$M_r = \frac{2.25_{(Qa + Q1)}}{Q_1} \quad \ldots\ldots (7)$$

For calculating the melt due to radiation, thermal quality is taken as 1.

Convective Melt

Besides radiation, the other important processes of heat exchange in Antarctica are convective transfer of heat at snow-air interface and latent heat released by condensate over snow surface. Considering the law of turbulent exchange of temperature, the convective melt (inch/day) may be given by

$$M_c = K_c (Z_a Z_b)^{-1/6} (T_a - T_s) U_b \quad (p/p_o) \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

where $K_c = 0.00629$

Za & Zb are the height (in ft.) where temperature and wind are recorded.

U_b = wind speed (miles per hour)

T_a & T_s are temperatures (°K) of ambient air and snow surface

p_o and p are the sea level and station pressures in mb.

The melt (cm) for 3 hours may be given by

$$M_c = 0.001816\ p/p_o\ (T_a - T_s)\ U_b \quad .. \quad .. \quad .. \quad (9)$$

(Here $Z_a = 3'$ & $Z_b = 4'$)

Condensation Melt

Similarly, considering the law of turbulent exchange for moisture content between air and snow interface, the condensation melt (inch/day) can be given by

$$M_e' = K_e\ (Z_a Z_b)^{-1/6}\ (e_a - e_s)\ (p/p_o) U_b \quad .. \quad .. \quad .. \quad (10)$$

where $K_e = 0.054$

(e_a & e_s) are actual and saturated vapour pressures in mb.

The melt (cm) for 3 hour may be given by

$$M_e = 0.0156\ (e_a - e_s) U_b (p/p_o) \quad .. \quad .. \quad .. \quad (11)$$

Other processes such as conduction and heat content of rainfall are insignificant. The melt (cm) computed by using equations (7), (9) & (11) are presented in Table 6.

TABLE 6

Snow Melt (mm)

Date	Period	Mr	Mc	Me	Total (M)
11th January 1982	03-06	0.51	- 0.41	- 1.51	- 1.41
	06-09	2.54	-0.29	- 1.19	+ 1.41
	09-12	3.05	-0.21	- 0.89	+ 1.95
	12-15	3.46	-0.30	- 1.26	+ 1.90
12th January 1982	06-09	1.05	+ 0.01	+ 0.03	+ 1.09
	09-12	2.00	-0.10	- 0.43	+ 1.47
	12-15	2.11	- 0.04	- 0.19	+ 1.88
	15-18	1.32	0.0	0.0	+ 1.32
13th January 1982	06-09	2.34	0.0	0.0	+ 2.34
	09-12	3.12	0.0	0.0	+ 3.72
	12-15	3.22	+ 0.05	+ 0.19	+ 3.46
14th January 1982	03-06	1.70	- 0.01	-0.29	+ 1.40
	06-09	0.71	- 0.09	-0.35	+ 0.27
	09-12	2.38	- 0.06	-0.21	+ 2.11
	12-15	1.41	- 0.05	-0.19	+ 1.17
15th January 1982	06-09	1.19	- 0.40	2 1.52	- 0.73
	09-12	1.38	- 0.25	-1.02	+ 0.11
	12-15	1.39	- 0.14	-0.61	+ 0.64

TABLE 6 (Contd.)

Date	Period	Mr	Mc	Me	Total(M)
16th January 1982	09-12	2.59	+0.04	4-0.17	+ 2.80
	12-15	2.22	+0.04	4-0.18	+ 2.44
	15-18	1.52	- 0.04	4-0.16	+ 1.32
	18-21	0.49	0.0	0.0	+ 0.49
17th January 1982	03-06	0.92	0.0	0.0	0.92
	06-09	1.04	0.0	0.0	1.04
	09-12	2.73	0.0	0.0	2.73
	12-15	2.84	+0.01	+0.06	2.91
	15-18	1.63	-0.03	-0.13	1.47
18th January 1982	00-03	0.28	- 0.06	- 0.20	0.02
	03-06	0.74	- 0.24	- 1.00	-0.50
	06-09	1.89	- 0.16	- 0.68	1.05

The mean 3-hourly melt rate are as follows :

Period (Hrs. GMT)	Mean Melt Rate (mm)
00 — 03	0.0
03 — 06	0.1
06 — 09	0.9
09 — 12	2.0
12 — 15	2.1
15 — 18	1.4
18 — 21	0.5
21 — 24	0.2

RESULTS

(i) The maximum intensity of solar radiations during the period of expedition has been observed between 09-12 hrs GMT (about 100 ly/3 hrs) and minimum intensity between 00-03 hrs GMT (about 20 ly/3 hrs) when the sun is at the lowest elevation.

(ii) The net radiative heat is positive only in the months of December and January. For the months March to October, the entire continent has negative radiation balance.

(iii) The maximum snowmelt is observed between 12-15 hrs GMT whereas maximum intensity of radiation occurs between 09-12 hrs.

(iv) Fig. 5, representing the various component of melt rates, reveals that the convection and condensation processes contribute negatively to the snowmelt. This may be attributed to the fact that ambient air temperature is generally lower than the snow surface temperature even during the summer months. Obviously, during winter when there is practically no sun shine, the snowcover is subjected to deposition only either by precipitation or by condensation. As such no ablation occurs under any process.

(v) Melt rate decreases sharply after 18 hrs GMT and remains low till 06 hrs of the following day (Fig. 6).

