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The Basis of Wind Chill

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ABSTRACT. The practical success of the wind chill index has often been vaguely attributed to the effect of wind on heat transfer from bare skin, usually the face. To test this theory, facial heat loss and the wind chill index were compared. The effect of wind speed on heat transfer from a thermal model of a head was investigated in a wind tunnel. When the thermal model was facing the wind, wind speed affected the heat transfer from its face in much the same manner as it would affect the heat transfer from a small cylinder, such as that used in the original wind chill experiments carried out in Antarctica fifty years ago. A mathematical model of heat transfer from the face was developed and compared to other models of wind chill. Skin temperatures calculated from the model were consistent with observations of frostbite and discomfort at a range of wind speeds and temperatures. The wind chill index was shown to be several times larger than the calculated heat transfer, but roughly proportional to it. Wind chill equivalent temperatures were recalculated on the basis of facial cooling. An equivalent temperature increment was derived to account for the effect of bright sunshine.

Key words: bioclimatology, cold injuries, cold weather, convective heat transfer, face cooling, frostbite, heat loss, survival, wind chill

RÉSUMÉ. La popularité de l'indice de refroidissement du vent a souvent été expliquée par le fait qu'on peut la relier plus ou moins à l'effet du vent sur le transfert thermique à partir de la peau nue, le plus souvent celle du visage. Afin de mettre cette théorie à l'essai, on a comparé la perte de chaleur du visage et l'indice de refroidissement du vent. On a étudié l'effet de la vitesse du vent sur le transfert thermique à partir d'une maquette thermique de la tête placée dans une soufflerie. Lorsque la maquette thermique faisait face au vent, la vitesse du vent affectait le transfert thermique à partir du visage à peu près comme il affecterait le transfert thermique à partir d'un petit cyclindre, comme celui utilisé dans les premières expériences de refroidissement dû au vent, menées dans l'Antarctique il y a cinquante ans. On a créé un modèle mathématique de transfert thermique à partir du visage et on l'a comparé à d'autres modèles de refroidissement dû au vent. Les températures de la peau calculées à partir du modèle correspondaient à l'observation de gelures et de sentiments d'inconfort à une gamme de vitesses et de températures éoliennes données. L'indice de refroidissement du vent s'est révélé plusieurs fois plus important que le transfert thermique calculé, mais en gros proportionnel à lui. On a recalculé les températures équivalentes à l'indice de refroidissement du vent en s'appuyant sur le refroidissement du visage. Une augmentation de température équivalente a été déduite, qui tient compte de l'effet de l'insolation.

Mots clés: bioclimatologie, lésions dues au froid, temps froid, transfert de chaleur par convection, refroidissement du visage, gelure, perte de chaleur, survie, refroidissement dû au vent

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INTRODUCTION

Until the recent discovery of the hole in the ozone layer over the South Pole, the best-known result of a century of polar research was the wind chill index, created by Siple and Passel (1945) in 1941. In the fifty years since its publication, it has been repeatedly criticized by experts for its lack of a theoretical basis and for its shaky experimental foundations (Burton and Edholm, 1955; Molnar, 1960; Steadman, 1971; Kessler, 1993). Despite its technical shortcomings, the wind chill index has remained popular because it seemed to work. However, in 1969, a publication of the Arctic Institute of North America warned: "the wind chill concept has not yet been rigorously defined by physiologists, and its usage and usefulness are consequently still open to considerable controversy" (Sater, 1969:173).

It has long been assumed that the sensation of wind chill relates to the cooling of areas of exposed skin, particularly the face. In the cold, some of the body's most important thermal control mechanisms seem to be actuated or modified by the effects of the weather on the face (Burton, 1960). Because the face is often bare, wind chill is felt there first and most acutely. To test the theory that facial cooling is the primary basis of the sensation of wind chill, heat loss from a physical model of a human head was investigated at a range of wind speeds in a wind tunnel. A mathematical model was then developed to predict skin temperature and heat transfer from the face.

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THE WIND CHILL INDEX

In Antarctica in 1941, Paul Siple and Charles Passel conducted a crude cooling experiment on the roof of one of the buildings of the Little America III expedition. In the darkness and extreme cold of the Antarctic winter, using leftover equipment from other research programs, they measured the time it took to freeze water in a small plastic cylinder, 6.35 cm (2.5 inches) in diameter. Knowing the latent heat of fusion of water, the surface area of the cylinder, and the air temperature, they were able to calculate heat transfer coefficients, which they called wind chill factors, h_{wc}. They related h_{wc} to the wind speed, V (m/s), by an empirical equation:

$$h_{WC} = 10.45 + 10V^{1/2} - V \qquad \{\text{kCal/m}^2\text{h}^\circ\text{C}\} \qquad (1)$$

The wind chill index (WCI), which was an estimate of heat transfer, was obtained by multiplying the wind chill factor (h_{wc}) by the difference between an assumed skin temperature (33˚C) and air temperature (T_{air}).

$$WCI = h_{WC}(33^\circ\text{C} - T_{air}) \qquad \{\text{kCal/m}^2\text{h}\} \qquad (2)$$

They calibrated their scale of numbers against cold sensation, much as the length of the column of mercury in a thermometer must be related to the temperature. They recruited volunteers to assess comfort at various levels of wind chill, and asked expedition field parties to keep notes of how the weather conditions affected their discomfort. These results were supplemented with previously published assessments of comfort in various weather conditions. They found that values of the index were associated with the same thermal sensations regardless of how wind and temperature had combined to create them. Siple and Passel marked their scale of numbers with descriptors such as Cold, Very Cold, Bitterly Cold and Exposed Flesh Freezes at the values of the wind chill index that they had found to be associated with those sensations. Unfortunately, when they published their results, they gave the wind chill index units of heat transfer, i.e., kCal/m^{2}h. Later, Siple regretted this decision and recommended that his index be used "just as numbers" (Siple, 1960:216). To avoid confusion, throughout this paper, the original units of the wind chill index will be used where units are necessary.

Given their limited resources and the difficulties of carrying out the experiments, Siple and Passel were surprisingly successful. One early critique of the wind chill index admitted:

> The index of "wind chill" has enjoyed a considerable, and deserved, popularity, for it has been proved in the field that it does indeed provide an index corresponding quite well with experience in the cold, i.e., of the discomfort and tolerance of man in the cold. Yet it can be easily shown that the scientific basis for "wind chill" is lacking so that its empirical success becomes a matter for investigation. (Burton and Edholm, 1955:111)

Other critics, such as Molnar (1960), saw only the errors. Molnar had attempted to duplicate the original experiments in a wind tunnel. He found that the original experiment had underestimated the area of the cylinder from which heat was lost and that the procedure for determining the freezing time had been faulty. He also criticized the analysis for failing to take into account thermal gradients in the ice and for underestimating the heat being extracted from the cylinder during the freezing period. Molnar pointed out that because forced convective heat transfer from a cylinder is inversely related to its diameter, the wind chill index formula could not be used to estimate heat loss from a human body, because the cylinder had been far too small. He also noted that because the cylinder had been made of plastic rather than metal, the wind chill factors were not simple surface heat transfer coefficients, for they included the effect of the cylinder wall.

