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SKIN TEMPERATURE, THERMAL COMFORT, SWEATING, CLOTHING AND ACTIVITY OF MEN SLEDGING IN ANTARCTICA

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SUMMARY

1. Three men were studied while dog-sledging 320 km in 12 days in Antarctica. Conventional Antarctic clothing ('sweaters and windproofs') was worn. Four hundred observations were made of medial thigh skin temperature, thermal comfort, sweating, clothing, activity and environmental conditions.

2. Work occupied an average of 11·0 hr/day and sleep 7·5 hr. Estimated daily energy expenditure averaged 5100 kcal (range 2740–6660 kcal).

3. Skin temperature fell on exposure to cold despite the clothing worn, but was not changed by the level of activity. Sweating, and thermal comfort, were directly related to both skin temperature and activity.

4. Inside the tent, the modal value of skin temperature was 33° C (range 27–36° C) and the men were comfortable in 94 % of observations.

5. During the 9·2 hr/day spent outdoors the modal value of skin temperature was 27° C (range 18–33° C) and the men felt too cold (but did not shiver) in 11 % (range 7–20 %) of observations, suggesting that cold stress was not negligible. However, they also felt too hot in 20 % of observations and were sweating in 23 %.

INTRODUCTION

It has been suggested (Amundsen, 1912; Rodahl, 1960) that men in polar regions are unlikely to acclimatize to cold because their clothing keeps them warm. This view has received support from observations in the Arctic on Lapps and Eskimos wearing fur clothing. Sub-clothing skin temperature of Lapps resting for 3 hr at −10° C air temperature remained between 31 and 34° C and the subjects felt warm (Scholander, Andersen, Krog, Lorentzen & Steen, 1957), and skin and rectal temperatures of

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Eskimos doing light work for 5 hr in a 12 m.p.h. wind at -24° C air temperature remained at the levels previously measured indoors (Milan, 1964).

Fur clothing, however, is expensive and scarce and is rarely worn by the members of modern Antarctic expeditions, who instead wear several layers of insulating clothing and an outer windproof garment. Whether this clothing provides its wearers with the 'almost tropical' microclimate (Scholander *et al.* 1957) enjoyed by the Lapps and Eskimos appeared to be a matter for further investigation. Observations were therefore made on three members of the 1959 party of the Australian National Antarctic Research Expeditions to Mawson (lat. 67° 36′ S, long. 62° 53′ E), throughout a 12 day journey by dog sledge. The main aim of the study was to assess the thermal stress of Antarctic sledging. Additional aims were to study the inter-relations of thermal comfort, sweating, skin temperature and activity, and to make an estimate of energy expenditure.

METHODS

The 320 km journey was made over sea ice in the spring (October). Nine days were spent travelling, 1 studying Emperor penguins (*Aptenodytes forsteri*), and 2 lying up in the tent during a blizzard. The average daily run was 35·5 km (range 16–51 km). Air temperature outdoors averaged -12° C (range -17 to -6° C) and windspeed 6 m/sec (range 0–36 m/sec); the weather was overcast on 7 of the 12 days. Air temperature inside the tent at the time of 'indoor' observations averaged $+12^\circ$ C (range -5 to $+28^\circ$ C).

Subjects and procedure. The subjects (B, K and M) were men of European descent aged 27–34 yr. Their average weight was 80 kg (range 74–87 kg) and their average height 182 cm (range 178–185 cm). Subject M was also a subject in a concurrent study that showed he had acclimatized to cold (Budd, 1962, 1964). Observations were made every waking hour (as nearly as possible), for 12 days on subjects K and M and for 7 days on subject B, whose thermistor then became unserviceable. The variables recorded at each observation were skin temperature, thermal comfort, sweating, clothing, activity, and environmental conditions; all observations were made by the author (subject B).

Of the 410 observations made, sixteen were discarded because of poor thermistor contact. Six of the remaining 394 observations lacked a record of air temperature (inside the tent) and one lacked a record of the clothing worn; these observations were therefore omitted from the analyses that involved air temperature or clothing. Observations whilst travelling were made as soon as the sledges halted for the hourly rest-period of 5–10 min. Skin temperatures observed inside the tent ('indoors') within 20 min of the subject's return from an excursion outdoors were found to be influenced by the cold weather, and were therefore classified separately, as 'transit' values.

