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Understanding Windchill

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Introduction

Everyone knows that it feels colder when the wind blows. Efforts to quantify this effect began early in the 20th century and continue to the present day. The most widely used and the most successful ways of characterising cold weather have been based on the windchill index, developed by Paul Siple in Antarctica in 1941. Despite its success and wide acceptance by the public, Siple's windchill index has been harshly criticised by experts over the years.

The experiments on which the windchill index was based were designed around the idea that the sensation of windchill was due to the cooling of unprotected skin. Recently, it has become possible to estimate heat loss in wind through clothing, with the assistance of mathematical models and computers. This has given rise to the idea that the effect of cold and wind should be determined from a consideration of whole body heat loss. The most widely touted calculation of this kind expresses the effect of wind and temperature as an Apparent Temperature (Steadman, 1971, 1984)

In this paper, we will examine the question of whether windchill should be calculated as an effect of exposed skin heat transfer or of whole body heat loss. Also, we will describe a test of the usefulness of any index of windchill and apply it to three proposed indices.

The Boundary Layer, Convective Cooling and Windchill

To understand windchill, some appreciation of the concept of a thermal boundary layer is essential. As it is not an obvious concept, some simple explanation is in order. If you dive into the ocean and come back out again, a thin layer of water will adhere to your skin. We live in an ocean of air, and air, like water, can be said to "wet" the skin or any other object that is immersed in it. Right at the surface of the skin, the adhering air is still. Because air has some internal stickiness or viscosity, there is drag between the adhering air and the air molecules farther away from the skin. As a result, next to the skin or any surface there is a zone of relatively still air that may be a few millimetres thick. The air in this layer is not as mobile as the air a few centimetres away. This is the boundary layer.

The boundary layer insulates your skin from the environment. If you blow on your arm, it can feel cool even though your breath is relatively warm because you have blown away the warm boundary layer air that was insulating the skin. If you do the same experiment in a hot sauna, instead of feeling cool, the spot you blow on can feel painfully hot, because you have blown away the boundary layer of sauna air that had been cooled by the skin and allowed the heat of the sauna to reach the skin more easily.

In a perfect calm, if free convection could be suppressed, the boundary layer is infinitely thick. It would not really exist as a layer. Add a wind, and the only still air that remains would be the air in the immediate vicinity of some surface, like the skin. The stronger the wind, the thinner the layer. Because the outer layers of still air are blown off more easily than the ones closer to the skin, a small increase in wind speed when it is nearly calm causes a much greater decrease in boundary layer thickness than the same increase in wind speed when the wind is already strong.

The insulation of the boundary layer depends on its thickness. Convective heat loss is really conduction, through an insulating boundary layer. When there is wind, the thermal resistance of the boundary layer is smaller, the heat loss is higher and the temperature of the skin is closer to the air temperature. Humans do not sense the temperature of the air. When we feel that it is cold outside, we are actually sensing the temperature of our skin. Because our skin temperature is lower when it is windy, we feel that it is colder when it is windy. That, in a nutshell, is windchill.

Siple's Windchill Index

The term "wind chill" was first used in Paul Siple's 1939 PhD dissertation on the adaptation of antarctic explorers to cold. He proposed a simple formula combining wind speed and temperature to give an index that he thought would be proportional to the severity of the weather. However, when he returned to Antarctica in 1940 and tried to use his index, he discovered that combinations of wind and low temperature that produced the same index value did not always produce the same degree of cold discomfort. As he couldn't find a simple mathematical way to combine wind and temperature, he decided to seek guidance from experiments.

Siple set up a simple experiment on the roof of one of the expedition buildings, using left-over equipment from other scientific programs (Siple and Passel 1945). From the rate at which water in a small cylinder froze when hung outside the expedition building, they determined what they called "wind chill factors" for each experiment. These were overall heat transfer coefficients. They related their windchill factors (WCF) to the wind speed (V) by a simple mathematical formula.

$$WCF = \sqrt{V \times 100} + 10.45 - V$$

Siple's windchill factors depended primarily on the thermal resistance of the boundary layer and the thermal resistance of the cylinder wall. A recent attempt to model their experiment (Danielsson 1996)concluded that the thermal resistance of the ice in the cylinder had only a small effect on the results.

Siple then added the effect of air temperature, T_a, in the "Wind Chill Index", K_0.

$$K_0 = WCF \times (33 - T_a)$$

The "33" is an assumed mean skin temperature. It really should be a core temperature of 37 °C because of the way the experiment was designed. The windchill index characterised the combined effect of wind and cold temperatures in a three or four digit number.

To test his new index, Siple compared it with previously published (Gold 1935) information on human thermal sensation and comfort in the cold . He also asked field parties to keep track of their cold discomfort and the weather conditions (Siple and Passel 1945). Further, in conjunction with the expedition medical officer, he asked members of the expedition to face cold winds for extended periods of time, sometimes until frostbite appeared on their faces (Frazier 1945). Siple found that any value of the windchill index consistently produced approximately the same level of cold discomfort, regardless of how wind and temperature had been combined to create it. This convinced him that he had found a useful formula.

Over the years, many experts have strongly criticised the design of the windchill experiment and the way the data was analysed (Molnar 1960; Steadman 1971; Kessler 1993; Brauner and Shacham 1995; Danielsson 1996; Bluestein 1998). One major criticism has been that the cylinder they used had a much smaller diameter than the average diameter of a human being, or head. Also it seemed odd to assume that the skin temperature was a constant 33 °C when it might be freezing. Despite such criticisms, the fact remained that the windchill index worked. One critic 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 (Burton and Edholm 1955).