Siple (1960) replied that even though it would have been much easier to use a metal can, they had made the cylinder out of a sheet of plastic because they hoped that thermally, it would more closely resemble human skin.

Although Siple and Passel's experiment had apparently been designed to simulate heat transfer from the core of the body through the body tissues to the air, the wind chill factors were treated as if they represented heat transfer from the skin to the air. In the wind chill index equation, the factors are multiplied by the difference between an assumed skin temperature of 33˚C and air temperature. Clearly, the constant temperature in the wind chill formula should have been described as a core temperature, and it should have been set higher than 33˚C. It makes no sense to assume that the skin is at 33˚C and then to claim that in some combinations of wind and temperature it is in danger of freezing; however, it is quite possible to have freezing skin with a core temperature of 37˚C.

All the technical objections, valid as they may be, miss the point. Siple and Passel were not seeking a formula to calculate the heat loss of a clothed or a nude human body, or some small part of one. They were looking for and found a mathematical way to combine wind and temperature to create a scale that they could calibrate to consistently reflect how cold different combinations of those factors would feel. Many would agree with Siple's response to the criticism:

> Looking back, we perhaps made a rather too naive approach, and we may have made assumptions which were a little careless. However, from the practical standpoint, I think we evolved a schema that has been of some use. (Siple, 1960:218)

WIND TUNNEL EXPERIMENT

Although there have been numerous investigations of the effect of wind on the transfer of heat from the whole body and from most individual body segments (Danielsson, 1993), the head has been comparatively neglected. Clark and Toy (1975) assumed that the cylinder model was appropriate when they transformed local heat transfer coefficients that they had measured at various locations around subjects' heads into overall heat transfer coefficients.

To determine how heat transfer from a face actually varies with wind speed, I carried out a series of wind tunnel experiments using a thermal model of a head.

Method and Apparatus

The thermal head simulator (Osczevski, unpubl. data) consisted of a rigid polyurethane foam headform to which heating circuits and a thermally conducting skin were applied. The outer surface was bright aluminum foil. Each of the four segments was covered with closely spaced temperature-sensing circuits of fine copper wire. The individual segments were maintained at an average temperature of 36.0˚C while the head was subjected to artificial winds in a large wind tunnel (3 m × 4.3 m × 15 m). Total heat transfer coefficients for the face, forehead and scalp areas were determined from the ratio of the electrical power per unit area supplied to each segment at steady state to the difference between the surface temperature and the air temperature.

Results

When the model head was facing the wind, the best-fit equation describing the effect of wind on convective heat transfer from the head was:

$$h_{head} = 11.5V^{0.68} \qquad \{W/m^2K\} \qquad (3)$$

Facial heat transfer, shown in Figure 1, was less sensitive to wind velocity than heat transfer from the entire head. Equation (4) describes the data for the face quite well ($r^2 = 0.997$):

$$h_{face} = 14.4V^{0.61} \qquad \{W/m^2K\} \qquad (4)$$

The forced convective heat transfer coefficient was derived by subtracting the radiative heat transfer coefficient from the total heat transfer coefficient measured by the experiment. The small radiative heat transfer component of the shiny aluminum surface, h_r, was estimated from:

$$h_r = 4\varepsilon\sigma \overline{T}^3 \qquad \{W/m^2K\} \qquad (5)$$

where the temperature is the mean of air and surface temperatures in degrees kelvin, σ is the Stefan-Boltzman constant and ε is the emissivity of the bright aluminum surface, estimated to be 0.04 (Cain and MacKay, 1991). There was also a small heat transfer component due to natural convection, but at wind speeds above 1 m/s it was negligible compared to the forced convection (Danielsson, 1993).

Discussion

The standard empirical relation for a cylinder in a cross flow of air (Özisik, 1977) can be written as:

$$h_c = 0.23\left(\frac{V}{\nu}\right)^{0.6} \frac{k}{D^{0.4}} \qquad (6)$$

where h_c is the convective heat transfer coefficient (W/m²K), D is the diameter (m) of the cylinder, V is the wind speed (m/s), k is the thermal conductivity (W/mK) of air and ν is its kinematic viscosity (m²/s). The last two are functions of temperature and are to be determined at the mean of the surface and air temperatures. The convective heat transfer coefficient calculated from equation (3) increases by only 5% as the mean of the air and surface temperatures varies from +30˚C to -20˚C. The effect of temperature on equations (3) and (4) must be of a similar order.

For comparison with the equations for the thermal head simulator, equation (6) can be written as:

$$h_c = 8.7V^{0.6} \qquad \{W/m^2K\} \qquad (7)$$

at room temperature with a surface temperature of 36˚C and D = 0.16 m. According to equation (6), the forced convective heat transfer coefficient of a cylinder is inversely proportional to the diameter to the power 0.4. Wind therefore has a greater effect on heat loss from small cylinders than from large ones, as Molnar had pointed out. The cylinder used by Siple and Passel was only about a quarter of the average diameter of the human body. Equation 6 was used to calculate heat transfer coefficients for a cylinder of the diameter of that used by Siple and Passel. As seen in Figure 1, the result is very close to that of the model face.

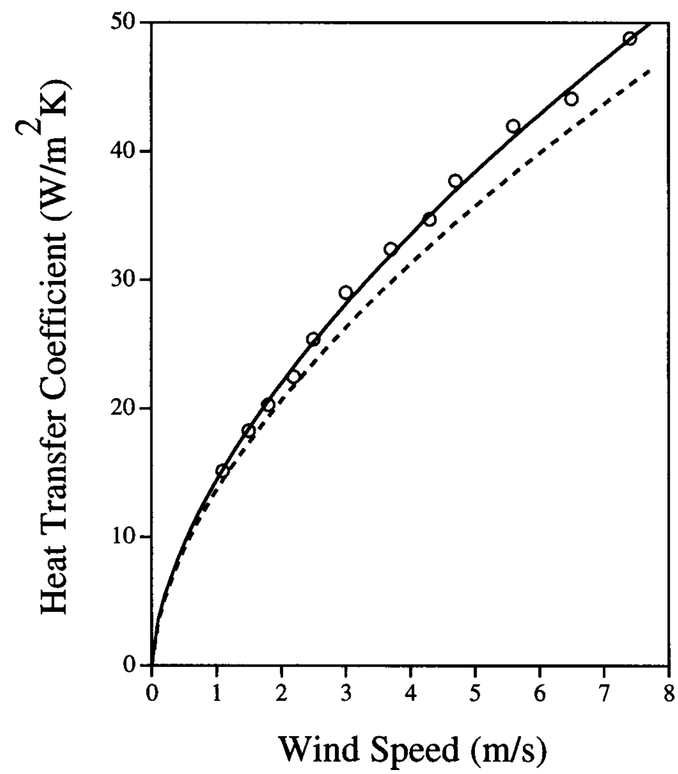

FIG. 1. The experimental values of the convective heat transfer coefficient of the face segment of the thermal simulator are plotted as a function of wind speed. The solid line is the best-fit curve, given by equation 5. The dashed line was calculated for a cylinder of the same diameter as that used by Siple and Passel for their cooling experiment in Antarctica.

