NORSK POLARINSTITUTT
SKRIFTER NR. 128

OVE WILSON

COOLING EFFECT OF AN ANTARCTIC CLIMATE ON MAN

WITH SOME OBSERVATIONS ON THE OCCURRENCE OF FROSTBITE

NORSK POLARINSTITUTT
OSLO 1963

DET KONGELIGE DEPARTEMENT FOR INDUSTRI OG HÅNDVERK

NORSK POLARINSTITUTT
Observatoriegt. 1, Oslo, Norway

Short account of the publications of Norsk Polarinstitutt

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ÅRBØKER

Årbok 1960. 1962. Kr. 15.00.
Årbok 1961. 1962. Kr. 24.00.

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Received for publication February, 1962
Printed November 1963

PUBLISHED BY NORSK POLARINSTITUTT
DISTRIBUTED BY UNIVERSITETSFORLAGET
OSLO 1963

Contents

Abstract

The antarctic climate at Maudheim is studied in terms of atmospheric cooling, using temperature, wind speed, radiation, and wind chill index. Weekly mean values for these factors are presented graphically, giving a synopsis of the climate. Weekly mean changes in temperature and wind chill are also given for the field parties travelling inland, and the deviations are discussed. Wind chill frequencies at different intervals of temperature have been calculated for Maudheim, as well as cumulative frequencies for each month. Differences in the mode of calculating mean wind chill are discussed. The mean wind chill index at Maudheim and at various other stations all over the antarctic continent are compared. Incidents of frostbite at Maudheim are studied in relation to temperature, wind speed and wind chill index, and the rate of occurrence in different seasons and at different temperatures is also discussed.

Introduction

As medical officer to the Norwegian-British-Swedish Antarctic Expedition (NBSX), 1949–52, I spent two years of alternating life at the base station Maudheim (71°03' S, 10° 56' W) and on sledging journeys into the interior of Dronning Maud Land. Besides having my share of the daily duties at the base, I conducted physiological investigations and took part in other research work continuously going on. This included participation in climatological measurements of various types. Through these investigations my interest was focused on the special problems of cooling effect on man, which are an important medical and hygienic problem. The climate of Antarctica provides meteorological conditions which must be regarded as a severe environmental stress to man and his heat regulation. It is, however, difficult to evaluate and measure the degree of the climatic stress to which man is exposed during a sojourn in the Antarctic. It cannot simply be expressed by a temperature curve or by giving mean values of meteorological data. The atmospheric cooling power at low temperatures is greatly increased by air movement. There is also the heat gain from solar radiation.

In this paper an attempt will be made to describe the antarctic climate in terms of atmospheric cooling as experienced at Maudheim and on sledging trips into the interior of the continent. The atmospheric cooling effect will also be correlated to incidents of frostbite as evidence of cold exposure.

General description of climate

For an account of the general aspects of antarctic weather, reference is made to RUBIN (1962), and to "Science in Antarctica" (WEXLER and RUBIN, 1961), which gives many important references on antarctic meteorology. The following description of the climate is mainly condensed from these reports. The antarctic climate is determined by the proximity to the pole, with yearly alternating

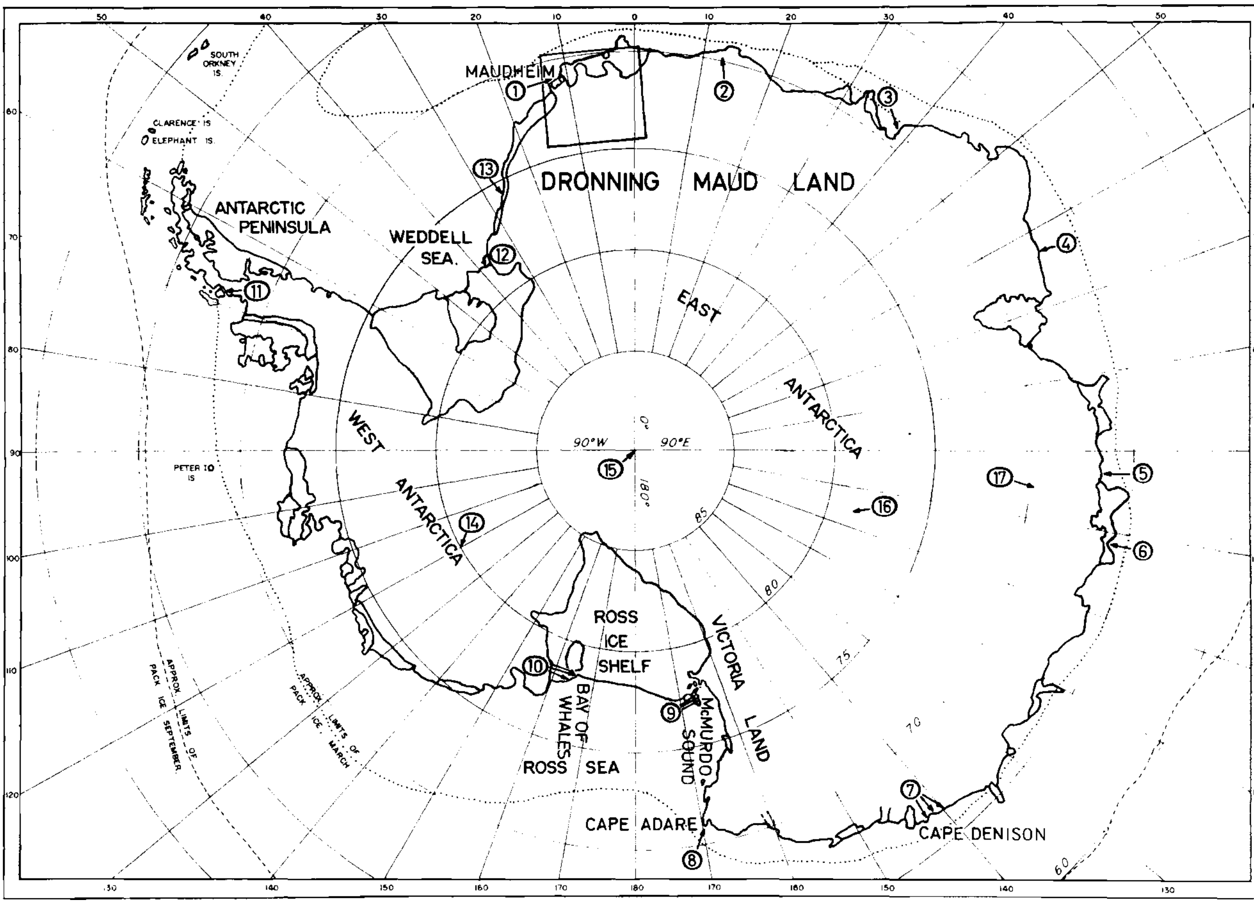

Fig. 1. *Antarctica. Inset shows area covered by Fig. 5. Numbers within circles refer to antarctic stations, see Table 5.*

periods of continuous polar night with total darkness and cold summer with intense light and midnight sun. Compared with the Arctic the Antarctic has a much more severe climate, being roughly 15° C colder. It is characterized by low atmospheric pressures and great windiness.

Large cyclonic vortices which form over the southern oceans move from west to east, and also southeastward into the large indentation of Antarctica known as the Ross Sea on the opposite side of the continent from Maudheim (Fig. 1). Some of these cyclons move across West Antarctica into the Weddell Sea close to Maudheim. Local drainage winds are quite common in Antarctica when the cold dense air, which is formed over the high plateau, flows down the glaciers and the slopes of the plateau. These drainage (katabatic) currents are only a few hundred meters thick and may flow quite smoothly in otherwise calm weather. For a moderate slope a typical wind speed is 10 m/sec. When the atmospheric circulation has the same general direction as the slope of the inland ice, the katabatic currents may develop into very strong winds accompanied by heavy drifting snow. Local topographic features, such as glaciers and ice-stream valleys, may further add to the turbulence. These katabatic winds come and go very suddenly and are responsible for the fierce but often rather short-lived local antarctic blizzards, where snow does not fall from the clouds but is picked up from the surface by the strong turbulent winds and transported over long distances.

Because of the high frequency of drifting snow, the direct measurement of actual precipitation is difficult to accomplish – if possible at all in Antarctica. The annual accumulation in terms of water equivalent varies from about 40 centimeters at Maudheim to about 7 centimeters at the South Pole, with an overall average for Antarctica probably about 15 centimeters.

In general the mean temperature of the year follows the expected decrease with increased latitude and altitude from an average value around —15° C at the coast. The difference between the warmest and coldest months of the year is quite large, ranging from more than 30° C on the plateau to about 20° C at the coast. The drop in temperature in autumn is largely completed by the time the sun has set for the winter and is followed by a much slower decline in the dark months, giving rise to a characteristic flat temperature curve throughout the winter months at many stations, coastal and interior. During part of the winter night, the mean temperature may even increase. Also, extremely large year-to-year changes in temperature are observed.

