Indices of Windchill of Clothed Persons

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ABSTRACT

The concept of windchill as a measure of the combined effects of low temperature and wind is reviewed. An analysis is presented of the effect of these variables on a person dressed for cold climates and takes account of all important modes of heat loss, including breathing and heat transfer through clothing. This analysis leads to two chief indices of windchill: the windchill equivalent temperature, which is tabulated and compared with existing tables, and the clothing thickness required to maintain a person in thermal equilibrium. The distributions of clothing thickness and of the windchill of exposed skin at 30C are described.

1. Introduction

Many environmental factors besides temperature have a bearing on subjective feelings of warmth or cold. More than 70 publications (Macpherson, 1962) deal with attempts to combine these factors into a single index. There is particular interest in having a simple measure of conditions which may be so cold as to limit military and other activities. Among these conditions temperature and wind predominate over such influences as humidity and solar radiation. Windchill and derived terms such as the windchill factor are based only on temperature and wind speed.

Two of the most common indices[1] of the combined effects of wind and low temperature are based on the work of Siple and Passel (1945). These are 1) the windchill index (kcal m^{-2} hr^{-1}), which expresses the cooling power of the wind for various combinations of temperature and wind speed, and 2) the windchill equivalent temperature, which presents the cooling power of the wind such as would be felt on exposed flesh in a light wind.[2]

Table 1 lists windchill equivalent temperatures in everyday use, based on Siple's formula, for a wide range of winter temperatures and wind speeds.

Very widespread use has been made of Siple's windchill data, notwithstanding limitations pointed out by Siple and by other writers (e.g., Molnar, 1960, and Court, 1948). Many meteorological publications[3] urge circumspection in the use of windchill indices. The present publication deals with some of these limitations and applies Siple's approach to extend the concept of windchill to clothed persons.

Widespread use has been made of the idea of windchill from a bare surface in determining the feasibility of outdoor activity, particularly military operations. The emphasis of the present work is an overall consideration of the clothed person, and of determining the amount of clothing insulation needed to perform outdoor operations under any specified combination of wind and temperature.

2. Conventional measures of windchill

Considerable official information is based on the empirical windchill formula of Siple and Passel. Thus, we have[4]

$$\dot{q}=h(33-T_\infty),$$

where T_∞ is the ambient temperature (°C) and h (kcal m^{-2} hr^{-1}) is given by

$$h=10.45+10\sqrt{v}-v,$$

where v is the wind speed (m sec^{-1}). The formula has been slightly modified by Court (1948) to give

$$h=9.0+10.9\sqrt{v}-v$$

using the same units.

The two equations are qualitatively similar and have in common the unique feature of being parabolic in $\sqrt{v}$. Substitution of Siple's equation shows that the heat loss would reach a maximum at 25 m sec^{-1} (56 mph), then diminish at even higher wind speeds. Correspondingly, some official windchill tables claim that wind speeds >40 mph have little additional cooling effect.

The low rate of increase of heat loss with wind speed at moderate and high speeds is probably related to

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[1] The definitions have been taken from the 1966 Canada Department of Transport, Meteorological Branch, brochure entitled "Wind Cooling Power (Windchill)."

[2] A "light wind" is defined in corresponding tables as a wind of 5 mph or 2.23 m sec^{-1}.

[3] See footnote 1.

[4] See Appendix B for a complete list of symbols.

Siple's stated underestimation of low wind speeds. Other writers (Currie, 1951; Winslow *et al.*, 1939) have found sensations of cold to be much more dependent on wind speed in strong winds.

In the present work, account is taken of other data relating wind speed to the heat-transfer coefficient, as applied to a model which simulates the effect of clothing and physiological variables.

3. The model

In order to provide a basis for considering the effects of wind and temperature on a clothed person, it is considered that the interest of accuracy is best served by assuming a human wearing appropriate winter clothing and by applying physical data obtained under reproducible laboratory conditions. This biophysical approach avoids the errors shown to be inherent in physiological experiments under very cold conditions and enables physical parameters of clothing to be incorporated readily into the discussion.

Most research on windchill has dealt with heat loss from unclothed skin, since frostbite may be a limiting factor in outdoor operations. The development of adequate face masks, however, has made such operations possible at lower temperatures, and activity is generally limited only by the ability of clothing to maintain warmth and dexterity. Since almost all of the body is clothed under such conditions, the clothing is at least as important a factor in environmental protection as temperature and wind. Existing publications on windchill pay little attention to the clothed parts of the body; moreover, they provide no direct guidance about the amount of clothing insulation which is required.

Table 1. Windchill equivalent temperatures (°F) from Siple's formula.