Clothing and shelter. Clothing was of the kind used on most British and Australian Antarctic expeditions since 1900, in which insulation is provided by several layers of woollen garments and a windproof outer garment, rather than by furs or pile fabrics. On the trunk, it consisted of a vest of cotton or loosely knitted string (the 'Brynje vest'), a woollen shirt, one or two woollen sweaters, and a windproof parka of double-thickness 'Ventile' material. Loose pyjama trousers, gaberdine trousers, and 'Ventile' windproof trousers were worn on the lower limbs. Mukluks or vapour-barrier boots, and woollen socks, were worn on the feet, woollen and windproof mittens on the hands, and woollen balaclavas or gaberdine caps (and sometimes the parka hood) on the head. On rare occasions a jacket of quilted down was also worn.

Overheating and chilling were controlled as far as possible by removing or putting on headgear, mittens, and sweaters, and by varying the ventilation of the clothing worn on the trunk, by means of drawstrings at the hem and throat of the windproof parka.

At each observation a complete inventory was made of the clothing worn. In accordance with the procedure used by Goldsmith (1960), Palmai (1962), and Lugg (1965), the number of layers of clothing worn on the trunk were later added together to give a convenient, if crude, index of the insulation provided. A shortcoming of this method of analysis is that it makes no allowance for the quite large variations in effective insulation produced by changes in ventilation, and by changes in mittens and headgear. Windproof clothing was counted as one layer, since it was worn nearly all the time and, being of a double thickness of material, provided insulation as well as windproofness. Down jackets were counted as two layers.

This clothing was adequate to maintain thermal comfort outdoors only during activity: to be comfortable whilst inactive the subjects had to be inside their tent, and also in their sleeping bags unless the primus stove was burning. The tent was a standard 'polar pyramid' type of 'Ventile' cloth, with a funnel entrance, and an inner lining of light nylon separated from the outer tent by an air space of several inches. Sleeping bags were of quilted down, resting on an air mattress and an insulating pad of 'onazote' material.

Skin temperature. This was measured by a single disk thermistor attached by a strip of adhesive tape 1 cm wide to the right medial thigh, 15 cm proximal to the adductor tubercle. Previous observers of the skin temperature of men outdoors in Antarctica have used either a wire-vest resistance thermometer (Wolff, 1958; Hampton, in Edholm & Lewis, 1964; Norman, 1965) or thermistors taped to the skin at ten sites (Milan, 1964). The former measures the temperature of the space between clothing and skin rather than the skin temperature itself, and the latter, although providing a reliable estimate of mean skin temperature, would be impractical for prolonged use in strenuous activities such as sledging. Teichner (1958) has shown that, under conditions similar to those of this study, the skin temperature of the medial thigh closely estimates mean skin temperature as determined by the weighted mean of 10 points; and Ramanathan (1964) has confirmed this finding for skin temperatures above 32·5° C. The medial-thigh site also had the important practical advantages that the thermistor was comfortable, did not cause skin irritation when worn continuously for 12 days, and stayed in place more readily than at any other site tested.

The leads from the thermistor ran to a plug which was carried in the subject's pocket when not in use. During observations it was connected to a null-reading Wheatstone bridge, which could measure a temperature change of 0·1° C, was unaffected by the range of air temperatures encountered, and was robust enough to withstand the shocks of sledge travel. The thermistors were inspected daily, or more often, to ensure that they were in good contact with the skin, and the adhesive tape renewed as necessary. They were calibrated against a standard thermometer in a well-stirred water-bath before and after the journey; no change in calibration could be detected.

Thermal comfort. At the same time as skin temperature was measured, thermal comfort of the trunk was reported in terms of a seven-point scale. There were three major grades: 'too cold', 'comfortable', and 'too hot'. These were further subdivided: 'comfortable' into 'comfortably cool', 'neutral', and 'comfortably warm', and the extremes into 'just too hot (or cold)' and 'much too hot (or cold)'. The subjects had been using the scale for 10 months in the course of another study, and so were well practised at describing their sensations in this way. Sweating (strictly, the presence of unevaporated sweat on the skin) or shivering, within the preceding 10 min, were also reported. Thermal sweating was readily perceived by the subjects and was usually on the trunk or lower limbs; emotional sweating was not observed.

Activity. Activity during the preceding hour (and also the preceding 10 min, if this differed) was briefly described, and later allotted to one of five grades (sleeping, sitting, light work, moderate work, heavy work), according to a subjective assessment of the effort involved. For example, lashing the sledge load and counting Emperor penguins were assessed as light work, feeding the dogs and butchering a seal as moderate work, and pushing the sledge, running beside the dogs, shovelling snow and cranking the radio generator as heavy work. 'Sitting' included lying awake in sleeping bags—generally reading or writing. From these hourly observations, supplemented by diary entries, the time spent in each grade of activity was estimated.