The physical property which gives Antarctica its distinctive climate is radiation. During the sunlit period, the extremely clear air and the low water vapour content (due to the low temperature) permits irradiation of the Antarctic continent by intense solar radiation. While snow-free ground will absorb most of the incoming solar radiation, a snow-field will keep only a minor part. Since more than 95 per cent of Antarctica is covered by a brilliantly white snow surface reflecting 80 to 90 per cent of the total incoming solar radiation, only a minor part of this strong insolation is retained in the surface layers of the snow. Besides, snow is a black-body radiator at temperatures below 0° C and it is a very poor conductor of heat. These properties of snow tend to increase the severity of the polar climate. During the brief summer season (mid-November to the end of January) the radiation balance at the surface (absorbed solar radiation minus outgoing net long-wave radiation) is generally positive, but for the rest of the year it is negative. This means that the surface loses radiation energy, except in the height of summer. When the radiation balance is negative, the temperature will drop until a balance is about reached between the radiation loss and the energy income to the surface. This takes part in the form of turbulent transfer of heat from the air and heat conduction from the snow. Such a balance is generally developed in the winter in fine weather situations, characterized by marked surface inversions, i. e. a pronounced increase in temperature with height in the surface air layers, often some 20° C from the surface to the 10 meter layer (LILJEQUIST, 1957 b). Thus the snow is protected from heavy energy losses by the development of a coating of cold air (an inversion), which makes the radiation losses small and which besides sets up a turbulent flux of heat from the air to the surface. Such an inversion may persist even with winds as high as 8 m/sec at the 10 meter level, which mainly is due to the very flat snow surface (causing comparatively weak turbulence). With wind speeds higher than 8–9 m/sec the inversions are generally destroyed, letting the warmer air above the inversion reach the surface. A sudden increase in wind may therefore be accompanied by a sudden rise in temperature, amounting to 10–20° C in the winter. A clouding-over is also usually followed by a marked rise in temperature, sometimes amounting to 10–20° C. This is explained by the fact that the base of low or middle clouds is generally warmer than the snow surface (owing to the surface inversion). As the clouds in general are black-body radiators, the net long-wave radiation to the snow will be incoming and the surface temperature will rise and also the temperature of the air near the surface (LILJEQUIST, 1956 b, 1958).

Heat exchange and wind chill

In a cold climate the environmental stress consists of a combination of air temperature, wind, and radiation, which determine the relative comfort sensation and may cause injury, such as frostbite, snow-blindness, damage to the skin, etc. The main factor concerned with relative discomfort and health hazard is heat loss. The mechanisms governing heat loss are described in detail by BURTON and EDHOLM (1955). In evaluating the cooling effect of the atmospheric conditions on the human body, one has to take into consideration the various ways in which the body exchanges heat with the atmosphere. These include convective exchange with the air, radiative exchange with objects and the sky, conductive exchange to the ground or other objects in contact, evaporation from the skin and from the respiration tract, warming and humidifying inspired air. Of these avenues of heat loss the convective is the most important and accounts for the major portion.

Important is also the heat loss through the lungs. Investigations (Webb, 1955; Brebbia, Goldman and Buskirk, 1957) indicate that at low environmental temperatures, in absence of sweating, the total heat loss from respiration will be a relatively constant fraction of the heat loss from the body, when in thermal balance, and may amount to about 17 %. During increased physical activity body heat production rises, perspiration begins, and the excess heat is removed by vaporization. One can assume that this avenue of heat loss is adequately controlled by the body and that the heat removed by evaporation does not exceed the additional heat produced by the muscular activity. However, condensation of perspiration in the clothes may lessen the insulation of the clothing and thus increase heat loss by convection. Conductive heat loss is also augmented in this way. But with adequate and appropriate polar clothing and suitable footgear, used with the experience one acquires in a polar climate, the conductive exchange is reduced to a minimum. An exception is when working with bare hands touching cold metal, in which case frostbite often occurs. At low temperatures (—40° C) and almost no air movement the radiative heat loss amounts to 20–30 % of the dry heat transfer, but with increasing air movement assumes a proportionally decreasing fraction and at 2 m/sec accounts for only 8 % (Burton and Edholm, 1955). Thus the main factor concerned with uncomfortable or deleterious heat loss is *convective cooling.*

Various formulas to express the dry convective cooling power of the atmosphere have been proposed. They have been extensively reviewed by Stone (1943), who cautions against extrapolation of formulas very far beyond the laboratory or experimental ranges over which they were originally evaluated. There are very few formulas based on actual observations in an extremely cold climate as in the Antarctic (Bodman, 1908; Siple and Passel, 1945; Sapin-Jaloustre, 1955; Vinje, 1962). Of these the formula of Siple and Passel (1945) is the only one that has more closely correlated atmospheric cooling to stages of relative human comfort sensations under very cold climatic conditions and established approximate limits for the onset of freezing of human flesh. Vinje (1962) has also calculated the cooling power at which human skin freezes in the Antarctic, but for his measurements he has used the kata thermometer, and Stone (1943) points out that human body-cooling computed from kata thermometer readings considerably exceeds the actual (directly measured) human heat loss. Because of the small size of the kata thermometer, air currents exert a greater cooling effect on it than on the human body. Therefore in physiology the kata thermometer is nowadays used almost exclusively as an anemometer (Bedford, 1948). The formula of Siple and Passel was developed from experiments conducted at Little America, Antarctica, at temperatures down to —56° C. This "wind chill" formula, given below, was calculated from observations of the cooling rate and freezing of water sealed in a plastic cylinder, and related to + 33° C (neutral skin temperature).

$$H = (\sqrt{100v} + 10.45 - v)(33 - t)$$

H = Heat loss (wind chill) in kcal/m²/hr
v = Wind speed in m/sec
t = Air temperature in ° C

The wind chill formula is calculated to measure the cooling power of wind and temperature on shaded, dry human skin, without regard to evaporation. The resulting heat loss is expressed in kilogram calories per square meter of exposed (nude) skin surface per hour. The term wind chill is applied to a scale of heat loss (Table 1) extending from an index of 50 (hot) to 2500 (intolerably cold). The formula has been further discussed by several authors (COURT, 1948; BURTON and EDHOLM, 1955; MOLNAR, 1960). It has been criticized for its lack of theoretical basis, because it is not feasible to express the effect of wind on heat loss without references to the amount of clothing that is being worn. The same wind speed will increase the heat loss of a lightly clad man very greatly, but increases only slightly the heat loss of a heavily clothed man. The dominant factor in determining heat loss should be the insulation of clothing worn. However, the calculation of insulation provided by polar clothing presents a major problem, as the insulation is different for various clothing assemblies and changes markedly under windy conditions. Experiments (BRECKENRIDGE and WOODCOCK, 1950) with cold-weather clothing have shown that in the wind there is a reduction in insulation, which is approximately proportional to wind speed, but the insulation curves for different clothing are very dissimilar. Individual "heat demand" charts were developed for predicting the cooling effect of wind on each type of clothing. It was found that the predicted values for heat loss from these individual charts differed as widely from each other as did the wind chill index on a relative basis. It was concluded that while heat loss is more quantitatively predictable with a "heat demand" chart for the specific clothing being worn, wind chill is sufficiently accurate as a relative index of cold stress on a clothed person.

Table 1.

Stages of relative human comfort and environmental effects of atmospheric cooling.

(After SIPLE and PASSEL, 1945, and SIPLE, 1945.)

Wind chill index	
600	Very cool. Considered as comfortable when dressed in wool underwear, socks, mitts, ski boots, ski headband, and thin cotton windbreaker suits, and while skiing over level ground at about 5 km/hr. (Metabolic output about 200 kcal/m²/hr.)
800	Cold.
1000	Very cold. Considered unpleasant for travel on foggy and overcast days.
1200	Bitterly cold. Considered unpleasant for travel on clear sunlit days.
1400	Freezing of exposed human flesh begins, depending upon degree of activity, amount of solar radiation, character of skin, and circulation. Travel or living in temporary shelter becomes disagreeable.
2000	Travel or living in temporary shelter becomes dangerous. Exposed areas of flesh will freeze within less than 1 minute for the average individual.
2300	Exposed areas of flesh will freeze within less than ½ minute for the average individual.

The wind chill formula should not be employed to express actual amounts of heat loss in kcal/m^2/hr, but should be considered as an empirical table, and the values used as index numbers on a relative scale. As such the wind chill index has been widely utilized, for it has been found by common experience in the field that it provides an index corresponding quite well with the discomfort and tolerance of man in the cold. This is because the tolerance will be determined by the parts of the body which are usually unprotected, such as the face and hands. The wind chill then applies to the naked face or the bare hands, where the pathological effect of cooling first will appear. Usually only general mention has been made of the occurrence of frostbite in relation to wind chill (Molnar, 1960). Except for some experiments made at Little America III (Siple and Passel, 1945) to determine the time required for the freezing of normal flesh exposed to cold wind, no work has been published on the correlation of simultaneous observations of wind chill and actual cases of frostbite. However, there is an extensive study of the epidemiology of cold injury in Korea (Schuman, 1954), where the relationship between daily incidence of cold injury and daily average wind chill has been considered. In this investigation were included all types of frostbite, primarily of the feet with considerably less cases of hand frostbite and only few of the face. The incidence was correlated to the daily average wind chill for the entire day and for the entire U.S. Front in Korea. It must be pointed out that in Korea in the winter the temperature range each day is enormous and temperature swings from —30° C to zero. Thus an average wind chill index cannot possibly be representative of the coldest conditions of the day, when the cold injuries no doubt occurred. Actually there was a somewhat closer relationship between the incidence of cold injury and daily minimum temperature. This is quite natural considering the fact that the recorded cases of frostbite were mainly cold injuries of clothed parts of the body and not of exposed skin.

Materials and methods

Data and meteorological studies of the climatic conditions at Maudheim have been published by the NBSX (Schumacher, 1952; Hisdal, Amble and Schumacher, 1956; Hisdal, 1958, 1960; Liljequist, 1954, 1956 a, b, 1957 a, b, 1958), and the methods used by the expedition have been described in detail in these papers. All instruments were carefully calibrated and continuously checked, and all necessary corrections have been applied. The wind speed (Liljequist, 1957 a) was measured continuously with an anemometer at a standard level of 10 meters above the surface and also at five different intermediate levels. The mean wind speed was determined for hourly intervals half an hour before and after each even hour. The temperature (Hisdal, 1960) was measured with mercury-thallium thermometers and thermographs, as well as with platinum thermometers at five different levels up to 10 meters (Liljequist, 1957 b). During the summer half-year the temperature measurements were strongly influenced by the intense solar radiation. On calm, sunny days, especially with a thin cloud cover, radiation within the screen could cause an error of as much as three to five degrees centigrade, i.e. the screen-recording would be that much higher than the true air temperature. Therefore readings had to be made upon a ventilated Assmann psychrometer to supplement the ordinary weather observations. The readings on the unventilated maximum thermometer in the screen could not be corrected for radiation error as could the temperature observations at fixed hours. It is very likely that the estimated correction of this error is frequently too small (Hisdal, 1960).