Temperature (°F)	Wind speed (mph)								
	Calm	5	10	15	20	25	30	35	40
32	66	32	22	16	11	7	5	3	2
30	64	30	20	13	8	5	3	1	−1
28	63	28	18	11	6	3	0	−2	−4
26	62	26	16	9	3	0	−3	−5	−7
24	61	24	13	6	0	−3	−6	−8	−10
22	60	22	11	3	−2	−6	−9	−11	−13
20	59	20	8	0	−5	−9	−12	−14	−16
18	58	18	6	−2	−8	−12	−15	−17	−19
16	57	16	4	−5	−10	−15	−18	−20	−22
14	56	14	1	−8	−13	−18	−21	−23	−25
12	56	12	−1	−10	−16	−21	−24	−26	−28
10	55	10	−4	−12	−19	−24	−27	−29	−31
8	54	8	−6	−15	−21	−26	−30	−32	−34
6	53	6	−8	−18	−24	−29	−33	−35	−37
4	52	4	−11	−20	−27	−32	−35	−38	−40
2	51	2	−13	−23	−30	−35	−38	−41	−43
0	50	0	−15	−26	−32	−37	−41	−44	−46
−2	49	−2	−17	−28	−34	−40	−44	−47	−49
−4	48	−4	−20	−30	−37	−43	−47	−50	−51
−6	47	−6	−23	−32	−40	−45	−50	−53	−54
−8	46	−8	−25	−35	−43	−48	−53	−56	−57
−10	45	−10	−27	−38	−46	−51	−56	−59	−61
−12	45	−12	−29	−40	−48	−54	−59	−62	−64
−14	44	−14	−32	−42	−51	−56	−62	−65	−67
−16	43	−16	−35	−45	−54	−59	−64		
−18	42	−18	−37	−48	−56	−62	−67		
−20	41	−20	−39	−51	−59	−65	−70		
−22	40	−22	−42	−53	−62				
−24	39	−24	−44	−56	−65				
−26	38	−26	−46	−58					
−28	37	−28	−48	−61					
−30	37	−30	−50	−64					
−32	36	−32	−52	−67					
−34	35	−34	−54						
−36	34	−36	−57						
−38	33	−38	−59						
−40	32	−40	−62						

The situation considered here is that of an average clothed mobile human exposed to any given combination of wind and temperature, the radiant temperature of the surroundings being taken equal to the air temperature (but see Appendix A). Under these conditions the surface heat-transfer coefficient is calculated and converted to windchill by multiplying by the temperature difference between skin and air. Hence the required thermal resistance of the clothing can be determined for any given rate of metabolic heat production and arrangement of clothing.

A detailed discussion of the conditions follows.

a. Dimensions

A typical adult human is considered, having a clothed surface area of $\sim$1.7 m^2, independent of the amount of clothing worn, and a height $\sim$1.7 m. Since heat loss is reckoned as heat flow rate per unit area, these dimensions are not critical.

b. Significant diameter

For calculations of convective heat loss the body may be treated as a long cylinder and the significant dimension used in determining the Reynolds number is taken as a diameter of 10 cm, to allow for curvature of the body, especially at the extremities. This is slightly higher than most other values in the literature, particularly Plummer's (1944) widely used value of 7 cm, because of the reduction in curvature and increase in effective diameter produced by thick winter clothing. It will become apparent that any error in this diameter will be reduced by a factor of 4 in the convective heat-transfer coefficient and will be even less significant as an error in total heat loss, since it does not influence the radiative heat-transfer coefficient.

c. Clothing

The model is clothed in three stages as follows:

1) The face, representing 3% of the body surface, is uncovered.

2) The hands and feet, representing 12% of the body surface, are covered with a layer of clothing thick enough to prevent damage to the skin but not so thick as to impair freedom of movement unduly. This thick-

ness is taken as corresponding to a resistance of 0.5 m^2 sec (°C) cal^{-1}, i.e., $\sim$7 mm of good mitten material or 2 cm of leather sole.

3) The remaining 85% of the surface is covered with the required resistance of clothing needed to maintain thermal equilibrium.

d. Human temperatures

Body temperature is taken as 37C. Since it exceeds skin temperature under cold conditions, it is of significance only in determining heat loss in exhaled air. Following Gagge *et al.* (1941), the temperature of the 85% of skin covered by adequate clothing is taken as 33C. The uncovered skin, however, normally becomes even colder and Siple's assumed value of 33C was not followed, in view of his remarks on the freezing of flesh at high windchill values. The value of 30C, which is consistent with outdoor comfort, is taken as the skin temperature of hands, feet and face, and forms the basis for calculations of windchill, i.e., the heat loss from the unclothed part of the body. It has been commonly observed (Burton and Edholm, 1955) that heat loss from exposed persons is lower than a formula based on 33C would indicate, since the insulation of the tissues reduces the skin temperature below 33C.

e. Activity

Typically, a person engages in moderate activity when out of doors in cold weather. Activity such as walking at 1.33 m sec^{-1} (3 mph) corresponds to a rate of heat generation of 45 cal sec^{-1} m^{-2} (162 kcal hr^{-1} m^{-2}). This value is slightly higher than that quoted by Newburgh (1949), in order to allow for the encumbrance provided by cold-weather clothing.

f. Ventilation rate

Heat loss through the lungs is widely overlooked, yet accounts for more than one-fifth of the body's heat loss under cold dry conditions. Neglect of this effect has caused the effect of temperature on human comfort to be underestimated and the effect of wind consequently exaggerated. Heat loss due to breathing is all the more serious because, apart from a slight heat-exchanger effect at the nose and in face masks, there is little that can be done to reduce it by clothing. Rates of breathing are expressed in terms of weight of air, since this is directly related to the body's oxygen requirements, rather than in terms of volume, which varies with the temperature of the inhaled air.