Conclusion

Heat transfer from a face looking upwind is affected by wind in much the same manner as heat transfer from a cylinder. Although the cylinder used by Siple and Passel was too small to represent a human body or even a head, it was nearly the perfect size to represent a face in wind.

A MODEL OF FACIAL COOLING

Heat Transfer to the Skin

In wind, the temperature of the skin falls until the heat being lost to the environment equals the heat that is supplied to the skin surface from the body. The heat supplied to the skin surface is limited by the thermal resistance of the skin and underlying tissues and is a function of tissue thickness and blood flow to the skin. Using a small calorimeter, Froese and Burton (1957) found that the thermal resistance of the tissues of the whole head in cold air was constant at 0.068 m^2K/W.

The nose, chin and cheeks are the coldest parts of the face in cold, still air (Edwards and Burton, 1960). Stroud (1990) found that in cold winds, the chin or the cheek was usually the coldest area. LeBlanc et al. (1976) showed that the cheek cooled more quickly than any other part of the face in exposures to a jet of cold air. The cooling of the cheek is therefore likely to be critical to facial comfort and so to the overall sensation of cold. An estimate of the steady-state thermal resistance of the cheek of a sedentary person in the cold was obtained from repeated measurements on a single individual (Osczevski, 1994). The thermal resistance of the tissues of the cheek was higher at low skin temperature, probably because blood flow decreased through the colder tissues. For this individual, the face was uncomfortably cold when the cheek temperature was below 15˚C and was painful when the skin temperature fell below 10˚C. As can be seen in Figure 2, the thermal resistance reached a maximum of about 0.07 m^2K/W when the skin temperature was between 10˚C and 15˚C. This value is very close to Froese and Burton's figure for the whole head. The data suggest that the thermal resistance of cold facial skin might be approximated by a constant value of 0.07 m^2K/W, at least for sedentary individuals. Using the value at the maximum provides a margin of safety, for it will underestimate skin temperatures near the freezing point if, as the limited data seem to imply, the resistance actually decreases near 0˚C.

Radiative Heat Transfer

In addition to the heat carried away by the wind, heat is also lost by radiation. The radiative heat transfer coefficient is given by equation (5), where the skin is assumed to have an emissivity of 1.0. The radiant temperature of the surroundings can be approximated by the air temperature. This will be a better approximation for cloudy, windy conditions than for calm, clear weather. Solar radiation is assumed to be absent, as it was in the winter in Antarctica when Siple and Passel carried out the measurements on which the wind chill index was based. A correction for insolation will be introduced later.

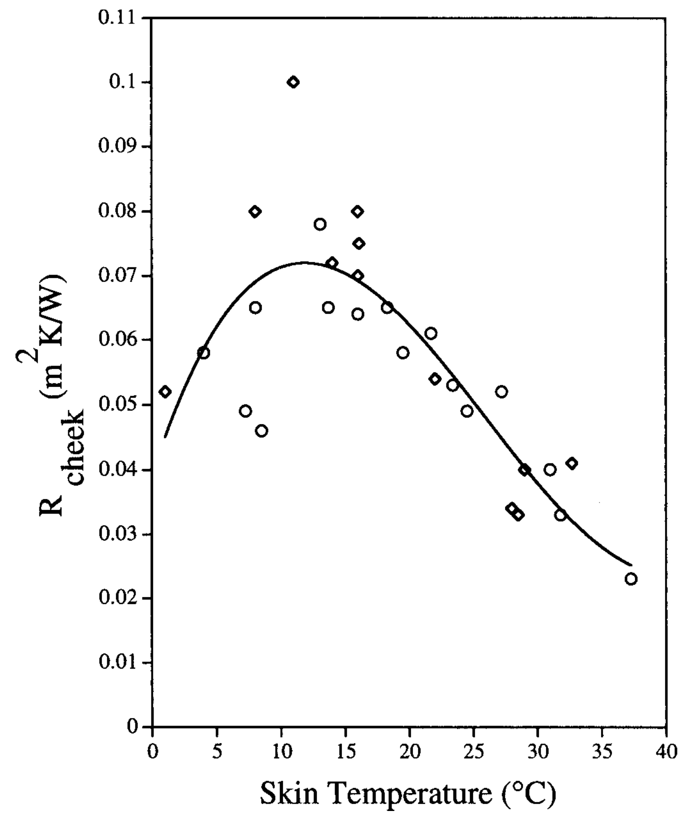

FIG. 2. The thermal resistance of the cheek at a range of skin temperatures. All data are from the same individual. ◇ = data from 1987, ○ = data from 1993.

Evaporative Heat Transfer

Froese and Burton (1957) estimated that evaporative heat loss from the skin of the head was less than 4% of the total heat flow in their experiments. Because temperature greatly affects the rate of diffusion of water vapour through hydrophilic membranes like skin (Osczevski, in press), evaporative heat loss will be even smaller at lower skin temperatures and can be safely ignored.

Steady-State Model of Facial Cooling in Wind

We can now combine the skin and tissue thermal resistance of the cheek with the convective heat transfer coefficients of the face of the thermal head simulator to see how wind speed and air temperature affect cheek skin temperature and heat flow. Assuming a core temperature of 37˚C, the heat flow per unit area, Q, at any given cheek temperature, T_{cheek}, is:

$$Q = \frac{\left(37^{\circ}C - T_{cheek}\right)}{R_{cheek}} \quad \{W/m^2\} \quad (8)$$

R_{cheek} at low skin temperatures is approximately 0.07 m^2K/W. For any wind speed, the air temperature at which this heat flow would occur can be determined from:

$$T_{air} = T_{cheek} - Q \cdot I_a \qquad \{^\circ C\} \quad (9)$$

where I_a is the boundary layer thermal resistance, often referred to as the insulation of the ambient air:

$$I_a = \frac{1}{h_r + h_c} \qquad \{m^2K/W\} \quad (10)$$

and h_r and h_c are given by equations (5) and (4) respectively.