(vi) The melt rate during peak summer is even less than 1 cm/day which contributes fresh water runoff to sea. The amount is negligible as compared to snowcover of the Himalayas where melt rate is about ten times higher during summer months.

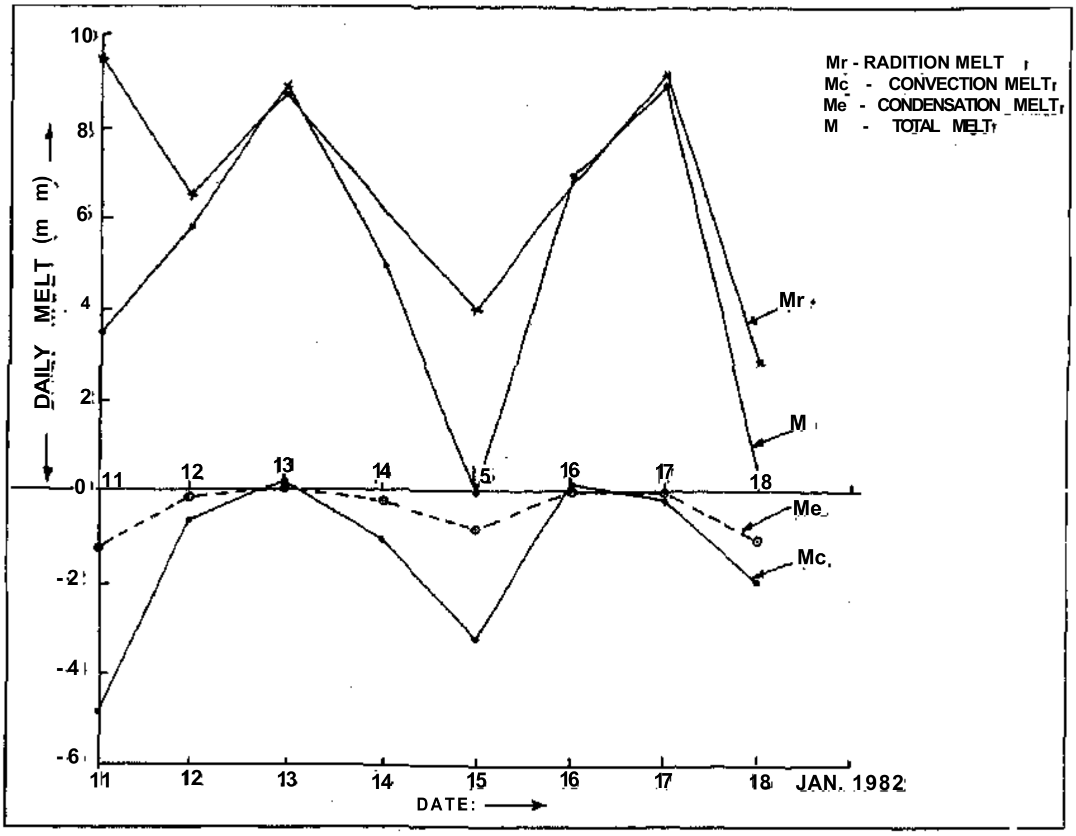

Fig. 5 : Various component of melts.

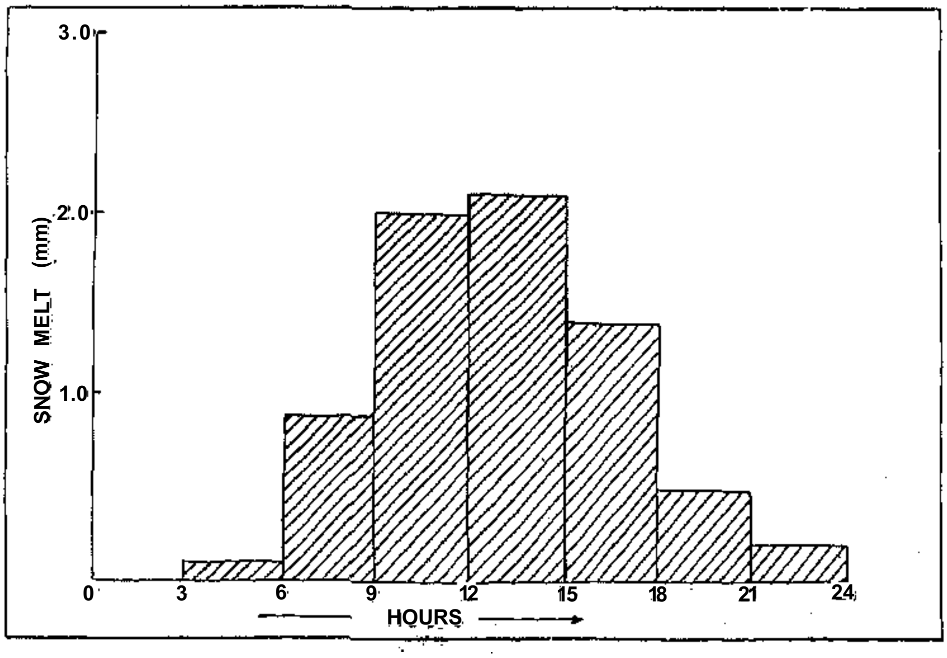

Fig. 6 : Histogram of mean snow melt.

(vii) Since radiation is the main factor responsible for melting, the melt rate decrease appreciably during cloudy days of summer.

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