The rate of breathing is taken as 0.22 gm sec^{-1} per square meter of body surface. In proportion to the corresponding value for metabolic heat output, that is slightly higher than the value quoted by Newburgh. Appreciable variations above and below this average value exist depending on the individual's capacity to utilize oxygen.

g. Dry heat loss from lungs

Given that the specific heat of air is 0.24 cal gm^{-1} $(°C)^{-1}$ and that air is exhaled at body temperature (37C), heat loss due to warming of air to body temperature is

$$0.24\times 0.22(37-T_\infty)=0.053(37-T_\infty)\ [\text{cal m}^{-2}\,\text{sec}^{-1}].$$

h. Evaporative heat loss from lungs

Because of the dryness of winter air, breathing accounts for an appreciable loss of moisture, hence of latent heat of evaporation. Inhaled air contains no more than 0.004 gram of water vapor per gram of dry air at freezing temperatures, and is exhaled at a moisture content somewhat below that of saturated water at body temperature (corresponding to moisture content of 0.04 gm gm^{-1}). As a first approximation, the increase of the absolute humidity is taken as 0.030 gm gm^{-1}. Since the latent heat of evaporation of water is 570 cal gm^{-1} at body temperature, heat loss is given by $\dot{q}''=\dot{m}''L=570\times 0.030\times 0.22=3.9$ cal m^{-2} sec^{-1}.

i. Wind speed

Confusion between wind speed as measured by anemometers and that encountered by a person at ground level has vitiated a number of studies on the effect of windchill. In practice, the former is commonly almost double the latter.

Recent work, particularly by Buckler (1969), has elucidated the effect of height above ground level on wind speed. Data obtained by Buckler at several heights above ground level at Saskatoon show a relationship

$$v=v_{10}(y/y_{10})^{0.21}$$

for the winter months.

For a person of height l, the average wind speed is obtained using the mean-value theorem. If the person's cross-sectional area is taken as independent of distance above ground level, the mean speed is given by

$$\bar{v}=\frac{v_{10}\int_0^l (y/y_{10})^{0.21}dy}{\int_0^l dy}=\frac{v_{10}}{1.21}(l/y_{10})^{0.21}.$$

If l is taken as 1.7 m for a typical adult, then $\bar{v}=0.57v_{10}$.

Percentage errors in the assumption of height are reduced by a factor of 5 when expressed as errors in the wind speed; the latter are negligible. In contrast, failure to consider the effect of vertical distance on wind leads to an error of $\sim$75% of the wind speed experienced by the person standing on the ground.

j. Radiative heat loss

At the long wavelengths at which heat is radiated from the human body, the emissivity of both skin and conventional clothing is, for practical purposes, unity. Stefan-Boltzman's law may be written as

$$\dot{q}=\sigma(T_s^4-T_\infty^4),$$

where T_s and T_∞ are in degrees Kelvin.

In order to determine the radiative heat-transfer coefficient in a form analogous to the convective coefficient, *viz.*, $\dot{q}''=h_r(T_s-T_\infty)$, the equation is factorized to give

$$\dot{q}''=\sigma(T_s^2+T_\infty^2)(T_s+T_\infty)(T_s-T_\infty),$$

i.e., the radiative heat-transfer coefficient is given as

$$h_r=\sigma(T_s^2+T_\infty^2)(T_s+T_\infty),$$

or, to a very close approximation,

$$h_r=\sigma[4T_\infty^3+6T_\infty(T_s-T_\infty)].$$

In a typical example the surface temperature exceeds that of the surroundings by about 5C. [This can be confirmed by multiplying this difference by a typical heat-transfer coefficient of 7 cal $\mathrm{m^{-2}\ sec^{-1}\ (^\circ C)^{-1}}$ to give the 35 cal $\mathrm{m^{-2}\ sec^{-1}}$ lost through the skin.] The value chosen for this temperature excess is arbitrary but not critical.

Hence, the computing formula for h_r is

$$h_r=0.0135\left[4\left(\frac{T_\infty+273}{100}\right)^3+0.3\left(\frac{T_\infty+273}{100}\right)^2\right].$$

k. *Convective heat loss*

For a long cylinder of 10 cm diameter, wind speeds commonly encountered correspond to Reynolds numbers of the order 10^4–10^5. At these values, Hilbert's (1933) data, which are considerably more precise than similar physiological results, indicate a relationship of approximately $\mathrm{Nu}=0.065\ \mathrm{Re}^{0.70}$ at room temperature, after allowance is made for radiative loss.