Using equations (4), (5), (8), (9) and (10), the combinations of air temperature and wind speed at which the skin would reach various steady-state temperatures can be calculated. An iterative solution is required, because the air temperature must be known before equation (5) can be used to calculate the radiative heat transfer coefficient, and the radiative heat transfer coefficient must be known before the air temperature can be calculated. A preliminary value for the radiative heat transfer coefficient must be assumed and used to calculate the air temperature using the set of equations.

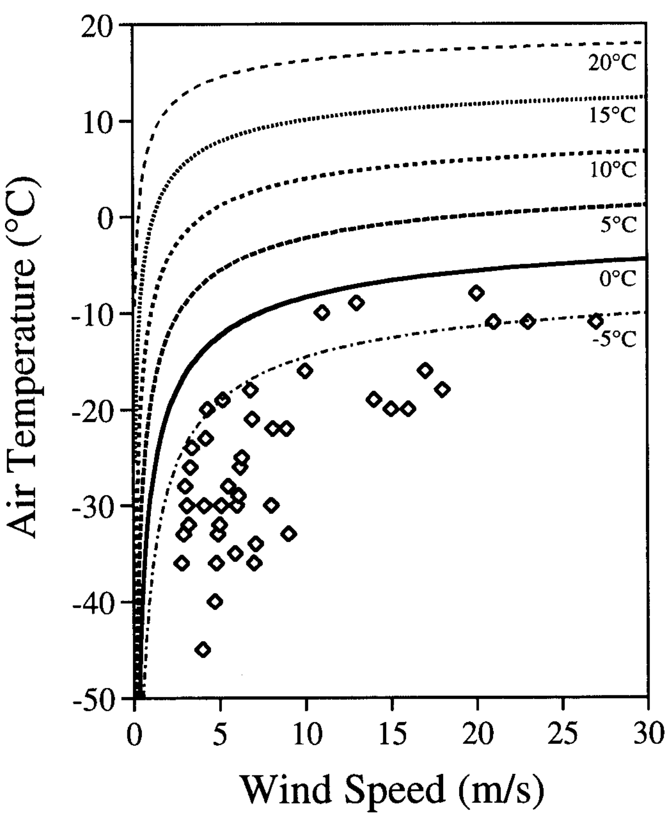

FIG. 3. Skin temperatures calculated from the facial cooling model. The scattered points represent conditions at which frostbite (◇) was reported by Wilson (1964) in the Antarctic.

This value of air temperature is then used to calculate a new radiative heat transfer coefficient, and so on. As there is rapid convergence to a solution, the system of equations may be conveniently solved on a computer spread sheet.

MODEL PREDICTIONS

Skin Temperature

Predicted steady-state skin temperatures over a range of wind speeds and air temperatures are displayed in Figure 3. The isotherms represent points of equal skin temperature. The scattered experimental points represent combinations of wind and temperature at which Wilson (1964) observed frostbite in Antarctica. These points represent mainly frostbite of the face. The upper limit of Wilson's data is of interest. It can be seen that all reported frostbites occurred at calculated skin temperatures below 0˚C, the highest at about -1.6˚C. Skin does not freeze at 0˚C. Keatinge and Cannon (1960) found that for slow cooling, the freezing point of finger skin was -0.5˚C. Wilson (1973) found that when the skin of the finger was cooled by wind, its freezing temperature was about -2.5˚C. Supercooling, sometimes by tens of degrees, usually preceded freezing in Wilson's experiments.

Heat Flow and Wind Chill Index

The model was also used to calculate the heat loss from the cheek over the range of wind speeds from 1 to 24 m/s at 5˚C increments of air temperature. The same data were also used to calculate values of the wind chill index, for comparison. At air temperatures between -40˚C and 0˚C the wind chill index was found to be a multiple of the predicted heat flow, in $kCal/m^2h$, minus a number that was a function of the air temperature:

$$WCI \approx 4.2Q - f(T_{air}) \qquad \{kCal/m^2h\} \quad (11)$$

Wind Chill Index, Cheek Skin Temperature and Comfort

Each point on an isotherm in Figure 3 represents a wind speed and an air temperature at which a particular skin temperature can be expected. Using equation (2), each pair of coordinates can also be used to calculate a wind chill index. The curves in Figure 3 can therefore be translated to wind chill values associated with a particular cheek temperature. Figure 4 depicts this transformation. It can be seen that any cheek skin temperature is produced by a narrow range of values of the wind chill index, which explains why Siple and Passel found that certain values of the wind chill index were associated with specific sensations of thermal discomfort.

Skin temperature can be roughly related to the average wind chill for each isotherm. The correlation of cheek temperature and the mean wind chill index of conditions that produce it is excellent ($R^2 > 0.99$). The relation can be represented by:

$$T_{cheek} = 33.7 - 0.026 \cdot \overline{WCI} \qquad \{^\circ C\} \quad (12)$$

In Table 1, equation (12) was used to find the cheek temperatures that correspond to discomfort boundaries defined by wind chill index values. These subjective boundaries are somewhat controversial (Rees, 1993) and probably vary from individual to individual.

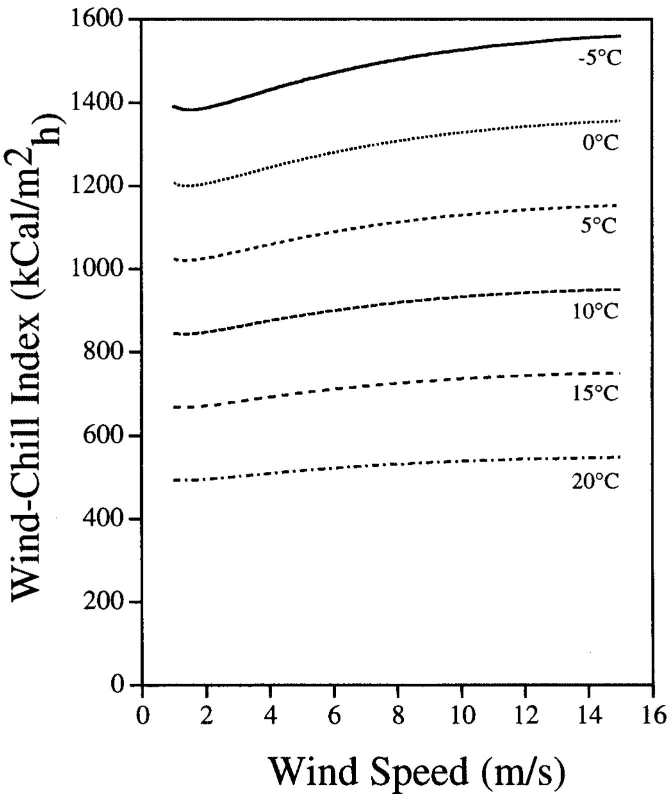

FIG. 4. The coordinates of points on the isotherms of Figure 3 have been converted to values of the wind chill index. Each facial skin temperature is associated with only a narrow range of values of the wind chill index.