The highest temperature ever read on a ventilated thermometer was a few tenths above 0° C, while values up to + 4°, 2 C were observed upon the unventilated thermometer in the screen. For measurements of the duration of sunshine a Campbell-Stokes sunshine recorder of a special design for high latitudes was used (LILJEQUIST, 1956 a).

For the present study additional data have been compiled from the original Maudheim records and from the log-books of the sledging parties. To be able to use means for shortest possible time intervals in the climatic analysis at hand and for the computation of mean and individual wind chill values, it has been necessary for the author to go back to the original primary observations and to recalculate the data to fit the requirements of the present investigation. This has required a complete going through of all the meteorological log-books of the base and of the various sledging parties for the whole two-year period. Individual daily values have been used in determining the weather conditions for each recorded case of frostbite, which work has been greatly facilitated by the detailed personal diaries kept by the author during the complete expedition period. Together with the medical records these notes have provided means for tracing individual activity and pinpointing the time of occurrence of frostbite and conditions associated with it.

The weekly arithmetical means for temperature, wind speed, and duration of sunshine have been calculated by the author for alternating periods of 8 and 7 days to make four "weeks" a full month. The daily temperature means are from measurements every third hour from 06.00 to 24.00 hours, including maximum and minimum values. The temperature data are representative of the layer 1.5–2.0 meters above the surface. The wind speed values have been recalculated for a layer 1–1.5 meter above snow level, where the speed is only 80 % of that at the standard 10 meter level (LILJEQUIST, 1957 a). The daily means for wind speed are from hourly means, computed from continuous recordings. The maximum and minimum hourly wind speed values, on the other hand, are only for the time period 08.00 to 22.00 hours. It contrast to minimum temperature which alone never limited outdoor activity, the maximum wind speed often was a deterrent factor, restricting outdoor activity during working hours to the least possible and abolishing it at night – except for the meteorologists. Accordingly, during night hours exposure to maximum wind speed values almost never occurred, which is the reason why they have not been included.

For the *sledging journeys* the meteorological data have been taken from the various log-books. Repeated daily observations were made during all of these trips. The mean number of daily observations on each trip varied from 3 to 5. Mostly 5 observations were made, and on one journey 6 or more daily observations were made during half of the time. The temperature was measured by sling-thermometers, calibrated and checked by the meteorologists at the base. Wind speed was estimated by experience. The constant necessity of having to evaluate weather conditions accurately led to a considerable personal skill in correctly judging wind speed, especially by expedition members in the field. Estimated values usually agreed well with measured wind speeds and were never much in error. An estimated wind speed may be regarded at least as accurate as a solitary observation obtained with instrument, compared with hourly mean values.

Wind chill values have been calculated from daily observations of temperature and wind at 09.00 and 15.00 hours at the base Maudheim, according to the tables of SIPLE and PASSEL (1945). These two term-hours have been chosen, rather than the one at 12.00, because the first will be representative of morning exposure and the second of afternoon conditions, and will thus indicate changes during the day. For the field parties wind chill has been computed as far as possible from meteorological observations made from camp to camp, which covers the time of exposure from breaking camp, on the trail, to erecting camp, whether travelling by day or night. For each day the simultaneous observation of temperature and wind which gave the highest wind chill index has been chosen. This implies that the daily values used for weekly mean wind chill are representative of the coldest conditions during sledging, which does not necessarily mean the very coldest encountered during each day, as wind chill values can be estimated only for the moments when weather observations were made. Cooling figures for sledging must therefore be regarded as only approximate.

Monthly mean wind chill indices have been computed also for 15 other antarctic stations from recent meteorological data. Monthly mean values for standard measurements of temperature and wind have been used (supplied by T. VINJE, Norsk Polarinstitutt, Oslo). In addition mean wind chill values for 7 antarctic stations occupied prior to 1941 have been taken from SIPLE and PASSEL (1945).

Data and results

Temperature

The mean temperature of the year at Maudheim (—17.5° C) is comparatively low for a coastal station. Weekly means of the temperature with maximum and minimum for the two-year period are plotted in Fig. 2. The typical flat winter minimum with large fluctuations is evident. In the summer season the mean temperature does not exceed 0° C, which is associated with the "temperature barrier" at 0° C, created by the extensive snow-fields. This phenomenon also affects the temperature frequency distribution in the summer, which shows a noticeable negative skewness. In temperate regions the frequency distribution of temperature is usually positively skew in the summer season (i. e. longer tail of distribution towards higher temperature values). During the antarctic summer there is a decrease of the temperature dispersion at term-hours, although there is a marked diurnal variation, but in the winter months, when there is no pronounced regular diurnal temperature variation, the dispersion is great, reflecting the alternation of anticyclonic and cyclonic weather situations (HISDAL, 1960).

Wind speed

The mean wind speed of the year is 7.7 m/sec at the 10 meter level and 6.1 m/sec at the 1–1.5 meter level. Weekly mean values of the wind speed together with maximum and minimum values are plotted in Fig. 2, which well illustrates the windiness of the antarctic continent. Note that the maximum and minimum

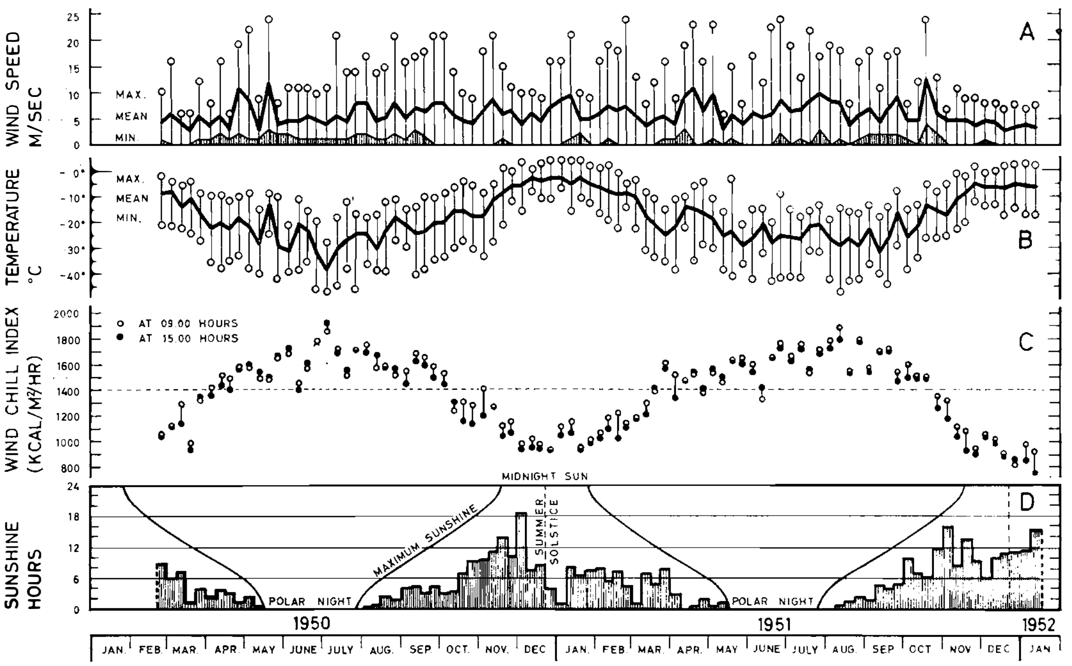

Fig. 2. *Climate at Maudheim during the period from February 22, 1950, to January 14, 1952.*

A. *Weekly means of wind speed from hourly means (meters per second at 1–1 ½ meter level). Maximum and minimum hourly values have been taken only from period between 08.00 and 22.00 hours. Shaded areas represent periods with no recorded hourly wind speed below 1 m/sec.*

B. *Weekly means of temperature (° C) with maximum and minimum from measurements every third hour from 06.00 to 24.00 hours. Maximum values during warmest months may be several degrees in error because of strong solar radiation.*

C. *Weekly means of wind chill index* (Siple and Passel, 1945) *as measured daily at 09.00 and 15.00 hours.*

D. *Weekly means from continuous recordings of sunshine as compared with maximum duration.*

values plotted are valid for the time period 08.00 to 22.00 hours, and that they refer to hourly mean values, i.e. they do not represent wind gusts. As can be seen, there were long periods (several weeks or even months) when air movement was never less than 1 m/sec (hourly mean), in some cases not less than 2–3 m/sec. The number of days in each month when wind speeds at 1–1.5 meter level exceeded 8 m/sec (fresh breeze) and 14 m/sec (moderate gale) during the time period 08.00 to 22.00 hours are given in Table 2. When the wind speed surpassed 8–9 m/sec at the 10 meter level the snow started drifting and above 15 m/sec the snow drift became dense (Liljequist, 1954, 1957 a).

There does not seem to be any marked annual variation of the wind speed, though the frequencies of gales may be somewhat lower in late spring and early autumn than in other seasons. In the coldest months there was a marked correlation between high wind speed and increase in temperature, which was especially apparent in July (Schumacher, 1952; Hisdal, 1960).

Table 2.

Number of days in each month when wind speeds (hourly means at 1–1½ meter level) exceeded 8 m/sec and 14 m/sec.