In order to take account of the penetration of fabrics by wind, a slightly higher exponent is called for. Other work by the writer at lower wind speeds (Steadman, 1965) indicates that the exponent of wind speed rises from about 0.7 for a bare cylinder to values varying from 0.7–1.0 for the same cylinder when covered with permeable fabrics. Accordingly, an exponent of 0.75 was chosen and the Nusselt number expressed by the relationship

$$\mathrm{Nu}=0.040\ \mathrm{Re}^{0.75}.$$

This exponent is higher than most values in the literature, but comparable with that (0.77) obtained by Lahmeyer and Dorno (1932). It has the further advantage of being capable of faster computation, since $v^{0.70}$ would have to be expanded in an infinite series.

The convective heat transfer coefficient is given by

$$h_c=\frac{\mathrm{Nu}k}{D}=\frac{0.040kv^{0.75}\rho^{0.75}}{D^{0.25}\mu^{0.75}}.$$

Substitution of the values for the physical properties of air (17) gives

$$h_c=1.72v^{0.75}$$

where v is in meters per second.

In practice, weather data quote wind speeds in miles per hour as measured by an anemometer. In order to convert these data into metric heat-transfer coefficients encountered by a person on the ground, the computing formula used to determine the convective heat loss experienced by a person on the ground is

$$h_c=1.72\left(\frac{0.57}{2.24}v_{10}'\right)^{0.75}=0.61v_{10}'^{0.75},$$

where v_{10}' is expressed in miles per hour.

The convective heat-transfer coefficient varies inversely with temperature because of the temperature dependence of density and viscosity, offset slightly by that of conductivity. Substitution of the values of these properties over the range −40 to +40C shows an approximately linear dependence of h_c on temperature and leads to

$$h_c=(0.67-0.0008T_\infty)v^{0.75},$$

where T_∞ is the ambient temperature (°F).

The effects of temperature on the convective and radiative coefficients are opposed. The combination shows that the total heat-transfer coefficient increases with temperature at low wind speeds, but reverses this trend at 15 mph.

Because of the considerable dependence of both coefficients on temperature, it is inaccurate to assume the existence of a "wind factor" for any temperature in determining windchill.

l. *Effective wind speed for moving persons*

A walking person is not only generating more heat than one who is stationary but, in general, the movement adds to the effective wind speed. Thus, a person walking at 3 mph in calm conditions would have an effective wind speed of 3 mph. Such a wind at ground level would be equivalent to $3/0.57=5.3$ mph as measured by an anemometer.

When moving in a light wind, the effective wind speed depends on the direction of movement relative to the wind. When $v^{0.75}$, which is proportional to the convective heat-transfer coefficient, is averaged for all directions using Simpson's rule, an effective wind speed (v_{10}') for a moving person on the ground is obtained, corresponding to any measured wind speed (v_{10}).

This procedure does not lend itself to routine calculations on a desk computer. In order to facilitate the conversion of anemometer data, a close empirical fit to the results obtained using Simpson's rule was obtained from the following equations, the computer being

TABLE 2. Windchill equivalent temperature (°F) based on clothing requirements. See text for explanation.

Temperature (°F)	Calm	5	10	15	20	25	30	35	40
	Wind speed (mph)								
32	34	32	27	24	21	17	14	12	10
30	32	30	25	21	18	15	12	10	7
28	30	28	23	19	15	12	9	6	4
26	28	26	21	17	13	9	6	3	1
24	26	24	19	14	10	7	3	0	−3
22	25	22	16	12	8	4	1	−3	−6
20	23	20	14	9	5	1	−2	−6	−9
18	21	18	12	7	2	−2	−5	−9	−13
16	19	16	10	5	0	−4	−8	−12	−17
14	17	14	8	2	−3	−7	−12	−16	−20
12	15	12	6	0	−5	−10	−15	−19	−24
10	13	10	4	−2	−8	−13	−18	−23	−28
8	11	8	1	−5	−11	−16	−21	−26	−32
6	9	6	−1	−7	−13	−19	−24	−30	−36
4	7	4	−3	−10	−16	−22	−28	−34	−40
2	5	2	−5	−12	−19	−25	−31	−38	−44
0	3	0	−7	−15	−22	−28	−35	−42	−49
−2	1	−2	−10	−17	−25	−31	−39	−46	−54
−4	−1	−4	−12	−20	−28	−35	−42	−50	−58
−6	−3	−6	−14	−22	−30	−38	−46	−54	−63
−8	−4	−8	−16	−25	−33	−41	−50	−59	−67
−10	−6	−10	−19	−28	−36	−45	−54	−63	
−12	−8	−12	−21	−30	−39	−48	−58	−68	
−14	−10	−14	−23	−33	−42	−51	−62		
−16	−12	−16	−26	−36	−45	−55	−66		
−18	−14	−18	−28	−38	−49	−59			
−20	−16	−20	−30	−41	−52	−63			
−22	−18	−22	−32	−44	−55	−66			
−24	−20	−24	−35	−47	−58				
−26	−22	−26	−37	−49	−62				
−28	−24	−28	−39	−52	−65				
−30	−26	−30	−42	−55	−68				
−32	−27	−32	−44	−58					
−34	−29	−34	−47	−61					
−36	−31	−36	−49	−64					
−38	−33	−38	−51	−67					
−40	−35	−40	−54	−69					