TABLE 1. Some cold discomfort boundaries.

Discomfort Descriptor	Wind Chill Index kCal/m²h	T_{cheek} Equation (12)	T_{eq} Equation (13)
Cold	800	+13.0˚C	-0.9
Very Cold	1000	+7.7˚C	-9.3
Bitterly Cold	1200	+2.5˚C	-17.5
Exposed Flesh Freezes	1400	-2.7˚C	-25.7

Equivalent Temperature

An equivalent temperature can be defined as the temperature at which the heat transfer from the face would be the same if there were no wind. It is:

$$T_{eq} = 37 - \frac{Q}{h_{ref}} \qquad \{^\circ C\} \quad (13)$$

where h_{ref} is the core to air heat transfer coefficient at 1.78 m/s (4 mph), and is equal to:

$$h_{ref} = \frac{1}{0.07 + I_{ref}} \qquad \{W/m^2K\} \quad (14)$$

where I_{ref} is I_a in equation (10) evaluated using the usual minimum wind speed of 1.78 m/s (4 mph). Between +10˚C and -40˚C h_{ref} varies by less than 2% from a mean value of 9.05 W/m²K.

The equivalent temperature that corresponds to any given cheek temperature can be determined by substituting equation (8) for the Q in equation (13).

$$T_{eq} = 37 - \frac{37 - T_{cheek}}{R_{cheek} \cdot h_{ref}} \qquad \{^\circ C\} \quad (15)$$

This equation was used to calculate the equivalent temperatures at the critical cheek temperatures for discomfort. These critical equivalent temperatures are listed in Table 1.

Sunshine

According to Siple and Passel (1945), the effect of bright sunshine is equivalent to a decrease of 200 kCal/m²h in the wind chill index. At any air temperature, its effect on equivalent temperature can be approximated from equation (16), which was derived by differentiating equations (11) and (13) with respect to Q:

$$\Delta T_{eq} = -\frac{1.16}{h_{ref}} \cdot \frac{\Delta WCI}{4.2} \qquad \{^\circ C\} \quad (16)$$

The factor of 1.16 is introduced to convert wind chill index units to SI units of W/m². A change of -200 kCal/m²h due to bright sunshine is equivalent to an increase of 6˚C (10˚F) in equivalent temperature. This is of the same order as the solar increments of 2.4˚C to 7.4˚C predicted by Steadman (1984) for a clothed individual.

DISCUSSION

The Cylinder Wall

The large factor by which the wind chill index exceeds the heat transfer from a face does not derive from the size of the cylinder Siple and Passel chose for their experiments, for it was almost the perfect size to simulate heat loss from a face in a frontal wind. A large part of the error must derive from the slight thermal resistance of its wall. It was made of Pyralin, which is cellulose nitrate. The thermal conductivity of this material ranges from 0.13 to 0.23 W/m K (Hodgman, 1953). Given that the cylinder wall was 3.2 mm thick, it must have had a thermal resistance of between 0.014 and 0.024 m²K/W. To adequately simulate human tissues, which for the cold cheek of a sedentary individual have a thermal resistance of about 0.07 m²K/W, the cylinder wall should have been three to five times as thick.

Thermal Discomfort and Wind Chill

The boundary of "Cold" corresponds to a cheek temperature of 13˚C. This is close to the temperature of 15˚C or 16˚C at which the face has been reported to feel uncomfortably cold (LeBlanc et al., 1976; Osczevski, 1994; Virokannes and Anttonen, 1994). “Very Cold” appears to correspond to a cheek temperature of 8˚C, at which facial skin is reported to become numb (Virokannes and Anttonen, 1994) and which is just below that at which facial skin has been observed to be painful (Osczevski, 1994). These sensations are apparently felt on the face at lower skin temperatures than they are on other parts of the body, and may vary between individuals.

The least subjective calibration point for the wind chill index is the frostbite value, 1400 kCal/m^{2}h. At the frostbite limit, equation (12) yields a steady-state cheek temperature of -2.7˚C, which is just below the freezing point of skin in wind according to Wilson’s (1973) experiments. Because the predicted comfort boundary temperatures correspond relatively well to published estimates, the value of tissue thermal resistance used by the model must be close to a mean value for the general population.

Equivalent Temperature

Wind chill equivalent temperatures have superseded the numerical values of wind chill index in most areas of the world. Unfortunately, they have usually been miscalculated and misunderstood (Kessler, 1993). Wind chill equivalent temperature is said to be the temperature at which it would feel as cold in the absence of wind. Just what would feel as cold has not been addressed, for all parts of the body are not equally exposed to the weather. Actually, equivalent temperatures have always referred to the cooling rate of the plastic bottle and only indirectly to human comfort.

Early attempts to define the equivalent temperature referred it to a zero wind speed. This resulted in equivalent temperatures that were obviously incorrect. Rationalizing that there is always some air movement outdoors and that people are rarely still, Eagan (1964) defined “calm” as 4 mph (1.78 m/s). This yielded equivalent temperatures that seemed more reasonable. In many areas of the world, equivalent temperature is calculated using a minimum wind speed of 5 mph (2.2 m/s). This is said to be walking speed (Dixon and Prior, 1987), but it seems rather brisk for most people.

As Steadman (1971) pointed out, a major error in many calculations of equivalent temperature stems from using wind speeds directly from official weather reports. Official wind speeds are measured by an anemometer at the top of a 10 m high mast, or are corrected to represent the wind at that height (Buckler, 1969). As anyone who has had to run to launch a kite knows, the wind at 10 m is usually stronger than it is at ground level where people normally experience it. Since Siple and Passel derived their formula using measurements of wind speed at the same height as their cylinder, a correction must be applied to scale the winds at 10 m down to the wind at face level before any equation or model of wind chill can be used correctly.

In a flat, open area, the correction to scale the wind at 10 m, V_{10}, to any height, y, in metres, was reported by Steadman (1971) to be:

$$\frac{V}{V_{10}} = \left(\frac{y}{10}\right)^{0.21} \qquad (17)$$

If the mean height of the average adult’s face can be taken as 1.5 m, the wind at that level in an open area is 67% of the reported wind speed at 10 m. In general, this correction depends on the scale of surface roughness and the temperature gradient near the ground (Geiger, 1971). Forests and urban settings have high values of “roughness” and necessitate larger corrections of airport wind speeds. Studies suggest that in parks, urban areas or forests, the face-level wind speed might be only 10% to 30% of the reported speed (Danielsson, 1993).

