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SCREEN TEMPERATURES AND 10 m TEMPERATURES*

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ABSTRACT. At places with an annual mean temperature lower than −20°C on the Greenland and Antarctic ice sheets, the temperature at a depth of 10 m is close to the annual mean at the surface and at the level of the meteorological shelter. With temperatures higher than about −35°C the size and sign of the differences vary. With lower temperatures the 10 m temperature becomes increasingly lower than the air temperature, at the coldest Antarctic station, "Plateau", by nearly 4 deg.

RÉSUMÉ. *Les températures à l'écran météorologique et à la profondeur de 10 m.* Sur les calottes glaciaires, dans les régions à température annuelle inférieure à −20°C, les températures du névé à une profondeur de 10 m sont près de la température moyenne au niveau de l'écran météorologique. Jusqu'à une température d'environ −35°C, les différences ne sont pas systématiques. Avec des températures plus basses, le névé devient de plus en plus froid en comparaison avec la température de l'air à la hauteur de 10 m. À la station la plus froide, "Plateau", la différence est presque de 4 deg.

ZUSAMMENFASSUNG. *Wetterhütten- und 10 m-Temperaturen.* In Gebieten des grönländischen und antarktischen Inlandeises mit einer mittleren Jahrestemperatur von weniger als −20°C liegt die Temperatur in 10 m Tiefe nahe bei der mittleren Jahrestemperatur an der Oberfläche und in Höhe der meteorologischen Wetterhütte. Bei Temperaturen über −35°C variieren die Unterschiede nach Grösse und Vorzeichen. Bei niedrigeren Temperaturen wird die 10 m-Temperatur zunehmend niedriger als die Lufttemperatur; an der kältesten antarktischen Station, "Plateau", erreicht der Unterschied fast 4 deg.

INTRODUCTION

It is generally accepted that in the accumulation areas of ice sheets the temperature of the firn at a depth of about 10 m is very close to the annual mean temperature of the air at screen level. This makes it possible to determine the latter temperature by one measurement in a bore hole. If, additionally, the vertical distribution of temperature and density is observed, it is possible to calculate the approximate annual temperature variation at the surface (Koch and Wegener, 1930). At a depth of 10 m the annual variation of temperature is reduced to about 1% of the surface variation, i.e. no more than 0.5°C, which is less than the standard deviation of the annual mean at screen level. The variation at "Byrd station" is 0.8°C and at the South Pole it is 0.5°C (Phillpot, 1967). Consequently this uncertainty can be neglected. The near-equality applies to those parts of the ice sheets in which the temperature rise in summer is not high enough to produce substantial melting near the surface and non-conductive heat transport downwards by infiltration and refreezing of melt water in the deeper layers. This region corresponds roughly to the parts enclosed by the isotherm of −6°C of the warmest month, Benson's "dry snow facies", and that part of his "infiltration facies" in which the mean maximum of the warmest month does not exceed 0°C (Benson, 1962). It covers about half of the Greenland ice sheet and the greatest part of the Antarctic ice sheet.

SHELTER TEMPERATURES AND SURFACE TEMPERATURES

Evidently the 10 m temperature depends not upon the temperature at screen level but upon the temperature of the snow surface itself. They need not be identical. Considering annual means, the surface temperature can be higher than the screen temperature. This is the normal condition over land where, during the hours of daylight, the strong absorption of solar radiation raises the temperature of the uppermost surface layers far beyond that of the air, whilst during the hours of darkness the surface cools relatively much less below the air temperature (Geiger, 1961). It might be different if a snow cover is present.