programmed to select the appropriate alternative:

$$v_{10}'=(v_{10}^2+10)^{\frac{1}{2}}, \qquad v_{10}\geqslant 6.4 \text{ mph},$$
$$v_{10}'=[v_{10}^2+10+7(6.4-v_{10})^{\frac{1}{2}}]^{\frac{1}{2}}, \quad v_{10}<6.4 \text{ mph}.$$

m. Resistance of clothing

The thermal conductivity of stationary winter clothing is taken as 1.00 cal m^{-2} sec^{-1} (°C cm^{-1})$^{-1}$. The value of 1.00 is higher than typical measured values for insulating fabrics in the range 0.8–0.9, in order to allow for non-uniformity in garments, the effect of windbreaks with high conductivity, and the reduction in insulation due to wind.

When a person moves, the insulation of clothing is reduced by the "bellows effects," which was investigated by Belding *et al.* (1947). The increase in conductance is estimated roughly as 30%, i.e., an effective conductivity of 1.3 cal m^{-2} sec^{-1} (°C cm^{-1})$^{-1}$ is assumed for clothing worn by a walking person. Any error in this assumption does not affect the relative values of required clothing thickness, and the tables of windchill and windchill effective temperature are independent of the thermal conductivity of the clothing.

n. Other assumptions

Heat loss by evaporation other than through the lungs is neglected. Under conditions in which protection against cold is considered, natural protective mechanisms against heat, such as sensible perspiration, play little part. Behmann (1960) has shown that when cold the peripheral tissues offer appreciable resistance to moisture transfer by insensible perspiration. This assumption will be invalid at higher temperatures, when both insensible and sensible perspiration may be appreciable, but this moisture loss is somewhat offset by reduced evaporation from the lungs as the moisture content of warmer air increases.

4. Computation

In order to maintain thermal equilibrium, the clothing must have such a resistance as to allow heat to be lost at the same rate as it is generated. Thus, for unit time and area (second and square meter), we have

heat generation
=loss due to heating breath
+evaporative loss in breath
+loss from uncovered skin
+loss from thinly clothed hands and feet
+loss from fully clothed parts.

Substituting the data of Section 3c through 3h gives

$$45=3.9+0.053(37-T_\infty)+\frac{0.03(30-T_\infty)}{R_s}+\frac{0.12(30-T_\infty)}{0.5+R_s}+\frac{0.85(30-T_\infty)}{R_F+R_s}, \quad (1)$$

where the clothing resistance is given by

$$R_F=d_F/k_F$$

and the surface resistance by

$$R_s=\frac{1}{h_r+h_c}.$$

Eq. (1) is processed by computer, the program being written so that the input is the temperature in degrees Fahrenheit and the wind speed, in miles per hour, as measured by an anemometer. These are converted, respectively, into temperature in degrees Celsius and wind speed as experienced by a moving observer on the ground. The windchill, given by $(30-T_\infty)/R_s$, and the required thickness of clothing, in millimeters, are printed. Since, by definition, there is a one-to-one correspondence between the required clothing thickness and the windchill equivalent temperature, the latter is readily obtained for any combination of wind and temperature (Table 2).

5. Results and discussion

Windchill and required clothing thickness over the commonly encountered ranges of wind and temperature are plotted in Figs. 1 and 2. The scope of these tables for certain applications is limited by the assumptions of the model, both being less valid at higher temperatures at which sensible perspiration may be appreciable. But some application may still be made of the tables at these temperatures, e.g., a windchill below approximately 30 cal m^{-2} sec^{-1} is desirable for sunbathing.

a. Windchill

Fig. 1 refers to heat loss from any uncovered object at 30 C. Since the effect of movement at 3 mph is slight in high winds, the chart may be used for stationary objects in winds $\gtrsim 10$ mph. At the same time, the effect of wind speed on the moving object at speeds up to about 5 mph is slight.

Fig. 1 may be plotted in a different form, showing lines of equal windchill on a graph of wind and temperature. This has been done in Fig. 3 for values of windchill of from 50 to 450 in steps of 50 cal m^{-2} sec^{-1}. Significantly, the slopes of these lines correspond closely to the sensation isopleths described by Currie (1951) but not to the official windchill charts (U. S. Army, 1964).