Equivalent Temperature Charts

The facial cooling model was used to recalculate the equivalent temperature charts. The new charts, in metric and English units, are shown in Figures 5 and 6. The wind speed was scaled to average face height by a conservative factor of 0.67 before the calculation was carried out. The charts can be used with winds measured at face level if those speeds are first increased by 50%. Isotherms of equivalent temperature are included. For continuity, these lines bear the original wind chill index numbers. The new equivalent temperatures are significantly higher than the old ones, especially at the high ends of the temperature and wind scales. For instance at -15˚C and 30 km/h, the old equivalent temperature was -35˚C while the recalculated value is -25˚C, and the fearsome wind chill equivalent temperature of -100˚F by the old scale is “only” -70˚F by the new.

A windproof outer clothing shell greatly reduces heat loss when it is windy and cool by keeping the cold wind out of the clothing insulation. However, because it has little intrinsic insulation value, it does next to nothing to the heat loss at the same equivalent temperature when it is nearly calm but very cold. When the same clothing is worn, cold but calm conditions should therefore feel colder to the protected areas of the body than cool and windy conditions even though the equivalent temperature might be the same. Equivalent temperatures apply only to the sensation of cold as felt by the face of an appropriately clothed person. They are not a reliable indication of how much insulation thickness one should wear to prevent uncomfortable cooling. Like the wind chill index, the facial cooling model cannot be used to predict hypothermia, whole-body heat loss, or frostbite on other body areas. It should be noted that cold injury can be caused by direct contact of exposed skin with a cold surface at any air temperature below freezing.

Comparison with Other Models of Heat Loss in Wind

In Figure 7 the heat loss predictions of the facial cooling model are compared to the wind chill index and two other models of wind chill at an air temperature of -15˚C. The best that a very strong wind can do is to strip off all of the insulation of the external boundary layer of air so that the skin cools to the air temperature. Because the thermal resistance of

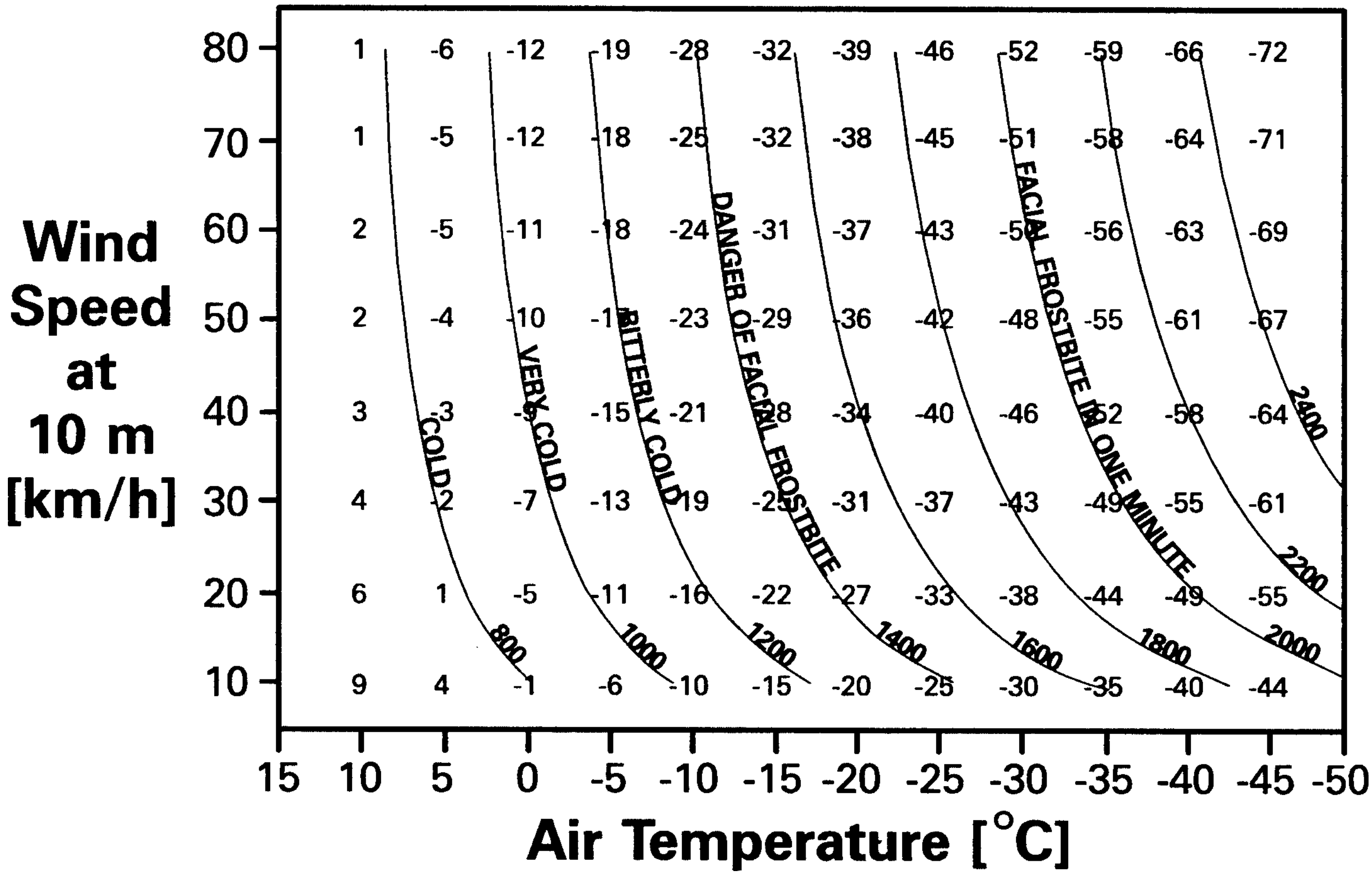

FIG. 5. Wind chill equivalent temperatures in °C, calculated at face level, using the facial cooling model. The curves are lines of constant wind chill index, which are also isotherms of equivalent temperature. Values of the index are noted on the tail of each curve, using the original notation, without units. Wind speeds are those measured at the standard height of 10 m. Increase wind speeds measured at face level by 50% before using the table. In bright sunshine, add 6°C to the equivalent temperature.

the tissues is constant, the curve for the facial cooling model flattens out at higher wind speeds. According to this model, at -15°C heat loss is limited to 740 W/m^2 by the thermal resistance of the cheek.