First, the high reflective power of the snow leads to a smaller heat intake at the surface, while the absorption of radiation by the air remains unchanged or might even be enhanced

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during the repeated passage of the reflected radiational flux (Loewe, 1963). Secondly, most of the incoming radiation absorbed by the snow is not retained at the surface itself but penetrates below the surface. Only part of this absorbed energy returns by convection and scattering to the surface; another fraction goes downwards. There are detailed studies of the temperature distribution above and below a snow surface (Geiger, 1961); but for regions without substantial melting in summer very few series of simultaneous shelter and surface temperatures extending over a whole year, as needed for the purpose of comparing shelter and 10 m temperatures, seem to be available. It is also difficult to obtain reliable data for the surface temperature of a snow cover. In most cases the authors of the following results extrapolated the surface temperature from thermo-electrical measurements at a small distance above or below the surface. The method of observation at the Soviet stations is not known.

Benson (1962), extrapolating from the first observations made in 1931 by Georgi (1943) at Eismitte, found that the mean annual surface temperature there was 0.7°C lower than the temperature in the shelter, and at Site 2 it was 0.6°C lower. At Maudheim the mean annual temperature at a height of 2.5 m is −17.6°C; at 0 m it is −18.0°C (Liljequist, 1956–57). During the summer months, November to February, the temperatures at these heights are identical, −7.1°C; however, the 0 m temperatures are extrapolated from observations 5 to 10 cm above the surface and might not be quite correct (Berg, 1957). At "Little America V" (Hoinkes, 1961) the surface temperature from April to August is about 1 deg lower than the temperature at a height of 2 m compared to 1.7 deg at Eismitte for the corresponding months (Georgi, 1943). Rusin (1961) has made extensive calculations of the difference between the temperature at 2 m and that at the surface for Antarctic stations. The available observations suggest that with decreasing temperature the surface gets increasingly colder than the shelter. This is clearly shown by surface temperatures given by Rusin (1961) for the Soviet stations in east Antarctica (Table I). Locations and heights of the stations are given in Tables III and IV.

TABLE I. SHELTER AND SURFACE TEMPERATURES (°C); ANNUAL MEANS

	Pionerskaya	*Komsomolskaya*	*Vostok*
Mean shelter temperature	−38.2	−52.5	−55.4
Mean surface temperature	−38.7	−53.8	−57.5
Shelter minus surface	+0.5	+1.3	+2.1

(Rusin's table 16 shows that at Pionerskaya there are amazing temperature differences between the monthly means at 0 cm and at 1 and 2 cm depth, but he has not stated how these observations were made.) At the South Pole (Dalrymple, 1961), hourly observations of temperature for 170 d gave the mean difference between the surface and 2 m height for different temperature intervals as shown in Table II.

TABLE II. TEMPERATURE DIFFERENCES (°C) BETWEEN AIR AT 2 m AND SURFACE AT SOUTH POLE

Temperature	>−40	−40 to −50	−50 to −60	−60 to −70	<−70
Mean difference (shelter minus surface)	−0.45	−0.05	+0.95	+1.15	+1.35

With lower temperature the surface temperature gets increasingly colder; this is corroborated by the fact that also between the shelter level and the level of the highest temperature the mean strength of the inversions increases with decreasing temperature (Liljequist, 1956–57). At Thule, Greenland, inversions starting from the surface are, from November to April, $2\frac{1}{2}$ times stronger than from May to October (Bilello, 1966); the mean shelter temperatures during these half years are −23°C and −1°C, respectively. We can thus expect a similar difference between the mean annual temperatures in the shelter and those at 10 m below the surface.

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Shelter temperatures and 10 m temperatures

In the appropriate regions of the ice sheets the 10 m temperatures normally decrease with increasing latitude and height (Bull, 1964; Mock and Weeks, 1965, 1966). But there are cases where the firn temperature rises with increasing height (Taylor, 1965; Cameron and others, 1968). These anomalous temperatures are found in regions with a substantial slope of the surface; and it is believed that the higher speed of the down-flowing wind near the surface and the resulting stronger turbulence lowers the level of the warm air above, produces stronger mixing and thus raises the temperature at shelter level and at the surface (Liljequist, 1956–57, fig. 21). If this explanation is accepted, the abnormally high 10 m temperatures are a consequence of the relatively warm temperature at and near the surface; they are not caused by an abnormal temperature difference between the shelter level and the surface.