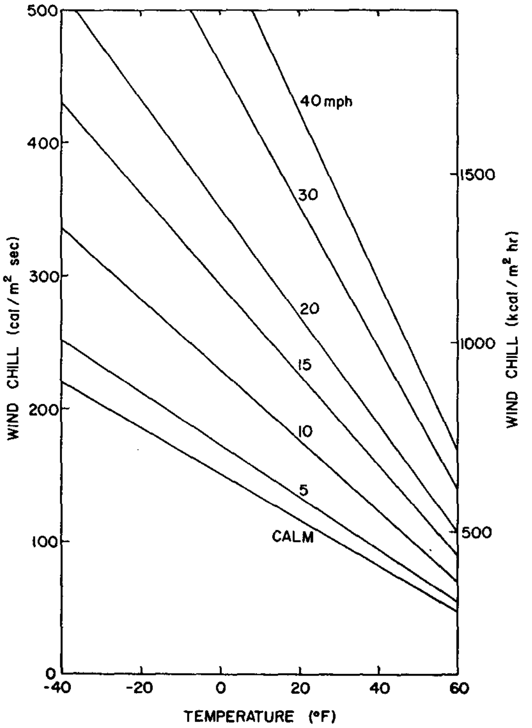

FIG. 1. Windchill as a function of air temperature for various wind speeds.

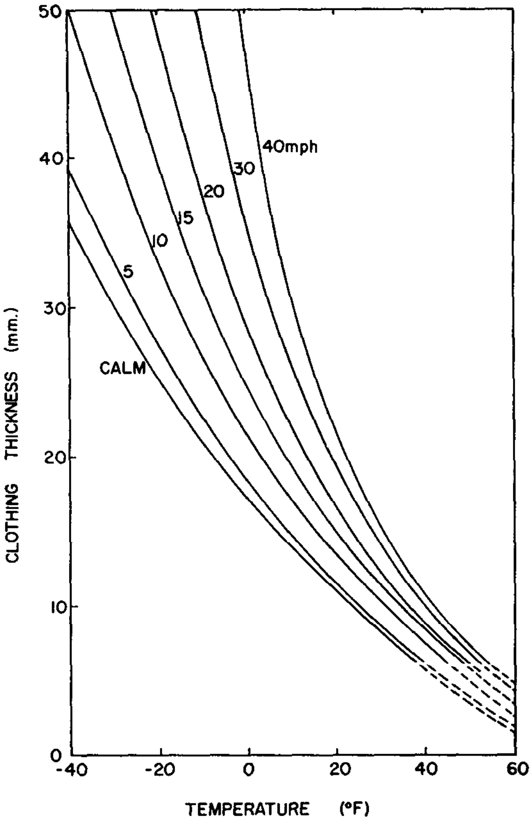

FIG. 2. Thickness of clothing (mm) required to insulate 85% of the body's surface (see text; data from Table 2).

The isopleths do not depart as far from linearity as previously published data, with respect to both wind and temperature, except at very low wind speeds. It follows, in contrast to earlier indices, that values of the windchill described here can be averaged over periods of up to a month with fair accuracy, since very low wind speeds are normally absent from data averaged over more than one day.

b. Clothing thickness

The thickness of clothing required to insulate 85% of the body's surface is shown in Fig. 2. It is apparent that under severe conditions no amount of clothing is sufficient to keep the model warm, an effect observed by football spectators and others whose metabolic output is low. Alternative methods such as voluntary activity or electric heating must be used to achieve equilibrium under these conditions. At the other extreme, because

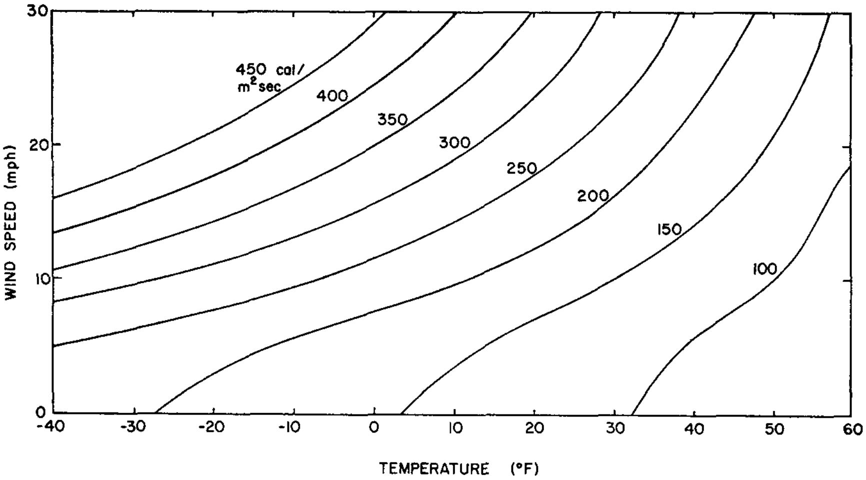

FIG. 3. Windchill isopleths shown as a function of wind speed and temperature.

the model is regarded as clothed for cold weather with a minimum of 7 mm of insulation, indicated values of clothing for the remainder of the body below 7 mm are not realistic and are shown by dotted lines. Although the model is intended only for winter conditions, values of clothing thickness may be computed for any value of temperature and wind. Regardless of whether these values correspond to achievable thicknesses of clothing, they can be used to relate any combinations of wind and temperature to one another, hence to determine windchill equivalent temperatures.

c. *Windchill equivalent temperatures*

Corresponding to any combination of wind and temperature, there is a temperature at which, in a wind of 5 mph, the model would wear an equivalent amount of clothing to maintain thermal equilibrium. These windchill equivalent temperatures are tabulated in Table 2 for common combinations of wind and winter temperature.