Although the wind chill index is of a different magnitude, it follows a pattern that is similar to the facial cooling model up to about 25 m/s. However, at higher wind speeds the heat transfer decreases, which is not physically realistic. Purely empirical equations often do not give the correct result outside the range of the data from which they were created. Siple and Passel circumvented this difficulty by limiting the calculation to lower wind speeds and stating that higher wind speeds do not greatly increase the wind chill. Although some have found this claim objectionable (Steadman, 1984), it is consistent with the theory that the primary cooling effect of wind is to erode the boundary layer over bare skin. The facial cooling model has also been extrapolated; however, 80% of the maximum effect of wind will have been felt by the time its experimental base has been exceeded.

The curve marked Steadman I in Figure 7 is the non-evaporative, bare-skin heat loss prediction of Steadman's 1971 model. In this model, the heat transfer continues to increase without limit, almost linearly with wind speed. This is clearly incorrect and stems largely from Steadman's assumption of a constant temperature of 30°C for bare skin. Steadman later revised his model, adopting a constant core temperature instead (Steadman, 1984).

The heat loss from bare skin in Steadman's newer model, Steadman II in Figure 7, decreases sharply with increasing wind speed. This is because the resistance to heat transfer includes the thermal resistance of the tissues, which does not change. Because Steadman's second model assumes a value of only 0.04 m^{2}K/W for the thermal resistance of cold skin, its maximum heat loss at -15°C is 1300 W/m^2. Cheek skin temperatures are also higher than those calculated by the facial cooling model. For example, at 11 m/s and -10°C, the facial cooling model predicts a skin temperature of -1.6°C while Steadman's model predicts +5.5°C. Since these conditions produced frostbite in Wilson's survey, the skin temperature and heat flow predictions of Steadman's model must be considered too high for relatively sedentary individuals.

Cheek skin temperatures are higher when individuals exercise in the cold (Beynon, 1973), suggesting that the effective thermal resistance of the tissues must be lower. Steadman's model may be more appropriate to exercising individuals. Otherwise, the two models respond similarly to increasing wind. If, as in Figure 7, we were to use 0.07 m^{2}K/W for the thermal resistance of the tissues in Steadman's second

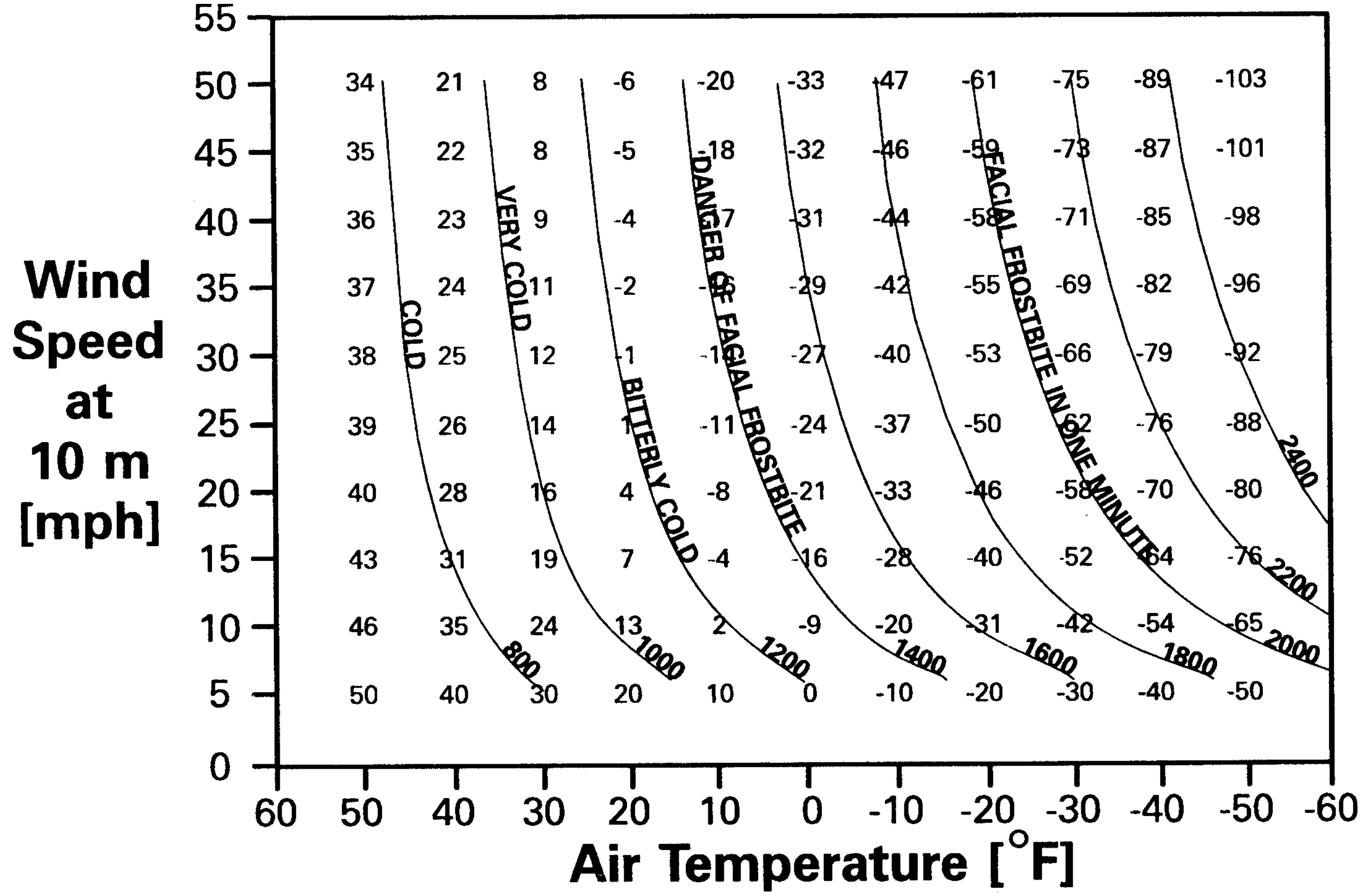

FIG. 6. Wind chill equivalent temperatures in °F, calculated at face level, using the facial cooling model. The curves are lines of constant wind chill index, which are also isotherms of equivalent temperature. Values of the index are noted on the tail of each curve, using the original notation, without units. Wind speeds are those measured at the standard height of 10 m. Increase wind speeds measured at face level by 50% before using the table. In bright sunshine, add 10°F to the equivalent temperature.

model, it would predict heat losses at all wind speeds that are close to those predicted by the facial cooling model. Obviously, the value chosen for tissue thermal resistance is critical.