If the 10 m temperatures are in fact determined by the mean annual temperatures at the snow surface itself, the question arises as to how far they can be identified with the air temperature at shelter level, as is frequently done. Tables III and IV give the mean annual temperatures in the shelter and at a depth of 10 m and the difference shelter minus 10 m in Greenland and Antarctica for those places that are outside the region of substantial summer melt and for which data at both levels are available.

As the tables show, there are some uncertainties since the different authors do not completely agree. In Greenland, with the exception of the lowest stations (Camp Century and Site 2), the air temperatures are markedly lower than the temperatures at depths of 8 and 10 m. The reason for this is not clear. The supply of geothermal and frictional heat from below is insignificant. It is very doubtful whether a very recent warm period could be the cause. But the sense of the difference corresponds to that found at the South Pole (Table II) for the same temperatures (>−40°C). The relative warmth of the firn might possibly have something to do with the fact that the accumulation, at Eismitte and Station Centrale (33 cm water equivalent), falls mostly with temperatures which exceed the average temperature considerably. At Eismitte, in cases of strong snowfall, the temperature is 6°C higher than on the preceding day (Loewe, 1935).

The conditions in Antarctica are different from those of the Greenland ice sheet. At annual means warmer than −30°C the difference between the temperature at shelter level and at a depth of 10 m is small. At colder places the temperature of the firn drops increasingly below that at the height of the screen. At the coldest station, "Plateau", the 10 m temperature is almost 4°C lower than the screen temperature. The difference is, however, much bigger than at the similarly situated station Vostok. It can be expected that the deficit of the 10 m

Table III. Temperatures (°C) at screen level and at 10 m, and differences shelter minus 10 m, Greenland

Station	*Location*	*Height* m	*Years*	*Temperature* shelter	*Source*	*Temperature* −10 m	*Source*	*Difference*
Camp Century	lat. 77° 10′ N. long. 61° 08′ W.	1 910	1960–63	−23.5	Hogue, 1964, table 35	−24.5	Mock and Weeks, 1965, p. 28	+1.0
Site 2	lat. 77° 03′ N. long. 56° 07′ W.	1 990	1953–57	−24.2	Hogue, 1964	−23.7	Mock and Weeks, 1965	—
				−23.9	Haywood and Holleyman, 1961	−24.3	Benson, 1962	
				−23.8	Benson, 1962	−24.4	Benson, 1962 (8 m)	
				−24.4	(Benson, 1962; surface, corrected)	−24.0	Hogue, 1964 (8 m)	
Northice	lat. 78° 04′ N. long. 38° 29′ W.	2 345	1952–54	−29.9	Hogue, 1964	−28.0	Hogue, 1964 (8 m)	−2.0
				−30.2	Haywood and Holleyman, 1961	−28	Bull, 1958 (no depth)	
Station Centrale	lat. 70° 54′ N. long. 40° 38′ W.	2 965	1949–51	−28.2	Hogue, 1964	−28.0	Hogue, 1964 (8 m)	
				−28.3	Ratzki, 1960	−27.4	Perez, [1952]	
Eismitte	lat. 71° 11′ N. long. 39° 56′ W.	3 000	1930–31	−30.2	Georgi, 1935; Loewe, 1935	−27.5	Mock and Weeks, 1965	−0.6
						−28.1	Sorge, 1935	−2.1
				−30.7	Hogue, 1964			
				−30.9	Benson, 1962; surface	−28.0	Hogue, 1964 (8 m)	

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TABLE IV. TEMPERATURES (°C) AT SCREEN LEVEL AND AT 10 m, AND DIFFERENCES SHELTER MINUS 10 m, ANTARCTICA