For comparison, values of equivalent temperature based on Siple's formula (2) are listed in Table 1. Inspection shows that on this system heat loss would be much more sensitive to wind at low than at high speeds. There is no independent evidence to confirm that, for instance, stepping from a barely perceptible light air into the calm of a unheated automobile would be equivalent to a temperature increase of the order of 40F.

d. *Diurnal variations in windchill*

In general, those times of day when the wind speed is high are near the times of maximum temperature, whereas morning winds and temperatures are both low. Thus, windchill is relatively steady during the period covered by a short-term forecast.

To elucidate the relation, one day, having an approximately average range of temperature and wind speed, was selected from each month's weather record. Windchill and clothing thickness were determined for each hour and the mean and standard deviation calculated for each day. The results, grouped into seasons, are shown in Table 3.

The relatively low coefficients of variation of these derived properties in all but the hot months—when

TABLE 3. Typical diurnal variations of windchill and clothing thickness.

Season	Windchill [cal m^{-2} sec^{-1} (°C)$^{-1}$] Mean	Windchill Coefficient of variation	Clothing thickness (mm) Mean	Clothing thickness Coefficient of variation
Winter	259	21.9	22.2	16.2
Spring	171	18.7	9.7	20.0
Summer	56	29.9	1.7	65.6
Autumn	118	19.0	6.7	28.2
Mean	151	24.4	10.1	32.5

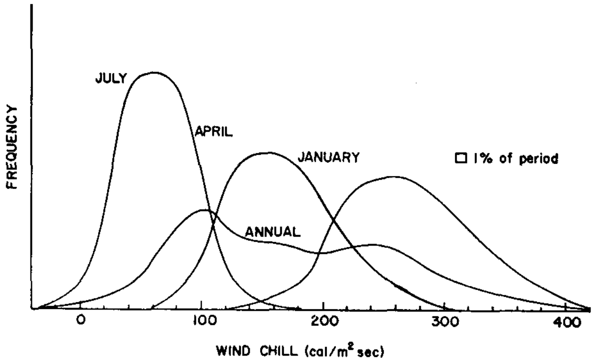

FIG. 4. Monthly and annual distribution of windchill for Winnipeg, 1969.

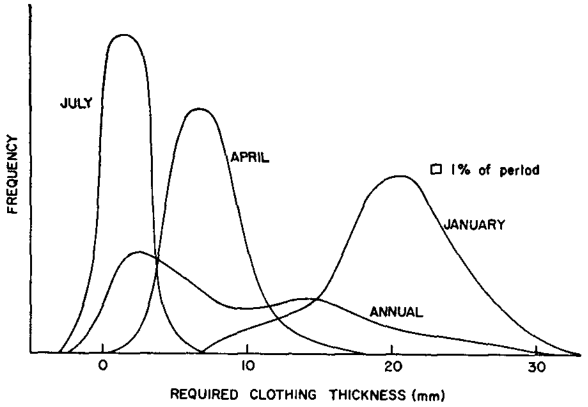

FIG. 5. Same as Fig. 4 except for clothing thickness.

some negative values are found—suggests that they may provide a precise single estimate of the effects of cold and wind over a whole day. A measure of clothing thickness may provide a useful index for daily forecasts.

e. *Application of results*

As single measures of climatic severity, windchill and clothing thickness, the first as an index of the environment and the second as a guide to personnel, have both been calculated and their distributions tabulated. The example chosen is Winnipeg, which has been shown to have the highest windchill of the major North American cities (Thomas and Boyd, 1957) and for which abundant climatic data are available.

The two indices were determined for each hour of 1969 and their distributions plotted for each month. By calculating these indices for the mean wind speed and temperature of each month and for the monthly normal means for the standard period 1931–60, the 1969 data were adjusted, where necessary, to provide normalized values of the distribution of these indices. Normal values of windchill distribution for January, April, July and the whole year are plotted in Fig. 4 and corresponding values of clothing requirements in Fig. 5.

6. Summary

The combined effect of wind and low temperature on a surface may be expressed as windchill, the rate of heat loss from a surface such as bare skin at 30C. Windchill is strongly dependent on wind speed.

When a clothed human is considered, account is taken of breathing and the insulation which the clothing provides for much of the skin surface. For a model in which physiological, clothing and environmental effects are considered in detail, the thickness of clothing required to maintain thermal equilibrium provides a single index of the effect of cold and wind in addition to its intrinsic use.

Corresponding to any clothing thickness determined in this way there is a windchill equivalent temperature. These temperatures show a lesser dependence on wind speed at all but high speeds than do conventional data based on Siple's formula.

Because of their relatively slight diurnal variation, these measures may provide a useful index for short-term forecasts and reports.