Wind speed		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
≥ 8 m/sec	1950	—	—	3	8	13	7	10	15	14	12	16	10
	1951	16	11	8	17	6	13	17	11	17	13	5	4
≥ 14 m/sec	1950	—	—	0	6	8	0	2	6	6	1	6	2
	1951	4	6	0	8	4	6	9	6	5	4	0	0

Radiation

Weekly means of the daily duration of sunshine are shown in Fig. 2. The sun appears for the first time above the horizon on July 26, from which date the intensity of sunlight rapidly increases, and by the middle of September the intensity of direct solar radiation (i. e. with normal incidence) is already about the same as in the summer in temperature regions, or about 750 kcal/m^2/hr. At the end of March it falls below this value again, and after May 19th the sun is definitely below the horizon for the winter. In November – January the intensity of the direct solar radiation exceeds 900 kcal/m^2/hr, and maximum values around 930 kcal/m^2/hr occur in November – December (Liljequist, 1956 a). It is also important to note that the reduction of the radiation flux in dull weather with an overcast sky is far less in the Antarctic, due to multiple reflexion between the snow surface and cloud base. Measurements of the global radiation at Maudheim (Liljequist, 1956 a) have revealed that even with a dense overcast, the intensity of diffuse sky radiation is usually 50–60 % of the incoming solar radiation on clear days. In temperate latitudes the corresponding value is generally less than 25 %.

Wind chill at Maudheim

The weekly means of wind chill index as computed from daily observations at 09.00 and 15.00 hours are plotted in Fig. 2. A marked seasonal variation is evident with the highest wind chill means occurring in the winter. As seen, the weekly mean wind chill index is often higher in the afternoon than in the morning, while the opposite is mainly the case in the light season. If the difference between the daily individual values are analyzed, it is found that during the dark months of May to August (which have a mean duration of sunshine per day of less than 1½ hour) about 50 % of the afternoon wind chill values are higher or the same as in the morning. In October – November this occurs only on about 25 % of the days and during the remaining months on about 35 % of the days. This is a consequence of the diurnal variation of the term-hourly temperature mean, which shows the largest daily amplitudes in the summer months (most pronounced in

October – November) with the highest temperatures occurring at 15.00 hours, while the deviations of the term-hourly means from their mutual mean are small and irregular in the dark months (HISDAL, 1960). In other words, in the sunlit season it is colder in the morning, while there is no special trend during the day in the dark period.

In the period of April – beginning of October 1950, and mid-March – end of October 1951, the mean weekly wind chill index was larger than 1400. Of a total of 685 days at Maudheim, when meteorological observations were conducted, 372 days had a wind chill index of more than 1400 measured at 09.00 hours. A wind chill of more than 2000 was observed on 11 days at either term-hour, with a maximum recorded index value of 2114. The lowest recorded index was 324.

The seasonal variation in wind chill approximately follows the temperature curve. The degree of correlation is better demonstrated by Table 3 and Fig. 3. Table 3 shows the wind chill frequencies at different temperatures at Maudheim measured daily at 09.00. At temperatures above —8° C no wind chill values over 1400 were observed. Below —18° C values over 1400 were predominating, and below —30° C only values over 1400 were found. In Fig. 3 wind chill frequencies at 09.00 are plotted against temperature. The curve shows the weighted mean and the range of the wind chill observations. In the figure the straight parameter lines correspond to wind speed values from 0 to 20 m/sec calculated from the wind chill formula. As can be seen, there is no linear correlation with temperature and there is a great dispersion of wind chill values observed at each temperature level. The largest deviations from the mean are observed at low wind speeds or no air movement. In the temperature range above —25° C one finds the most frequent wind chill values to be those caused by a wind speed of about 5 m/sec. At temperatures below —25° C the most frequent values occur at a lower wind speed of 3–4 m/sec, which is quite natural considering the fact that the temperature tends to rise when wind speed increases and upsets the surface inversion.

Cumulative frequencies of wind chill have been calculated for each month from daily values for 09.00 and 15.00 for the whole period at Maudheim. It was found that for several months the cumulative frequency curves, when plotted on a normal probability paper, followed each other closely. Therefore frequency values for coinciding months were combined and joint curves were drawn. They are presented in Fig. 4, which shows that during the months of May to September the daytime wind chill index will be higher than 1400 during more than 85 % of the time, and that a wind chill index of 1400 or more will be encountered during half of the time in April and October.

Calculation of mean wind chill index

The wind chill formula was developed for measuring the cooling effect of *simultaneous* conditions of wind and temperature. A wind chill index obtained from *mean* temperature and *mean* wind speed over a certain period may not be the same as the mean wind chill index computed from daily individual observations over the same time. In order to evaluate the variance with different methods of calculation, monthly means were computed in several ways. The *monthly* mean values for temperature and wind speed were calculated from daily measurements at 09.00 hours. They were found to agree surprisingly well with monthly mean values calculated from 7 term-hourly temperature readings and 24 hourly mean wind speed recordings made daily. The average difference in

Table 3.

Wind chill frequencies at different temperature levels, within intervals of two degrees centigrade and 200 kcal/m²/hr, measured daily at 09.00 hours from March 1, 1950, to January 14, 1952, at Maudheim. All temperatures (°C) negative.

Temperature	0–1	2–3	4–5	6–7	8–9	10–11	12–13	14–15	16–17	18–19	20–21	22–23	24–25	26–27	28–29	30–31	32–33	34–35	36–37	38–39	40–41	42–43	45	46	Number of days
Wind chill																									
355– 599	2	1	1	1			1		1			1													8
600– 799		3			2																				5
800– 999	7	17	16	14	3	4		1		1															63
1000–1199	3	13	35	20	14	8	9	8	2	2	4	2		2											122
1200–1399		1	4	10	9	10	10	15	18	23	4	3	3	4	1										115
1400–1599					3	8	14	9	10	15	25	16	13	17	5	11	4	1	2	1					154
1600–1799								7	11	23	15	7	15	9	22	17	13	10	3	6	1	1	1		161
1800–1999										3		6	3	4	2	1	7	7	9	4	4	2		1	53
2000–2114																				1	2	1			4
Weighted mean	870	950	1040	1070	1150	1250	1310	1370	1410	1500	1510	1530	1610	1550	1670	1630	1730	1770	1800	1780	1930	1900	1700	1900	
Number of days	12	35	56	45	31	30	34	40	42	67	48	35	34	36	30	29	24	18	14	12	7	4	1	1	685

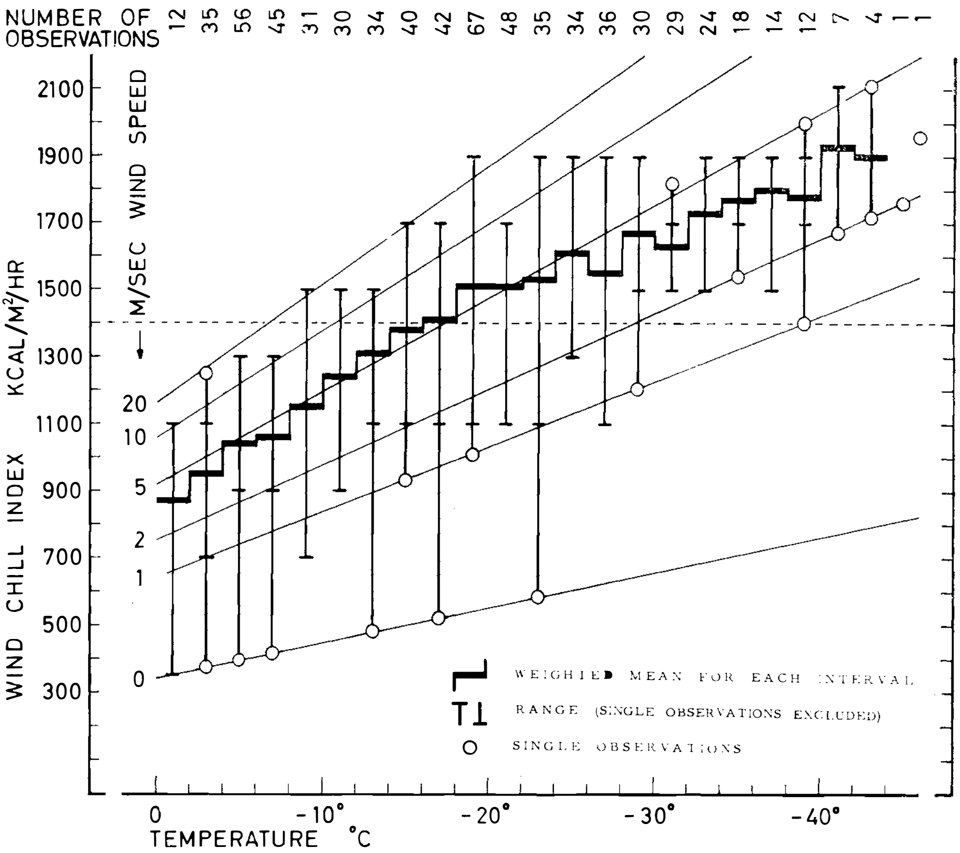

Fig. 3. *Wind chill frequencies at different temperature levels with intervals of two degrees centigrade, measured daily at 09.00 hours at Maudheim from March 1, 1950, to January 14, 1952.* (See also Table 3.) *The straight parameter lines correspond to wind speed values from 0 to 20 m/sec calculated from the wind chill formula.*

mean monthly temperature was only 0,5° C and in wind speed as small as 0,1 m/sec. From each of the two sets of values for monthly mean temperature and wind speed, the monthly wind chill index was computed. As expected, both curves agreed almost completely. The average difference between the monthly indices did not amount to more than 1 % (or 15 kcal/m^2/hr). The wind chill as estimated from observations at 09.00 hours thus seems to be representative of the average conditions of the whole day, judging from mean values. Monthly mean values of wind chill were computed also from the daily individual wind chill index at 09.00 hours. When the monthly mean indices based on individual observations are plotted against the indices estimated from monthly mean values of daily mean temperature and wind, the two curves follow each other continuously equidistant, the wind chill computed from monthly mean weather data giving systematically too high values, amounting to 6 % in the summer and 5 % in the winter.