Basal metabolic rates were taken from the tables of Robertson & Reid (1952) and used as the energy cost of sleeping (1·2 kcal/min). The estimates of Masterton, Lewis & Widdowson (1957) were used for the energy cost of sitting, light work, and moderate work (1·9, 3·2 and 5·6 kcal/min, respectively), but the estimate of the energy cost of heavy work by these authors (12·5 kcal/min) seemed rather high for the activities allotted to this grade in the present study, and a value of 10·0 kcal/min, taken from the tables of Passmore & Durnin (1955), was used instead. The records of activity during the 10 min before each observation were used in the analysis of the results for skin temperature and thermal comfort.

Environmental conditions. Air temperature in the tent was measured by a thermometer suspended at the level of the upper part of the subjects' bodies. As a reasonable approximation, values recorded by the weather observers at Mawson were used for outdoor temperatures, since temperatures along the nearby coast are generally within a few degrees of those at Mawson. No portable anemometer was available and windspeed had to be estimated, but after 9 months at Mawson the observer was well practised in such estimations. From the results for outdoor temperature and windspeed the wind chill (Siple & Passel, 1945) was calculated, to the nearest 50 units. The presence or absence of sunshine, and of drifting or falling snow, were also recorded.

RESULTS

General description

The distribution of the observations according to location and activity (in the preceding 10 min) is shown in Table 1. More than 90 % of the 'working' observations were made outdoors, and all of the 'sleeping' and 'sitting' ones were made indoors. 'Sleeping' observations were made immediately after waking the subject, while he was still in his sleeping bag; 10 % of the 'sitting' observations were also made in sleeping bags. The indoor observations were thus characterized by lower levels of activity, a warmer environment, and in many instances warmer clothing (sleeping bags), than the outdoor ones.

Thermal comfort, sweating, and shivering. Table 2 shows that inside the tent the subjects were comfortable in 94 % of the observations. Outdoors they dressed for comfort, but failed to achieve it in one-third of the observations. Surprisingly, they were too hot twice as often as they were too cold, and were sweating in one-quarter of all observations. Shivering was rarely seen. There were marked differences between subjects. Subject *M* was too hot in 41 % of observations and was sweating in 47 %, whereas subject *K* was too hot in only 7 % and was sweating in 6 %—possibly because he was working hard less often, owing to a knee injury (see 'Effects of activity', below). Subject *B* underdressed to the extent of being too cold in 20 % of the observations, and adjusted his clothing frequently in order to avoid sweating, yet was still too hot in 11 % of the observations and was sweating in 15 %.

Skin temperature. Figure 1 shows that there were two distinct distributions of skin temperature, according to whether the subjects were inside the tent or outdoors. Indoors, skin temperature ranged from 27 to 36° C, 95 % of the values lay between 30 and 35° C, and the mode was 33° C. Outdoors, by contrast, skin temperature ranged from 18 to 33° C and the mode was 27° C. The values below 24° C were observed during the coldest weather, which occurred after subject *B*'s thermistor had become unserviceable.

TABLE 1. The number of observations at each level of activity and in each location. Transit observations were those made indoors within 20 min of the subject's return from outdoors

Activity		Location			
Grade	Description	Indoor	Outdoor	Transit	Total
1	Sleeping	24	0	0	24
2	Sitting	89	0	5	94
3	Light work	10	64	7	81
4	Moderate work	7	102	1	110
5	Heavy work	1	84	0	85
	Total	131	250	13	394

TABLE 2. Frequency of each thermal sensation, and of sweating and shivering. The values are percentages of the number of observations for each subject, which is shown in brackets at the head of each column

A. Indoors

Thermal category	Subjects			Total
	B (22)	*K* (55)	*M* (54)	(131)
Too hot	18	2	0	4
Comfortable	68	98	100	94
Too cold	14	0	0	2
Sweating	23	0	4	5
Shivering	0	0	0	0

B. Outdoors

Thermal category	Subjects			Total
	B (65)	*R* (95)	*M* (90)	(250)
Too hot	11	7	41	20
Comfortable	69	85	51	69
Too cold	20	7	8	11
Sweating	15	6	47	23
Shivering	0	0	1	0

Effects of activity

Thermal comfort and sweating. Table 3 shows that the subjects felt warmer, and sweated more often, when they worked harder. They were rarely too hot during light work, and rarely too cold during heavy work. Most sweating occurred when the subjects were feeling too hot, but sweating was sometimes reported by subjects who felt comfortable, and once by a subject who was too cool. The latter, and probably some of the observations of 'comfortable' sweating as well (in two of which the subject felt 'comfortably cool'), might have been due to the subject cooling down slightly before the observation was made.