Station	*Location*	*Height* m	*Years*	*Temperature* shelter	*Source*	*Temperature* −10 m	*Source*	*Difference*
"Little America III"	lat. 78° 30′ S. long. 163° 50′ W.	30	1939–40	−23.7	Wexler, 1961; corrected	−23.7	Wade, 1945	0.0
				−23.2	Court, 1949	−22.9	Court, 1949	
"Little America V"	lat. 78° 11′ S. long. 162° 12′ W.	42	1957–58	−22.8	U.S. Weather Bureau, 1962	−23.5	Crary, 1961	+0.7
				−23.3	Phillpot, 1967			
Ellsworth	lat. 77° 43′ S. long. 41° 07′ W.	43	1957–58	−23.4	U.S. Weather Bureau, 1962–	−24.3	Aughenbaugh and others, 1958, p. 39	+0.8
						−24.1	Aughenbaugh and others, 1958, p. 40	
Eights	lat. 75° 18′ S. long. 77° 07′ W.	450	1964–65	−25.9	U.S. Weather Bureau, 1962–	−24.8	Shimizu, 1964	−1.1
"Byrd"	lat. 80° 00′ S. long. 120° 00′ W.	1 515	1957–67	−28.3	U.S. Weather Bureau, 1948, 1962	−28.3	Dalrymple, 1966	+0.2
						−28.6	Koerner, 1964	
					Phillpot, 1967	−28.2	Anderson, 1958	
				−28.1	Dalrymple, 1966	(−27.9)	Marshall and Gow, 1958	
Charcot	lat. 69° 22′ S. long. 139° 01′ E.	2 400	1957–58	−37.3	Centre National de la Recherche Scientifique, 1961	−38.0	Lorius, 1964	+0.7
Pionerskaya	lat. 89° 44′ S. long. 95° 31′ E.	2 740	1956–58	−38.0	Rusin, 1961; Dalrymple, 1966	−39.4	Aver'yanov, 1958; Dalrymple, 1966	+1.4
South Pole	lat. 90° 00′ S.	2 800	1957–67	−49.3	Dalrymple, 1966	−50.8	Giovinetto, 1960; Dalrymple and others, 1963	+1.5
Komsomolskaya	lat. 74° 06′ S. long. 97° 30′ E.	3 500	1958	−52.2	Rusin, 1961	−53.9	Aver'yanov, 1958; Dalrymple, 1966	+1.7
				−52.5	Dalrymple, 1966			
Vostok	lat. 78° 28′ S. long. 106° 48′ E.	3 490	1958–67	−55.6	U.S. Weather Bureau, 1948–	−57.3	Aver'yanov, 1958; Dalrymple, 1966	+1.7
				−56.4	Dalrymple, 1966			
"Plateau"	lat. 79° 18′ S. long. 40° 30′ E.	3 620	1966–68	−56.6	U.S. Weather Bureau, 1948–; personal information	−60.5	Radok and others, 1968	+3.9
						−59.9	Kuhn, unpublished	+3.3

temperature increases with lower temperatures, because many observations show that the inversions of temperature from 2 m upwards get stronger with lower temperature (Liljequist, 1956–57; Bilello, 1966), and the same is likely to occur between the surface and 2 m also. The correlation between the mean temperature at the seven coldest Antarctic stations and the temperature deficit of the 10 m temperatures is of the order of 0.7; but it must be conceded that the very big deficit of the coldest station, "Plateau", contributes very strongly to its size. If only regions of insignificant melting are considered, it still appears established that in the interior of the Greenland ice sheet the temperatures at a depth of 10 m are mostly higher than at shelter level. On the Antarctic ice sheet and on the ice shelves down to a mean annual temperature of −30°C, the temperature at a depth of 10 m is similar to the annual mean in the meteorological screen. In colder regions the 10 m temperature is systematically colder than the air at 2 m height. The difference increases by about 1 °C for a drop of the mean temperature of 10°C. This difference might be taken into account if temperatures at a depth of 10 m are used to derive the mean annual temperatures of the air near the surface in the interior of the Antarctic continent.

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