Wind chill during sledging journeys

In the summer season sledging journeys were made to the inland mountain region, where the parties usually stayed for several months, in one case for 163 days. Eight men were in the field during the first summer period, and nine men during the second. The sledging parties worked from Advanced Base (a large depot

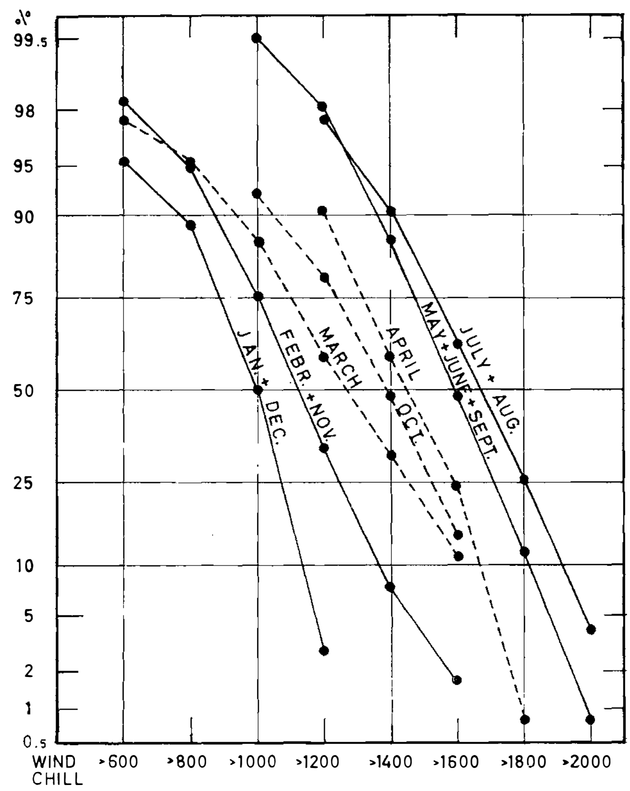

Fig. 4. *Cumulative frequencies of wind chill per month presented on a normal probability paper. Data computed from daily observations at 09.00 and 15.00 hours at Maudheim from March 1, 1950, to January 14, 1952.*

with food and equipment) making long trips into the interior, where the mountain ranges were explored and climbed, and then returning to Advanced Base to replenish their food supplies. The climate of the mountain area is of course much more severe than at the coast, owing to the higher altitude and latitude and the greater distance from the sea. Therefore the temperature and wind chill conditions encountered by the field parties have been studied and compared with the Maudheim data. The results are plotted in Fig. 6, and the duration of the various field trips are shown. An explanation of the travel routes with information of approximate altitudes and latitudes are given in Table 4, and a map (Fig. 5) shows their extent. As can be seen from Fig. 6, the mean wind chill index is markedly higher in the interior than at Maudheim in the same season, and the difference is usually greater than could be expected from the difference in mean temperature. This is due partly to greater windiness, reflecting local katabatic air currents from the south, and partly to the fact that the Maudheim wind chill data are mean values from 09.00 and 15.00 in the daytime, while the field values are representative of travel (exposure) conditions, mostly at night during the warmer periods. Of several daily values of wind chill the highest have been chosen as most indicative of the cold stress in the field. Several peaks (a–e) in the wind chill curves for the field parties are observed and will be discussed later.

Table 4.

Sledging journeys and seismic trip.

M = Maudheim (71° 03′ S, 10° 56′ W, altitude 37 meters)
AB = Advanced Base (72° 16′ S, 3° 49′ W, altitude 1332 meters) 300 kilometers from Maudheim.

Party	Trip No.	Main direction of trip	Furthest S or N from AB	Approx. main altitude(s)	Highest altitude
I. Reconnaissance party (4 men)	1.	Southeast towards the mountain area	"AB"	40–1000	1500
	2.	Return to Maudheim	M	1000–40	1500
II. Glaciological party (4 men)	3.	Outward journey and northern trip	M–71°.3 S	40–500	1330
	4.6.	Southern trips	72°.7 S	1700–2000	2420
	5.	Eastern trip	72°.3 S	950–1300	1450
	7.	Return to Maudheim	M	1000–40	1500
III. Geol.-topogr. party (4 men)	8.	Towards AB	AB	40–1000	1500
	9.	South of AB	72°.5 S	1800	2600
	10.	Eastern trip	72°.2–72°.8 S	1000–2000	2500
	11.12.	Southern trips	73°.0 S	1900	2580
	13.	Return to Maudheim	M	1000–40	1500
IV. Geol.-(topogr.) party (2–4 men)	14.	Towards AB	AB	40–1000	1500
	15.	Southern trip	73°.7 S	2000	2600
	16.	Northern trip	71°.6 S	800–1400	1700
	17.	Return to Maudheim	M	1500–40	1700
V. Seismic party (3–4 men)	18.	Towards AB	AB	40–1000	1500
	19.	Southern trip up on polar plateau	74°.3 S	1600–2400	2700
	20.	Return to Maudheim	M	1000–40	1500

Mean wind chill indices for other antarctic stations

The mean wind chill index for the year as well as for the coldest and warmest month are given in Table 5 for 4 interior and 20 coastal stations all around the antarctic continent.

Discussion

Use of mean values for wind chill

In several papers (SIPLE and PASSEL, 1945; FALKOWSKI and HASTINGS 1958; SCHUMAN, 1954) wind chill values have been calculated from mean temperature and mean wind speed instead of from individual term-hourly observations. It has been argued (COURT, 1948; FALKOWSKI and HASTINGS, 1958) that in practice the error would not be significant, because the common assumption that the lowest temperatures in any locality always occur with calm weather or very light winds is not valid for a majority of arctic and subarctic stations, where light to moderate winds (1–8 m/sec) occur even at temperatures near the lowest on record at each station. Wind chill values were computed by COURT (1948) from bi-hourly observations of temperature and wind speed at a northern station in January, and the mean was compared with the value obtained from means of the same weather elements for the tree-week period. He found the latter index value to be only

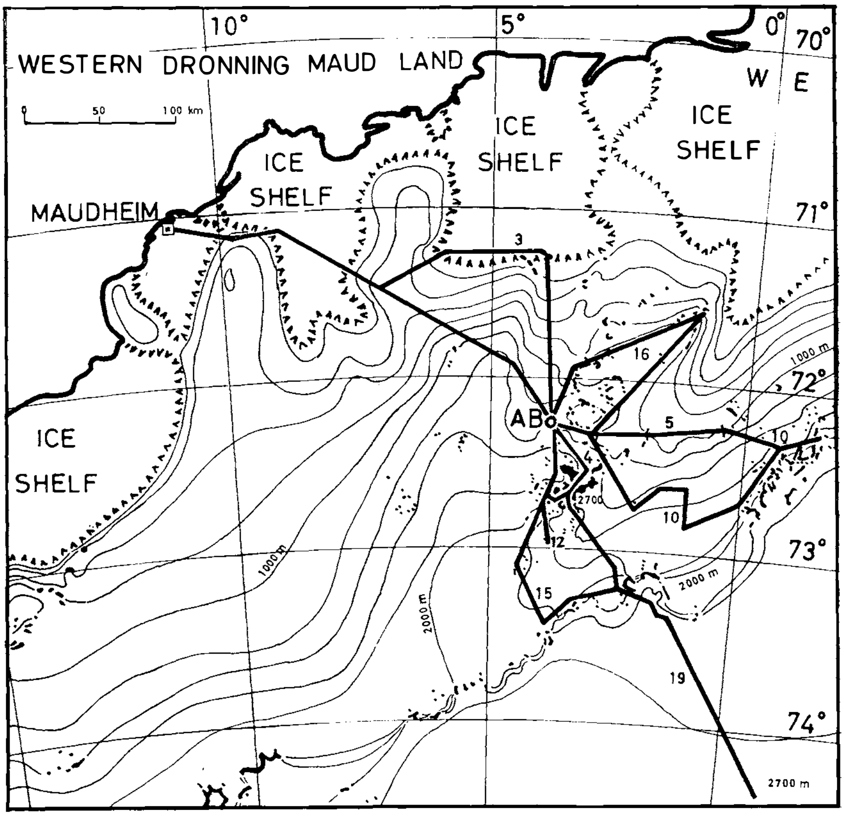

Fig. 5. *Map of Western Dronning Maud Land, showing the main routes of the inland field parties. For details see Table 4.*

1.8 % above the true mean wind chill index obtained from 250 individual determinations. Falkowski and Hastings (1958) made an analysis of 10 years of January data from Fort Churchill, Canada, and found the wind chill index resulting from the use of mean temperature and mean wind speed data for the period to be only 1.9 % greater than the value obtained by averaging 3700 individual bi-hourly wind chill values for the same period.

At Maudheim wind speeds of 2–7 m/sec were usual at temperatures below —40° C, and for long periods of the year the minimum hourly mean wind speed never was less than 1 m/sec, for some periods not below 2–3 m/sec. In spite of this, the wind chill index computed from monthly mean values of temperature and wind for the two coldest months of the year was found to be more than 5 % greater than the mean value from daily simultaneous observations. Similarly 5–6 % too high values were found for all the other months of the year. This might be due to the use of the daily 09.00 observations only, instead of bi-hourly values, but the complete agreement of the monthly means of temperature and wind speed from this term-hour with the monthly means of the total term-hourly observations, contradicts this assumption. It is more likely that the different climatic conditions are responsible. Maudheim is characteristic of a coastal station, while Fort Churchill is situated in the interior of Canada.