Skin temperature. Table 4 shows that the differences in skin temperature between sweating and non-sweating subjects were negligible. The apparent decrease in skin temperature with increasing activity is explicable in

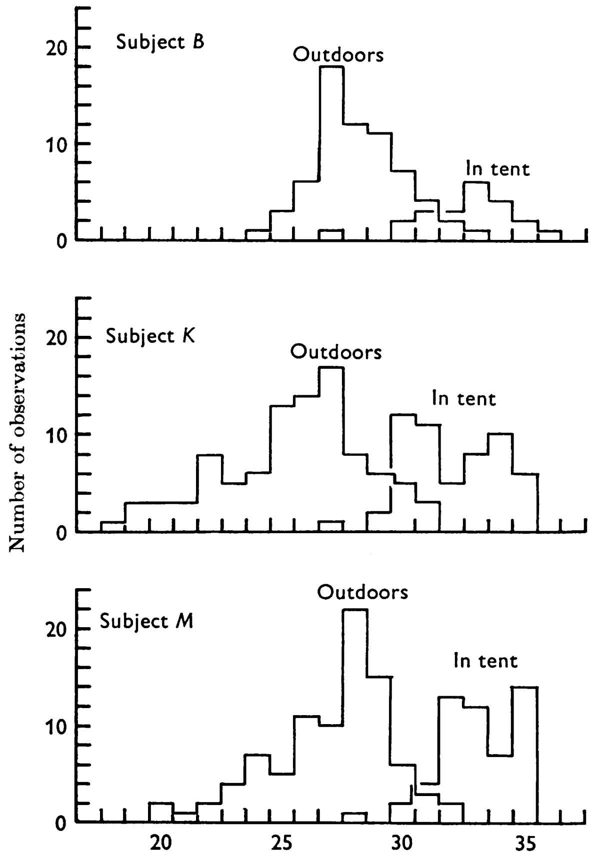

Fig. 1. The frequency of observation of each skin temperature.

terms of environment and clothing, for grade 1 took place in sleeping bags, grades 1 and 2 inside the comparatively warm tent, and grades 3, 4 and 5 mostly outdoors. Environment and clothing (that is, the number of layers worn on the trunk) were similar in the three work grades, and skin temperature was the same in light and heavy work, suggesting that activity had no effect on skin temperature. Graphical analysis within each combination of subject, environment and clothing confirmed this impression.

TABLE 3. The incidence of sweating, expressed as a fraction of the total number of observations within each combination of activity and thermal comfort

	Thermal comfort			
Activity	Too cold	Comfortable	Too hot	All grades
Sleeping	0/0	2/24	0/0	2/24
Sitting	0/2	4/86	2/6	6/94
Light work	0/16	2/64	0/1	2/81
Moderate work	0/10	5/76	23/24	28/110
Heavy work	1/3	7/55	20/27	28/85
All activities	1/31	20/305	45/58	66/394

TABLE 4. Effects of activity and sweating on skin temperature. Values shown are the mean of all observations in each category; the figures in brackets indicate the number of observations

Activity		Skin temperature (° C)		
Grade	Description	Non-sweating	Sweating	Mean
1	Sleeping	35·1 (22)	34·3 (2)	35·0 (24)
2	Sitting	32·5 (88)	32·5 (6)	32·5 (94)
3	Light work	28·0 (79)	30·8 (2)	28·1 (81)
4	Moderate work	26·6 (82)	26·6 (28)	26·6 (110)
5	Heavy work	28·1 (57)	28·5 (28)	28·3 (85)
Mean (grades 1 and 2)		33·0 (110)	32·9 (8)	33·0 (118)
Mean (grades 3, 4 and 5)		27·5 (218)	27·7 (58)	27·6 (276)

Effects of thermal environment and clothing

Indoors. Figure 2 shows that neither skin temperature nor thermal comfort was much affected by variations in indoor air temperature between -5 and $+28°$ C. Above $+6°$ C there was little relation between air temperature and the amount of clothing worn, but in 87 % of the observations below $+6°$ C the men were in sleeping bags and skin temperatures were between 34 and 36° C, except on four occasions. On two of these the men had been in their sleeping bags only 5 min; on the other two it was the last morning of the journey and the bags were damp from 11 days' accumulation of condensation.