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APPENDIX A

The Effect of Insolation

A person standing in sunlight with insolation G [cal m^{-2} sec^{-1}] will receive the equivalent of normally incident insolation only over a small proportion p of his surface area, even when terrestial reflection is allowed for. Of this, a fraction is absorbed at the surface, either by skin or clothing. Thus, the additional heat load at the surface is given by

$$\dot{q}''=\alpha_s pG,$$

and net heat losses from skin and fabric are respectively

$$\left.\begin{aligned}\dot{q}''&=h(T_0-T_\infty)-\alpha_s pG\\ \dot{q}''&=\frac{T_0-T_\infty}{\dfrac{d_F}{k_F}+\dfrac{1}{h}}-\frac{\alpha_s pG}{1+\dfrac{hd_F}{k_F}}\end{aligned}\right\}. \tag{2}$$

The reduction in heat loss from the clothed part, $(\alpha_s pG)/[1+(hd_F/k_F)]$, clearly depends greatly on the amount of clothing worn, and it is not realistic to equate insolation with a fixed decrease in heat loss or windchill. (Official tables state that sunshine reduces windchill by 100 kcal m^{-2} hr^{-1}.)

Allowance must also be made for heat loss through the lungs. This is approximately proportional to the temperature difference between the skin and the air, independent of the amount of sunshine received. It may be expressed in terms of heat flow rate from the body's surface as

$$\dot{q}''=b(T_0-T_\infty), \tag{3}$$

where b is a constant having the approximate value 0.18 cal m^{-2} sec^{-1} (°C)$^{-1}$ for a person breathing 0.22 grams of air per second per square meter.

Combination of Eqs. (2) and (3) gives the total heat loss, after rearrangement, as

$$\dot{q}''=\left(b+\frac{k_F h}{hd_F+k_F}\right)\left[T_0-T_\infty-\frac{\alpha_s pG}{h+b+\dfrac{hbd_F}{k_F}}\right],$$

i.e., the absorption of sunlight is equivalent to an increase in ambient temperature of

$$[(\alpha_s pG)/h+b+(hbd_F/k_F)]$$

degrees Celsius. Since h is usually much the greatest term in the denominator, this increase is practically independent of the amount of clothing worn. The order of magnitude of the increase, for "favorable" conditions, i.e., full sunshine not near sunrise or sunset, is determined as follows:

1) The absorptivity of most winter clothing, and of human skin, is approximately 0.8.

2) The results of Underwood and Ward (1960) indicate that under very cold conditions, associated with a low angle of solar altitude and with reflection from snow, p may be taken as $\sim\frac{1}{3}$ for an upright human.

3) Direct insolation at all but very high altitudes averages $\sim$240 cal m^{-2} sec^{-1}, under the conditions described above.

4) The heat-transfer coefficient varies between 4 and 8 cal m^{-2} sec^{-1} (°C)$^{-1}$, depending on wind speed.

5) Clothing thickness is of the order of 1 cm.

Hence, sunshine effectively raises the ambient temperature by approximately

$$\left[\frac{0.8\times 1/3\times 240}{4+0.18+(4\times 0.18\times 1/1.3)}\right]=14\text{C}$$

under nearly calm conditions, and ~7C in a strong wind.

APPENDIX B

Symbols Used in the Text

D	diameter (cm or m)
G	insolation (cal m^{-2} sec^{-1})
L	latent heat of vaporization (cal gm^{-1})
R_F	resistance of unit area of clothing [m^2 sec (°C) cal^{-1}]
R_s	resistance of unit area of surface [m^2 sec (°C) cal^{-1}]
T	temperature (°C or °F)
T_0	skin temperature (°C)
T_∞	ambient temperature (°C or °F)
b	heat transfer coefficient referring to exhaled air [cal m^{-2} sec^{-1} (°C)$^{-1}$]
d	fabric thickness (cm or mm)
h	heat transfer coefficient [cal m^{-2} sec^{-1} (°C)$^{-1}$]
k	thermal conductivity [cal m^{-2} sec^{-1} (°C cm^{-1})$^{-1}$]
l	height of typical human (1.7 m)
$\dot{m}''$	moisture flow rate per unit area (gm m^{-2} sec^{-1})
p	proportion of body's surface effectively receiving normally incident radiation
$\dot{q}''$	heat flow rate per unit area (cal m^{-2} sec^{-1})
v	wind speed (m sec^{-1} or mph)
$\bar{v}$	mean wind speed encountered by person standing on ground
v'	effective wind speed experienced by moving person
v_{10}	wind speed registered by anemometer 10 m above ground
v_{10}'	equivalent anemometer wind speed corresponding to effective wind speed experienced by observer
y	height above ground (m)
y_{10}	reference height of anemometer above ground (10 m)
Re	Reynolds number, $=vD\rho/\mu$
Nu	Nüsselt number, $=hD/k$
α	absorptivity
μ	viscosity of air (gm m^{-1} sec^{-1})
ρ	density of air (gm m^{-3})
σ	Stefan-Boltzmann constant, $=1.35\times10^{-8}$ cal m^{-2} sec^{-1} (°K)$^{-4}$

Subscripts

c	by convection
F	clothing
r	by radiation
s	surface of skin or clothing

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