Table 5.

Mean wind chill values for some antarctic stations south of 66° S. Wind chill index computed from monthly mean temperature and wind speed. For geographical position of the stations see map (Fig. 1). Latitude is given to the nearest half degree.

No. on map	Station (Nation)	Year	South lat.	Annual mean	Coldest month	Warmest month
	(Coastal stations)					
1	Maudheim (Norw.–Brit.–Swed.)	1950–52	71°	1540	1860	1100
2	Lazarev (U.S.S.R.)	1959	70°	1570	1860	1140
3	Syowa (Japan)	1957–59	69°	1270	1560	980
4	Mawson (Australia)	1954–57	67½°	1430	1780	1030
5	Mirny (U.S.S.R.)	1956–58	66½°	1440	1740	1050
6	Oazis (U.S.S.R.)	1957	66½°	1220	1530	900
7	Pointe Géologie (France) Dumont d'Urville (France)	1952 1959	66½°	1420	1660	1050
	Port Martin (France) Cape Denison (Australia)	1950–52 1912–13	67°	1590	1850	1200
8	Cape Adare (U.K.)	1899–1900	71½°	1120	1420	830
9	McMurdo Sound (U.K.) (3 stations)	1902–03 1908–09 1911–12	77½°	1490	1790	1000
10	Framheim (Norway) Little America III & V (U. S.)	1911–12 1940, 1957	78½°	1610	2030	1110
11	Horseshoe Island (U. K.)	1957–58	68°	1120	1370	910
12	Shackleton (U. K.)	1956	78°	1670	2130	1030
13	Halley Bay (U. K.)	1957–58	75½°	1520	1840	1040
	(Interior stations)					
14	Byrd (U. S.) (altitude 1500 m)	1957–59	80°	1890	2240	1370
15	Amundsen-Scott (U. S.) (2800 m)	1957	90°	2410	2870	1510
16	Vostok II (U.S.S.R.) (3400 m)	1958	78½°	2420	2880	1740
17	Pionerskaya (U.S.S.R.) (2700 m)	1957	69½°	2280	2610	1740

Relative level of mean wind chill at Maudheim

The antarctic climate at Maudheim (71° S) has a relatively large cooling effect on man, as compared to some other coastal stations in the Antarctic (Table 5). *At lower latitudes* two places with greater atmospheric cooling are found. One site is at Cape Denison (67° S) and Port Martin close by. Cape Denison is famed for its windiness, with a yearly mean wind speed of 19 m/sec (7.5 m/sec at Maudheim), and has earned the name of "Home of the Blizzard". It has a yearly mean index of 1610 (as compared to 1540 at Maudheim). This high wind chill is typical only for a limited area (including Port Martin) with local fierce gales. The corresponding index for Pointe Géologie (Dumont d'Urville) in the same region is but 1420. Greater windiness also accounts for the relatively high wind chill at Lazarev (70° S), which is about the same as at Maudheim (71° S).

At higher latitudes stations with lower wind chill are encountered as far south as 77½° S. The yearly mean wind chill index of 3 stations in McMurdo Sound (77½° S) amounted to 1490. Halley Bay (75½° S) had 1520, while Cape Adare (71½° S) at about the same latitude as Maudheim, had only 1120.

The stations *in the interior* of the continent, of course, show considerably higher wind chill values, which partly is due to higher altitude. The South Pole has a yearly mean index of 2410, which, however, is exceeded by Vostok II (78½° S) with an index of 2420. Although positioned much further to the north this station is situated in an intensely cold area near the "Pole of Cold".

It must be noted that all these values are based on monthly mean temperature and monthly mean wind speed at standard anemometer height (8–10 meters). VINJE (1962) has made corresponding calculations for the dry-kata cooling power at these antarctic stations, but as earlier mentioned, this cooling power does not represent the power of the environment to cool the human body (BEDFORD, 1948).

The considerably higher wind chill values found for the intra-continental stations, however, do not represent a correspondingly higher cooling power of the atmosphere. At the altitudes prevalent in the interior, the density of the air is much lower, which means a decrease in the heat-carrying capacity of the air. The term representing convective heat loss must therefore be multiplied by the square root of the ratio of density at altitude to that at sea level (BURTON and EDHOLM, 1955). At the South Pole Station (altitude 2800 meters), as compared to Little America (sea level) where the wind chill formula was developed, this factor would be about 0.83 for the coldest as well as for the warmest month. This means that the cooling effect of the atmosphere at a wind chill index of about 1700 at the South Pole would be equivalent to an index of 1400 at the coast. This agrees with the observation that men at the South Pole are able to tolerate very high wind chill values and work outside even in the wind at temperatures below —60° C (SIPLE, 1958). On one occasion two men at the South Pole Station (SIPLE, 1960) spent 3–4 hours out of doors in a wind chill of 3100–3200 (about —71° C and 6–8 m/sec) by the normal compution method, which would be equal to an index of about 2600 at sea level. A wind chill value of this order has actually occurred at Little America (SIPLE and PASSEL, 1945).

In the *Northern Hemisphere* comparable wind chill conditions are only found in the winter in the coldest regions of the Arctic. The mean wind chill index of the coldest month at Maudheim (about 1875 in July) is generally found only well into the North Polar Basin at considerably higher latitudes, along part of the northern coast of Siberia (70° N), on the inland ice of Greenland, and in Central Arctic Canada north of Fort Churchill (FALKOWSKI and HASTINGS, 1958). This latter area, however, extends as far south as 60° N. The wind chill index of the warmest months at Maudheim (about 1100 in December–January) is comparable to values for the coldest months in Northern Sweden and Norway, Central Iceland and on the coast of South Greenland. It must be remembered, however, that in this comparison the strong solar radiation at Maudheim in the summer has not been taken into account. It contributes greatly to lessening the effect of atmospheric cooling during this season.

Contribution of solar radiation

Due to the exceptional purity of the air and the low water vapour content, the direct solar radiation in the Antarctic even at a sun elevation of 35° reaches values, which are otherwise only observed in the mountains at an altitude of 2000–3000 meters and at a sun elevation of 50° in temperate regions (LILJEQUIST, 1956 a). To this must be added the fact that the sun is in perihelion during the antarctic summer, but in aphelion in the northern summer. Under the same atmospheric conditions and with the same solar altitude one will therefore observe about 6 % higher solar intensity values in summer in the Antarctic than in the corresponding season in the Arctic. For comparison can be mentioned that in the European Alps (HANN and SÜRING, 1939) the intensity of the direct solar radiation at a sun elevation of 50° in the middle of June at Davos (1600 m) is definitely lower, while those from Zugspitze (2962 m) are about the same as at Maudheim at sea level. The highest solar altitude at Maudheim is 42°.4.

It has been estimated (GOLD, 1935, SIPLE and PASSEL 1945), that the effect of bright sunlight is equal to a decrease in wind chill index of about 200, while light cloud conditions are equal to a reduction of about 100. The contribution of solar radiation in Antarctica in terms of heat gain for the human body has been studied by CHRENKO and PUGH (1961) using radiation values from Maudheim. Their results show that the solar heat gain in the Antarctic at the height of summer is from two to four times greater than the heat gain in the desert regions. Because of the high albedo of snow, the heat gain continues to rise with increase in solar altitude. The total solar heat gain in $kcal/m^2/hr$ was found to be 200 at a solar altitude of 10° up to almost 400 at 40°. The contribution of solar radiation to warming the body may be considered as equivalent to elevating the air temperature by an amount designated by BURTON (BURTON and EDHOLM, 1955) the «thermal radiation increment". This increment varies with wind speed and solar altitude, and at a solar altitude of 40° may be 15° C at 2 m/sec and 11° C at 6 m/sec. In exceptionally calm weather in the height of the summer a thermal radiation increment of 25° C may occur. This would be equivalent to raising an ambient temperature of —5° C to +20° C, which makes it possible for men to work stripped to the waist in subzero air temperatures. Even with higher wind speeds the increment varies between 5° C and 10° C, and also considering the more severe inland conditions it is often about 10° C.

During sledging inland in Dronning Maud Land at the height of summer the thermal radiation increment was of such magnitude that travelling was mostly done at night to spare the dogs from the heat load. The rate of heat absorbtion by the dark cloth of the double-walled pyramidal tent due to solar radiation was at times so high that when sleeping during the daytime one could lie practically naked on top of the sleeping-bag with the tent-entrance wide open in air temperatures well below freezing. Investigations in the Antarctic by PUGH and CHRENKO (1962) have shown that the effect of intense solar radiation on man inside a tent of this type may be equivalent to raising the external temperature by about 19° C. In overcast weather the solar heat gain from reflected radiation is also remarkable, as previously mentioned. The wind chill is thus considerably modified by radiation in the summer season.

Wind chill conditions during sledging

Wind chill conditions on sledging journeys have been briefly discussed by SIPLE and PASSEL (1945) in connection with relative comfort estimations. In Fig. 6 the weekly mean wind chill index is plotted for the major field parties in Dronning Maud Land. As seen in Table 4 the altitude varied considerably during sledging, ranging from 40 meters (ice shelf) to 2700 meters (polar plateau). This implies that the wind chill values in the field should be corrected for altitude. However, this correction has in fact already been applied by using estimated wind speeds. The speed of the wind, when estimated, is obtained from the dynamic pressure exerted by the wind (e. g. the Beaufort scale), which is proportional to the density of the air and the wind speed. Therefore the estimated wind speed values in the field have been judged according to the density of the air prevalent at the local altitude in agreement with the decreased cooling power of the air, making a correction unnecessary. Some of the changes in wind chill for the field parties are worth discussing.