Outdoors. Figures 3 and 4 show that in the colder weather (colder because of either increased wind chill or lack of sunshine) more clothing was worn yet skin temperatures were lower; the subjects were also less comfortable, owing to more frequent discomfort from cold with little compensating reduction in the discomfort from heat and sweating.

These findings would seem to show that the insulation provided by the additional clothing was insufficient to prevent a fall of skin temperature. It would be expected, however, that within the range of skin temperatures observed at any particular level of wind chill and sunshine, the warmer values would be associated with the greater amounts of clothing. In fact the reverse was true: even at constant wind chill and sunshine, skin temperatures were lowest when the most clothing was worn. Detailed graphical analysis showed that this paradoxical relation was true of individual subjects, at each level of activity.

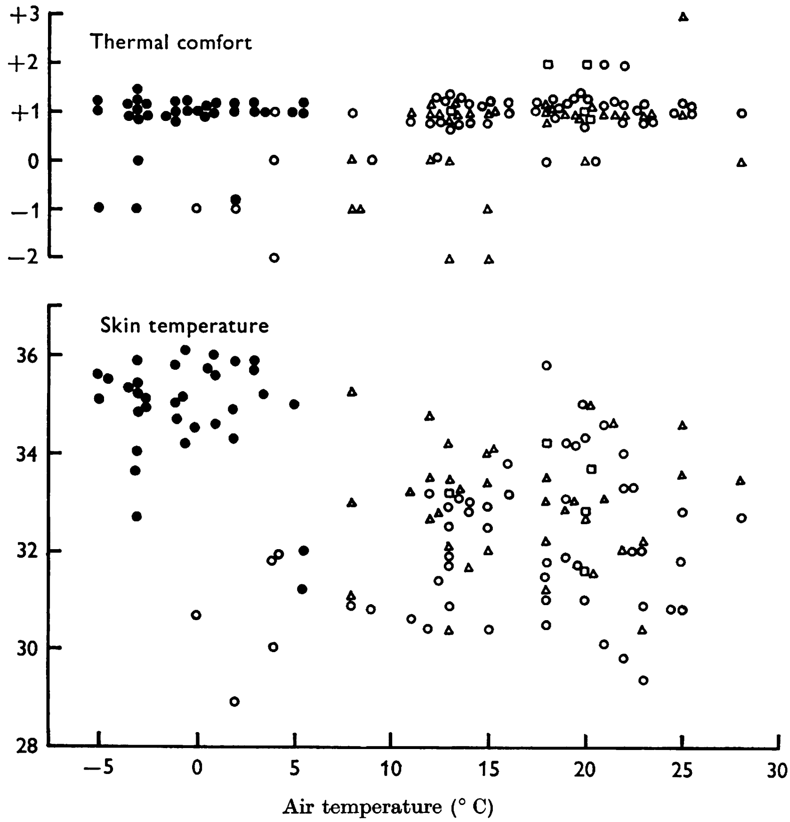

Fig. 2. Skin temperature and thermal comfort indoors, in relation to air temperature and the number of layers of clothing. Each point represents one observation. The grades of thermal comfort are: much too hot (+3), just too hot (+2), comfortably warm (+1), neutral (0), comfortably cool (−1), just too cold (−2). □, two layers of clothing; △, three layers of clothing; ○, four layers of clothing; ●, sleeping bag.

Inter-relations of thermal comfort, sweating, skin temperature and activity

Figure 5 shows that sweating, and discomfort from heat and from cold, occurred over a wide range of skin temperature. The lowest skin temperature associated with sweating and discomfort from heat was 20·8° C and was seen during moderate work; the highest skin temperature associated with discomfort from cold was 33·4° C and was seen during sitting. Nevertheless, the frequency of each thermal sensation appeared to be related to the skin temperature, and this relation varied with activity.