The Saskatoon Study of Wind Chill and Thermal Sensation

In a classic paper, Currie (1951) reported on the daily cold sensations of 70 individuals during two winters in Saskatoon, a city on the Canadian prairies. Most of the subjects were first-year meteorology students and indoor workers who noted their thermal sensations each morning while waiting for the bus or while walking to work or to classes at the university. The wind speed and temperature were measured at the university weather station. Thermal sensations were plotted on a chart of wind vs. temperature using different coloured dots to represent the different sensations. Isopleths, or lines of constant sensation, were then drawn by inspection.

Surprisingly, Currie found that the sensations of cold did not correspond to consistent values of the wind chill index. Also, they seemed to be more sensitive to wind velocities above 9 m/s (20 mph). This was unexpected as the wind chill index is less sensitive to changes in wind speed at higher wind velocities. Currie explained that the stronger winds produced greater cooling because they penetrated clothing to a greater extent. Critics (Steadman, 1971; Dixon and Prior, 1987; Rees, 1993) have used this finding to attack the contention that wind chill is almost independent of wind speed in strong winds.

A different explanation is suggested by the fact that most of the observations occurred in the early morning. Sensations might not have corresponded to consistent values of the wind chill index because the ratio of the wind speed at face level to the wind speed recorded at 10 m was not constant. This ratio depends on whether or not the air in the lowest 10 m is stably stratified with respect to air temperature (Geiger, 1971). When there was a stable inversion, as would often have been the case when Currie's students were on their way to morning classes, winds at face level would have been a smaller fraction of the wind at the standard measurement height than in normal conditions. Because temperature inversions and high winds are mutually exclusive, when it was windy the ratio would have been higher. Thermal sensation might have been more sensitive to wind at higher wind speeds because a bigger fraction of a stronger wind was felt at face level, not because it was disproportionately more able to penetrate the clothing.

The sensation of "Cold" appears to have been easily recognized by Currie's subjects. When the coordinates of points taken from the isopleth for Cold are used in the model, it predicts cheek temperatures ranging from 2°C to 7°C. These are significantly lower than the 13°C that should be expected for that sensation according to Table 1, for the facial cooling model uses a scale factor of 0.67, which is appropriate to an open area. Since a university campus, with its large buildings and park-like open spaces might be considered something between a city centre, which would have a scale factor of 0.1 (Danielsson, 1993), and an urban park, where the scale factor would be 0.3 (Danielsson, 1993), a value of 0.2 might be more appropriate. With this change, the model predicts skin temperatures ranging from 6°C to 10°C. Because the model represents a worst case of continuously facing the wind for an extended period of time, it predicts lower skin temperatures than would result from routine exposures.

The Saskatoon study indicates that the discomfort or hazard associated with routine exposures of individuals in an urban setting will be smaller than that predicted by the calculated equivalent temperatures of Figures 5 and 6. The conservative scale factor of 0.67 used in making those figures provides a considerable margin of safety for city dwellers.

CONCLUSIONS

For clothed individuals, wind chill is primarily caused by the local cooling effect of wind on the bare face. Siple and Passel (1945) used a cylinder of the appropriate dimensions to simulate this cooling, but because its plastic wall was too thin to adequately represent human tissues, their wind chill index was much larger than the heat transfer from a face.

The original wind chill experiments were carried out under difficult conditions. They were of necessity crude, and were imperfectly analyzed. However, the wind chill index that resulted worked because any value was associated with a narrow range of facial skin temperatures and therefore a narrow range of sensations of cold. Although the numbers were not representative of heat transfer from the human body, they were roughly proportional to facial heat transfer. They could be calibrated against cold sensation, which appears to be related to facial skin temperature.

The old wind chill index has value as a scale of unitless numbers with descriptors for general guidance. People can personally calibrate the scale with experience. Although it has been somewhat vindicated by this study, the classic wind chill index formula still has its faults. It may be time to bury the wind chill index rather than to praise it. In most of the world it has been dead for many years, succeeded by improperly calculated and misleading wind chill equivalent temperatures.

Calculation of wind chill is complicated by the effects of terrain and temperature structure on the relation between the wind at measurement height and that experienced at face level. Exposure time is also a factor, for the sensation of discomfort depends on skin temperature, which may take up to an hour to reach its lowest value. Avoidance of cold, variations in physiology and the degree of acclimatization may also be confounding factors. However, the facial cooling model of wind chill can be used to make a worst-case estimate of heat transfer and skin temperature. It can also be used as a rough guide to predicting cold discomfort and the risk of facial frostbite.

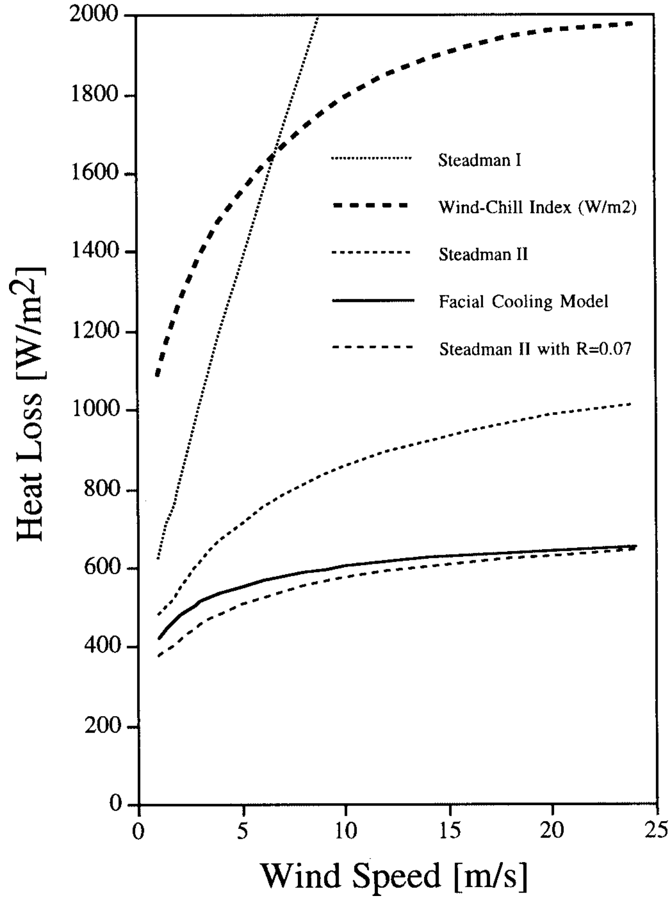

FIG. 7. Comparison of models of the effect of wind on the heat lost from bare skin.

Although the worst-case equivalent temperatures calculated from the facial cooling model of wind chill are as much as 20°C (36°F) higher than the old ones, they still exaggerate the thermal discomfort that most individuals will experience in routine exposures. It would seem that winter may not be as cold as previous wind chill calculations have led us to believe, which should be good news to many.

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