Party I made the first major sledging trip into the interior and started early in the season (October). The wind chill (a) encountered on the trip was markedly higher than at Maudheim, mainly due to greater wind speeds (mean 9 m/sec). Even higher wind chill values (d) were encountered by Party IV in the same month (October) next season with similar wind speeds. Characteristic of the early approach to the interior is travelling against downhill air currents at relatively low temperatures. A later approach will meet much more favourable conditions as shown by the index values of Party II and III. Their diverging wind chill curves for the outward journey to Advanced Base (AB) also illustrate the effect of different routes (Fig. 5). Party III took the straight course southeastward to AB, quickly reaching a higher altitude and latitude. Party II departed from the main track at a low elevation and descended again to an ice shelf, travelling eastward to a point about 100 kilometers due north of AB before turning south and ascending to AB (trip 3, Fig. 5). At this point the two wind chill curves meet again, the index being relatively high for the season, because both parties travelled mainly by night. Otherwise the wind chill indices during the main part of the summer (mid-November to mid-February) were moderate and should be even further greatly reduced because of the high intensity of solar radiation during this period.

Only Party V experienced wind chill values well above 1400 at the height of the summer. This was because they travelled furthest to the south and ascended the polar plateau (trip 19, Fig. 5). The party spent one week (e) at 74°.3 S at an altitude of 2700 meters with a mean wind chill index of 1650.

A member of this party has described the weather conditions as follows (GIAEVER, 1954): "During these six days on the ice plateau the weather showed an uncanny regularity. Each day the temperature at noon had been close to —17° C and each night a minimum thermometer laid on the snow registered —32° C. In the mornings a fresh easterly breeze would chill the camp, but things would begin to feel warmer as the wind gradually dropped and as the sun, which shone each day, climbed in the sky."

As the summer came to an end, considerably more rigid weather conditions ensued with low temperatures and frequent gales, and the wind chill increased to

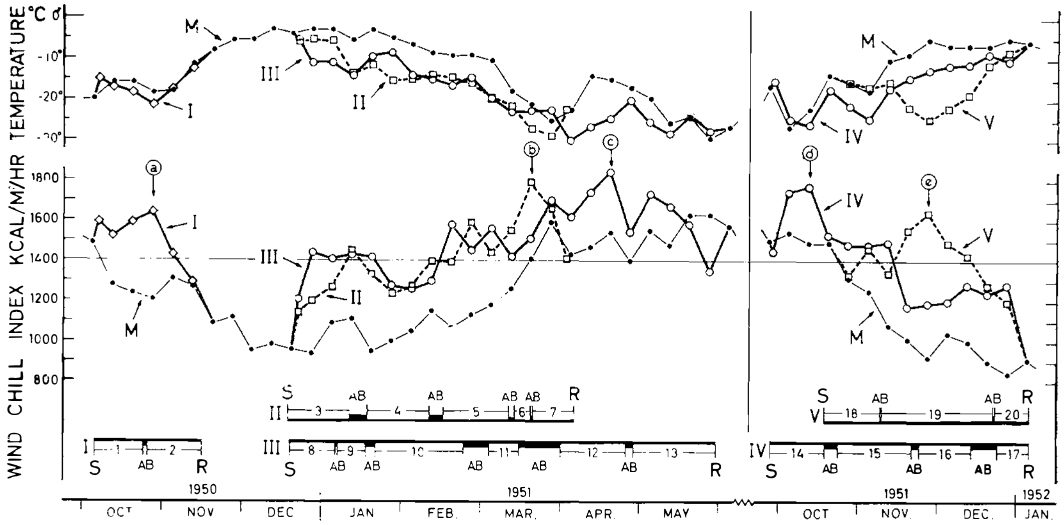

Fig. 6. *Wind chill conditions during the two summer field seasons. Weekly mean values of temperature (top) and wind chill index (center) at Maudheim (M) and for the major field parties (I – V). The duration and extent of the various trips (bottom) are explained more in detail by Table 4. AB = time spent at Advanced Base. S = start from Maudheim. R = return. a – e are discussed in the text.*

high values. Party III stayed the longest in the field and experienced the highest values (c). A vivid description of the weather conditions during this wind chill peak, written by one of the members of this party, can be read in the official account of the expedition (GIAEVER, 1954). On one occasion (GIAEVER, 1952) the wind chill index was estimated roughly at 2450, which was probably as high as it ever got during actual exposure.

The present author was a member of Party II, which returned earlier but nevertheless met with severe wind chill conditions (b). The effect of such conditions on sledging and living in a tent is best illustrated by a first hand account, written while actually being experienced. The following is an excerpt from the author's sledging notes for this period. "At noon to-day the warmest temperature measured was —33° C. We really feel that it is late in the season, the days are growing shorter, the sun is low and gives no warmth, katabatic air currents blow continuously from the south with gales and drifting snow. When we made camp this evening it was —37° C. The inner walls of the tent are like glazed parchment with several millimeters thick ice-armour, at places even 1 centimeter thick. Every night several centimeters of hoarfrost accumulate on the walls, and each time you inadvertently touch the tent cloth a shower of ice chrystals fall down in your face and melt. The sleepingbags are wet and never get time to dry before they freeze. In the night large patches of hoarfrost from my breath spread around the opening of my sleepingbag and melt in the morning.

The whole front of my sleepingbag is like a well starched dress-shirt, and last night when I had to pass urine (cold diuresis) the zipper was frozen fast and I spent some time in thawing it loose. The shoulder part of the sleeping bag facing the tent-side is permeated with hoarfrost and ice and crackles when I roll up the bag. The reindeer fur mattress is soaked through and stands out in a half-circle after freezing in a rolled up state. The ski-boots never dry and freeze as soon as you go out in the morning. When camp is broken and you try to put on your skies, you find the soles frozen in the wrong angle on your feet. The stiff leather chafes our feet and Valter has acquired tendovaginites. When the boots are taken off, the insides are quite covered with white frost several millimeters thick and our woolen socks are usually frozen fast and have to be torn loose, the rime is scraped out with a spoon. – For several weeks now my fingers have been permanently tender with numb finger-tips and blistering at the nails after repeated frostbites. Valter has his nose and right cheek frostbitten. – All food is frozen to ice, ham, butter, tins, etc., and it takes ages to thaw out everything before being able to eat. At the depot we could not cut the ham, but had to chop it in pieces with a spade and threw ourselves hungrily at the chunks and chewed with the ice crackling between our teeth. You have to be careful with what you put in your mouth. The other day I put a piece of chocolate from an outer pocket directly in my mouth and promptly got a frostbite with blistering of the palate."

Frostbites

Selection of cases

Freezing of the skin can be taken as an indicator of the degree of cooling. While it is true that injurious effects of frostbite are less common than expected in very cold regions (because of the experience of the residents) it is certainly not true that freezing of the skin is uncommon, on the contrary it is continuously experienced. Of the many occasions of frostbite experienced by the seventeen members of the NBSX, a fair number have been recorded accurately enough to allow calculation of the wind chill index at the time of occurrence. Only incidents of frostbite affecting exposed (or insufficiently protected) skin have been considered in this connexion, such as face, ears, neck, wrists and hands. Thus the 3–4 cases involving freezing of toes and penis have been excluded, as well as cold injury caused by touching cold objects, such as ice, metal instruments, tools, motor parts, etc. As a frostbite has been considered *every case of freezing of the skin* – even without resultant injury. Accordingly included are also temporarily frozen spots, characterized by a white, circumscribed area, hard to the touch and usually preceded by a sting, which left no lasting injury when thawed out within a few minutes (except for peeling skin). This definition has been adopted (cf. SCHUMAN, 1954) for the present study, because mostly it is only a question of duration until such a superficial frostbite will cause a more extensive injury, the longer time the more severe the effect. Therefore no attempt has been made here to classify the cases of frostbite according to the degree of injury, nor have frostbites occurring simultaneously at several sites or repeatedly during a prolonged period of the day in the same person been regarded as more than one case. But if two persons were affected at the same time, it has been recorded as two separate incidents.

Usually no injury resulted from these frequently occurring superficial frostbites, but now and then, when the freezing went unnoticed or when adverse circumstances did not permit immediate thawing-out, more persisting injuries ensued with blistering and loss of skin. About 20 cases of second degree cold injuries of face, ears, and fingers were observed, but it is certain that there were incidents of blistering finger-tips which never were reported to the author. With the exception of a frozen toe, which had been frostbitten during a previous stay in Antarctica, there were no third degree injuries.

Wind chill and frostbite

Sixty-nine cases of frostbite recorded on the NBSX, ranging from the blanching of temporarily frozen skin to second degree injuries, have been plotted in relation to temperature and wind speed in Fig. 7. The curved parameter lines in the figure correspond to wind chill indices of 1400, 1800 and 2000, computed from the wind chill formula.

It must be pointed out that the temperature and wind observations for these cases have not been made *simultaneously* with the occurrence of frostbite. For 37 of the cases accurate temperature and wind speed data are available for the time at which they occurred. In 15 other cases shifting weather conditions have made necessary the use of means of the extremes in temperature or wind at the time of occurrence. The remaining 17 cases were recorded in the field and for these accurate temperatures are available, but the wind speed was estimated. The error in the estimation of wind speed will be larger at higher wind speeds, but the differences between the wind chill values also diminish with increasing wind speed. The error in the estimation of wind speed was probably not much more than about ± 10 %, but to be on the safe side it will be regarded as ± 20 %. The error of the calculated wind chill values would in this case amount to ± 5.8 % at 4 m/sec to ± 1.6 % at 20 m/sec at any temperature. An error of 1° C in temperature would mean an error of 1.5 – 2.5 % in wind chill, depending on the wind speed. The presence of drifting snow probably contributed to the risk of freezing. Experiments by MASSEY (1959) in the Antarctic have shown that the added cooling factor of drift snow often results in frostbite.