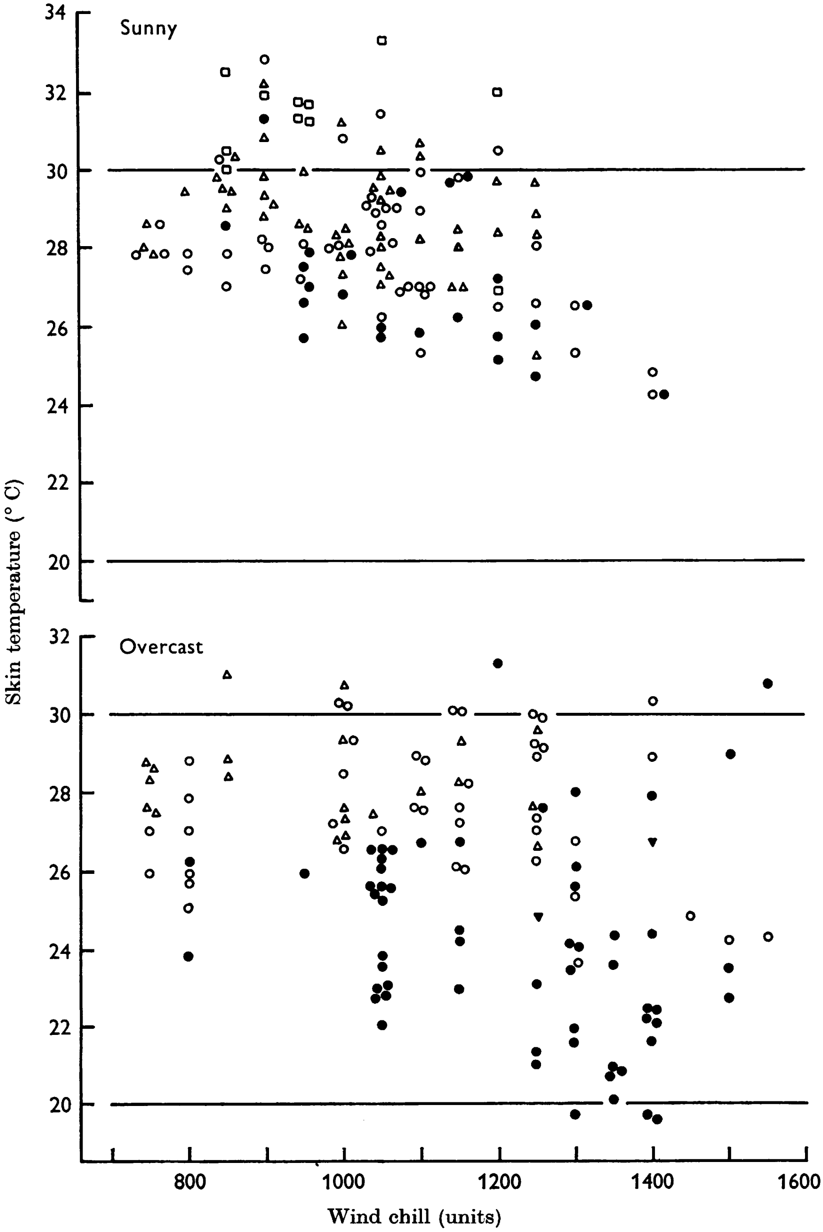

Fig. 3. Relation between skin temperature outdoors and wind chill, for each clothing combination, in sunny and overcast weather. Each point represents one observation. Symbols □, △ and ○ as for Fig. 2, but symbols ● and ▼ represent five and six layers of clothing respectively.

During sleeping and sitting there was very little discomfort from either heat or cold, over the range 30–36° C. During light work discomfort from heat was negligible but skin temperatures below 28° C were associated with an increasing frequency of discomfort from cold. Discomfort from cold was slight during moderate work and negligible during heavy work, but in both these activities skin temperatures above 28° C were associated with an increasing frequency of discomfort from heat. In other

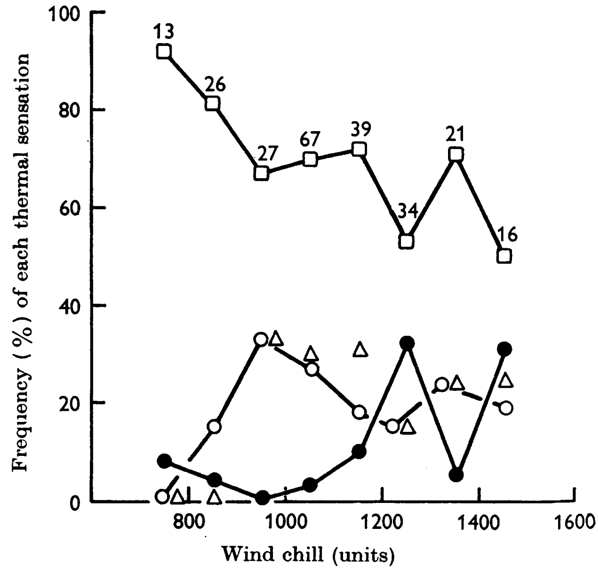

Fig. 4. The distribution of thermal comfort and sweating outdoors of each level of wind chill, grouped by intervals of 100 units. Frequencies are expressed as a percentage of the number of observations in each interval, which is shown next to the symbol for 'comfortable'. Frequencies based on less than 10 observations were discarded. □, comfortable; ●, too cold; ○, too hot; △, sweating.

words, at skin temperatures above 28° C the subjects tended to feel comfortable during light work but too hot during heavy work, and at skin temperatures below 28° C they tended to feel comfortable during heavy work but too cold during light work. Figure 5 also suggests that the incidence of sweating varied with skin temperature at constant work rate, and with work rate at constant skin temperature.