From Fig. 7 it is evident that no frostbites occurred at temperatures above —8° C, and Table 3 shows that no wind chill values over 1400 were observed above this temperature. All cases of frostbite have occurred at wind chill values between 1400 and 2100, with the exception of one borderline case at 1380. This case occurred during sledging against the wind (described as "bitterly cold"). The results are strongly in evidence of SIPLE's assumption (Table 1) that exposed flesh begins to freeze at an index of 1400. Accepting this value, one will find from Table 3 and Fig. 3 that apparently there was no risk of frostbite at temperatures above —8° C at Maudheim, while below —30° C the hazard was permanently present. In the intermediate zone the chance of acquiring a frostbite depended entirely upon the wind speed conditions.

Rate of occurrence

In the beginning of the sojourn at Maudheim, careful note was made of all occasions of freezing of the skin. But as one became used to the conditions, less notice was paid to the continuous occurrence of frost marks. When a slight stinging sensation gave warning of a freezing spot, or when admonished by a companion, one regularly thawed out the frostbite by the application of the warm, naked hand, or went indoors. One's face, ears, and finger-tips were constantly peeling from these small, iterated frostbites, especially during the winter season. MASSEY (1959) found that after 6 weeks in the Antarctic there was an increased resistance to numbing of fingers exposed to wind and low temperature. He also found indications of greater immunity to frostbite under experimental conditions in men staying a second consecutive year. Although nearly three times as many frostbites were recorded during the first year of the NBSX, this cannot be taken as definite evidence of a successive decrease in the occurrence, but rather a tendency to report only the more marked cases. At the same time as one learned by experience to protect oneself better, more exposure was also tolerated. There was an inclination

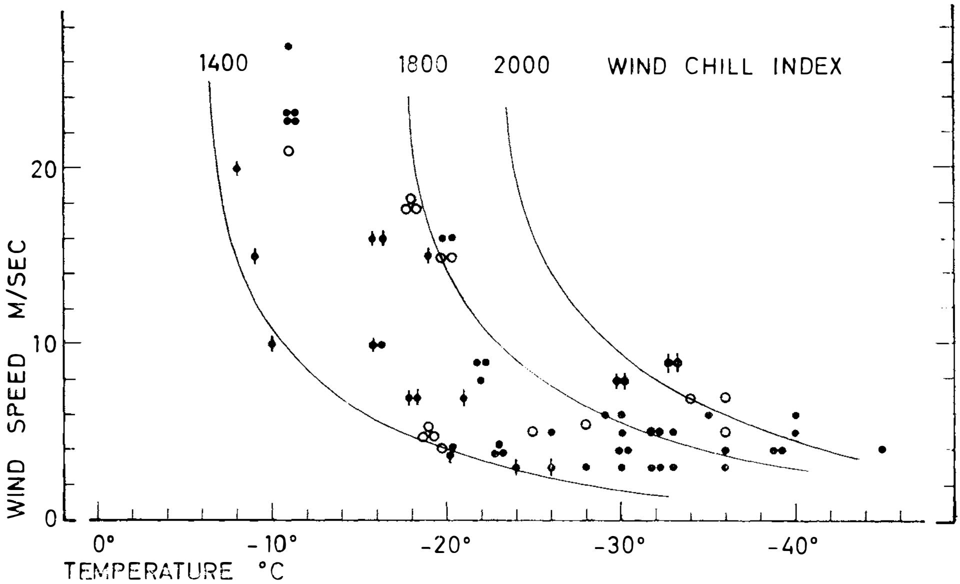

Fig. 7. *Recorded cases of frostbite in relation to temperature and wind speed. Open circles mark cases of frostbite that have occurred during shifting meteorological conditions (the mean of the extremes in temperature and wind is plotted). Dots with a vertical bar indicate cases of frostbite observed during sledging (wind speed estimated). Black dots are frostbites with established data for temperature and wind speed. The curved parameter lines correspond to a wind chill index of 1400, 1800, and 2000 respectively.*

for the men to wear less clothes during the course of the NBSX, as they became more used to the cold, and this was noticed especially during sledging trips, when the cold was more continuous. A study by GOLDSMITH (1960) gives evidence that there is a voluntary reduction in the amount of clothing worn as men become more acclimatized to the antarctic climate.

During more than half of the time at Maudheim it was possible for frostbite to occur, as a wind chill index greater than 1400 was experienced on 55 % of the days. The distribution of the risk over the year can be estimated from Fig. 4. In March a wind chill of 1400 or more will be encountered only during 30 % of the time, and during less than 10 % of the time in November to February. This agrees well with the recorded occurrence of frostbites. Only 7 cases were recorded in November to February (5 of these were observed by the author on himself). It must be pointed out that these seven cases all occurred during sledging inland where higher wind chill values were experienced than at Maudheim. Furthermore, all of these frostbites occurred while travelling at night hours and were mainly situated on the shaded portion of the face. Snow drift was usually present. Quite a number of frostbites were seen in March (although only 2 cases were actually recorded), but only during sledging and at wind chill values well above 1400 (Fig. 6). By far the major part of frostbites were observed during the months of April to October. There are two definite peaks during the year, in April – May and in August – October, most cases being encountered in April and

October. This is not surprising, considering the fact that these were periods with daylight encouraging almost as much outdoor activity as in the summer. Sledging in April and October contributed to the greater frequency. During the completely dark months (June – July) outdoor activity was low and only few frostbites were recorded.

Below -20° C no frostbites were observed at wind speeds higher than 10 m/sec (Fig. 7). This is probably explained by the fact that at these low temperatures wind speeds higher than 10 m/sec became increasingly uncomfortable, and at -30° C and more than 10 m/sec it was almost unbearable to travel against the wind. During such conditions the face or skin was shielded as extensively as possible from direct wind, but during sledging this was extremely difficult to accomplish.

An example of such exposure conditions with repeated occurrence of frostbite, is given by the following passage from the author's diary describing travelling on his first sledging trip. "Date 16/9 1950, minimum temperature —38° C, maximum —32° C, wind speed 9 m/sec (wind chill index 2200–2000). – Peter and I started homeward at noon in radiant sunshine but with a bitterly cold wind. The first hour was a nightmare, trying to hold the dogs on the trail, to protect one's face from the wind, to keep the sunglasses free from snow and hoarfrost, to thaw out cheeks and nose, where white frostbite spots re-appeared with few minutes interval, sometimes in one place, sometimes in another, to get your mittens back on your ice-cold, stiff fingers between each thawing-out, the whole time keeping pace with the sledge on your skies. Your one hand had to juggle with the tow-rope to the sledge, with the ski-pole, with your mittens, trying not to drop them and to keep them from blowing away, while thawing out a frostbite with your bare other hand, the sunglasses milky and frosted again, your fingers stiffening and aching. Always twisting your head and your parka hood in a vain attempt to shield the face from the tormenting wind and at the same time peer forwards along the trail against the wind – well, then you damm the whole Antarctic!"

Summary

1. A study is made of the antarctic climate at Maudheim in terms of atmospheric cooling, using temperature, wind speed, radiation, and wind chill index according to SIPLE. Incidents of frostbite are correlated to these factors.

2. An introductory general description of the antarctic climate is given, and the principles of heat exchange and the application of wind chill are outlined.

3. Weekly mean values for temperature, wind speed, duration of sunshine, and wind chill are presented graphically (Fig. 2), giving a synopsis of the climate at Maudheim. The data are characteristic of an antarctic coastal station with a comparatively low mean temperature of the year and great windiness. The intensity of the direct solar radiation is very high.

4. Differences in the mode of calculating mean wind chill index are discussed.

5. The mean wind chill index at Maudheim and at various other stations all over the antarctic continent are compared. The index at Maudheim is relatively high, considering the latitude. On more than half of the days at the base a wind chill index over 1400 was encountered.

6. The variation in wind chill shows no linear correlation to temperature, although the seasonal change approximately follows the temperature curve (Fig. 2). Wind chill frequencies at different intervals of temperature have been calculated (Fig. 3), as well as cumulative frequencies for each month (Fig. 4).

7. Weekly mean changes in temperature and wind chill are shown for five field

parties travelling inland (Fig. 6), with a description of travel routes. The higher wind chill indices encountered in the field are compared to those at Maudheim, and the deviations are discussed.

8. Factors influencing wind chill, as solar radiation and snow drift, are considered.

9. The 69 incidents of freezing of exposed skin at Maudheim, for which meteorological data are available, are studied in relation to temperature, wind speed, and wind chill index. It is found that all the cases (Fig. 7) have occurred at wind chill values between 1400 and 2100 (at temperatures ranging from —8° C to —46° C), which confirms the assumption of SIPLE that exposed flesh begins to freeze at a wind chill index of 1400.

10. The rate of occurrence of frostbite in different seasons and at different temperatures is also discussed.

Acknowledgements

To my comrades, ALAN REECE (who so unfortunately lost his life in the Arctic, after two sojourns in the Antarctic), FRED ROOTS, and CHARLES SWITHINBANK, I wish to express my great appreciation of their perseverance in carrying out the meteorological observations in the field during sledging under adverse circumstances. I gratefully acknowledge the invaluable criticism and kind help of Professor HANS RONGE, Head of the Department of Hygiene, University of Lund. I also wish to thank Professor GÖSTA LILJEQUIST, meteorologist of our expedition, and Docent VALTER SCHYTT, my sledging companion during two field seasons, for critically reading the manuscript and offering their advice. My work has been carried out with the aid of a grant from Norsk Polarinstitutt, for which I express my sincere gratitude.

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