Activity and energy expenditure

The time spent outdoors averaged 12·3 hr/day for the 9 travelling days and 9·2 hr for the total 12 days of the journey. These values represent 51 and 38 %, respectively, of each day, and 70 and 56 % of waking hours—that is, of the time available for outdoor activities. The average distribu-

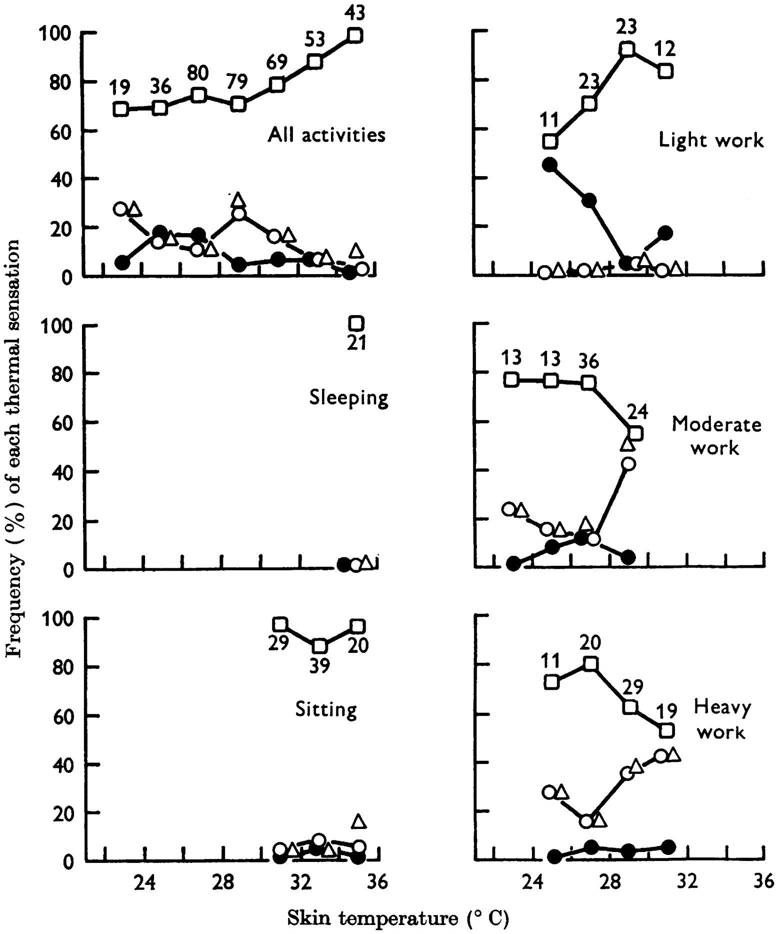

Fig. 5. The distribution of thermal comfort and sweating at each skin temperature (grouped by intervals of 2° C), for each level of activity and for all activities combined. Frequencies are expressed as a percentage of the number of observations in each interval, which is shown next to the symbol for 'comfortable'. Frequencies based on less than ten observations were discarded. Symbols as for Fig. 4.

Table 5. Hours per day spent in various activities by the three subjects on the 9 travelling days, the 2 'lie-up' days, and the total 12 days of the journey

		Travelling	Lie-up	Total
Sleeping		6·5	11·2	7·5
Sitting		4·0	10·6	5·5
Working:	Light	3·0	1·2	2·8
	Moderate	7·4	0·5	5·8
	Heavy	3·1	0·5	2·4
	All grades	13·5	2·2	11·0

tion of activity is shown in Table 5. The subjects slept only 6·5 hr/night while travelling, but made up for it by sleeping 11·2 hr on the two 'lie-up days' (when a blizzard prevented travel), so that over the 12 days they averaged 7·5 hr.

Work occupied 11·0 hr/day of the journey, and 13·5 hr/travelling day. Even on lie-up days 2·2 hr were spent in such work as cooking, and cranking the radio generator, inside the tent; and in feeding the dogs, tightening tent guys, and making weather observations, outdoors.

The estimated daily energy expenditure averaged 5100 kcal over the 12 days and 2740 kcal on the lie-up days. On travelling days it averaged 5860 kcal (range 5070–6660), of which 3280 kcal (56 %) were spent in sledging. Daily food intake was not recorded, but standard sledging rations providing 4800 kcal were eaten, varied on two days by fresh seal meat and by canned food from a depot. Fasting body weight 12 hr after return to Mawson (that is, after rehydration) was 4·1 kg (range 2·3–5·9 kg) less than it had been before the journey, and 45 hr after return it was still 2·3 kg (range 0·5–4·6 kg) below the initial values.

DISCUSSION

Activity and energy expenditure

The estimates of energy expenditure agree well with those of other workers. Masterton *et al.* (1957) estimated the energy expenditure of men sledging in Greenland to be between 5000 and 5400 kcal/day, although the men worked only 6·5 hr/day as against the 11·0 hr of the present study. Edholm & Lewis (1964) cite a value of 4000 kcal for 8 hr sledging, which suggests that the present estimate of 3280 kcal for 8·6 hr sledging might be a conservative one. Daily food intakes of 5000–5500 kcal have been found necessary to prevent weight loss during Antarctic sledging (Edholm & Lewis, 1964), and in the present instance weight loss occurred despite a calorie intake of approximately 4800 kcal/day.

Inter-relations of thermal comfort, sweating, skin temperature and activity

The distribution of medial thigh skin temperatures, indoors and outdoors, is strikingly similar to that observed by Hampton (in Edholm & Lewis, 1964) and Norman (1965) for subclothing temperatures of the trunk, and the modal values (33° C indoors and 27° C outdoors) are within 1° C of the mean skin temperatures observed indoors and outdoors in Antarctica by Milan (1964). The range of 'comfortable' skin temperatures for sleeping and sitting men (30–36° C) is similar to, but somewhat wider than, that (31–34° C) reported for resting subjects by Winslow, Herrington &

Gagge (1937)—possibly because of greater variations in activity, or possibly because of an increased tolerance. That thermal comfort is related to skin temperature is in agreement with these authors' conclusions, and that this relation varies with activity supports the observations of Winslow & Gagge (1941) and of Yaglou (1949), who found that the mean skin temperature associated with thermal comfort decreases with increasing activity. The findings that skin temperature is unaffected by activity, and that sweating is related to both skin temperature and activity, agree with the conclusions of Winslow & Gagge (1941), Belding, Russell, Darling & Folk (1947), and Robinson (1949).

Belding *et al.* (1947) have raised the question whether men who were underdressed to the point of feeling cool would avoid thermal sweating. The results suggest that they would, since only on three out of sixty-six occasions was sweating associated with feelings of coolness, and usually—as noted by Ellis (1953), and by Hindmarsh & Macpherson (1962)—it was associated with discomfort from heat.

All three subjects had sledged before, and appreciated the importance of avoiding sweating—yet in spite of their best efforts they failed to do so. Their failure emphasizes the difficulty of maintaining thermal comfort during strenuous exercise in a cold climate. Any change in activity or weather (particularly wind or sunshine) changes the clothing requirement, often at a time when it is not convenient to make the necessary adjustments. Consequently the subjects of this study tended to alternate between feeling too hot and too cold, and were generally too cold (particularly when their clothing was damp with sweat) by the end of the hourly rest halt, however warm they may have been 5 min earlier when the observations of thermal comfort were made.

The thermal stress of Antarctic sledging

The thermal stress experienced by men wearing conventional Antarctic clothing is evidently very different from that experienced by men wearing Arctic fur clothing. When Lapps and Eskimos wearing furs go outdoors into the cold their skin temperatures do not change (Scholander *et al.* 1957; Milan, 1964), owing to the extremely high insulation provided by their clothing (Rodahl, 1960). When the subjects of this study went outdoors wearing sweaters and windproofs, their skin temperatures fell, sometimes by as much as 10° C, to a level which was largely determined by the coldness of the environment. Their low skin temperatures, however, do not necessarily indicate that the subjects were vasoconstricted because, as Burton & Edholm (1955) have pointed out, for a given skin temperature vascular tone varies with activity. In this study the thermal sensations associated with a given skin temperature also varied with activity, and it therefore seems reasonable to assume that the subjects were vasodilated when they felt too hot and vasoconstricted when they felt too cold. On this interpretation the subjects were vasoconstricted in 11 % of the outdoor observations, and, since they were outdoors for more than 9 hr a day, it would seem that the cold stress experienced by men sledging in Antarctica is not negligible.

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