DCIEM Facial Cooling Model

A mathematical model of the cooling of a face in wind suggests why Siple's windchill index works. The facial cooling model was based on the experiments with the face of a thermal manikin head in wind. This was combined with a model of how heat is transported from the body core to the skin.

In the original model (Osczevski 1995), the thermal resistance of the tissues of the face was assumed to be constant at the maximum value measured in physiological experiments (Osczevski 1994). A recent revision calculates the thermal resistance of the tissues of the face as a function of the cheek skin temperature, using a quadratic equation fitted to the previously published data (Osczevski 1994). The regression equation was extrapolated to a skin temperature of –5 °C. At skin temperatures below this value, the thermal resistance is assumed to be constant at the –5 °C value.

Wind speed is normally measured at 10 m, or corrected to that standard height. Anyone who has run to launch a kite that stayed up once it gained a few metres of altitude knows that the wind up there is stronger than the wind below 2 m, where most of us experience it. This is an effect of the Earth's boundary layer. The DCIEM facial cooling model uses a correction factor of 0.67 to calculate the wind at face height from the wind at standard height. This factor is an average for open land. In residential areas, the factor is generally smaller. It is not constant from day to day or hour to hour in the real world. When we are on our way to work on cold winter mornings, the air is often stratified and stable. Less than the average fraction of the measured wind speed is felt down where we are. If it is stormy, the air in the lower 10 metres of the atmosphere is mixed and the wind at our level is a bigger than average fraction of the wind measured on the tower at the airport. Ideally, wind speed should be measured at face height when it is to be applied to windchill.

The model predicts that each value of the windchill index will produce a narrow range of facial skin temperatures. Because facial skin temperature and thermal comfort are related, the windchill index values are related to consistent levels of thermal discomfort. Thus the windchill index works because any combination of wind and temperature that produces a particular value of the index also produces a consistent skin temperature on the exposed skin of the face.

The sensation of cold on the face can have a disproportionately large effect on the overall sensation of discomfort (Cabanac 1979; Nielsen 1987, Maidment 1994, Nadel 1973). The hazard of windchill, if not the sensation, is due to the temperature of the skin on the most exposed part of the body. This is very often the face. In the worst case, which is the one we are most interested in, a person will be facing the wind. Even in calm conditions, he or she may be producing a relative wind by walking, skiing, or driving an open vehicle such as a snowmobile.

In Siple's tests, his subjects were adequately clothed with only their faces exposed. Their cold discomfort probably had much more to do with facial cooling than with whole-body cooling. Although pedestrians are normally not as well protected from the cold as the explorers who validated the windchill index, they seem to have found the index to be useful in forecasting their discomfort. This suggests that even in normal conditions, windchill is related largely to the cooling of faces.

The model confirms this. Conditions perceived as "Cold" have been reported at windchill index values of about 750 $\mathrm{kcal/m^2h}$ (870 $\mathrm{W/m^2}$) (Siple and Passel 1945). The revised facial cooling model says that winds and temperatures that produce this windchill index will result in a skin temperature of 14 ± 0.7 °C. This agrees with observations that facial skin feels the sensation identified as "Cold" when its temperature reaches 15 °C (LeBlanc 1976; Osczevski 1994).

Also, conditions that combine to produce a windchill index of 1400 $\mathrm{kcal/m^2h}$ (1625 $\mathrm{W/m^2}$), which Siple identified as the limit at which frostbite sometimes occurs, produce facial skin temperatures in the revised model of −1.2 ±0.5 °C, which is about the freezing point of human skin (Keating 1960; Wilson 1973).

Wind affects the convective heat transfer from a face in much the same way as it does the heat transfer from a cylinder of the size of the one used by Siple and Passel (Osczevski 1995). Therefore, although Siple's cylinder was much smaller than the one that many of his critics might have preferred he'd used to model convection from a human in wind, because he made it so small, it was about the right size to model heat transfer from a face looking upwind.

The critics made the error of assuming that a whole cylinder is the appropriate model for windchill calculations when it seems that just the windward side of the cylinder is a better choice. Wind not only has a greater cooling effect on cylinders of small diameter, but also on the upwind side of cylindrical objects (Achenbach 1975). Heat transfer from the upwind side of a head-sized cylinder is very similar to the heat transfer from a face in wind (Osczevski, unpublished) and from Siple's cylinder.

Apparent Temperature

Apparent Temperature, or AT, is an index of the severity of the weather calculated from considerations of whole body heat loss (Steadman 1971, 1984, 1994). It is determined from the thickness of clothing required to maintain thermal equilibrium at the prevailing wind speed and air temperature. Adequate clothing, with a wind resistant cover, is assumed. AT is the air temperature that would be required to maintain thermal balance, if the wind were to drop to zero while wearing the same clothing as in the wind.

As it would seem that AT strictly applies only to people wearing adequate clothing, it is fair to ask if people normally dress for weather conditions. It seems likely that many do not, relying instead on behaviour, such as limiting their degree or length of exposure, to compensate for any clothing inadequacy. People tend to wear seasonal outfits that they do not vary significantly in response to weather conditions (Hori-Yamagishi 1994).

During the 1957-58 Trans Antarctic Expedition, Rogers looked for evidence of acclimatisation to cold by taking note of the clothing worn by expedition members and the weather throughout the expedition (Rogers 1971; Rogers 1973). The expedition members had daily access to a wide range of clothing and could wear whatever they thought was appropriate. After the expedition, the thermal insulation of some of this clothing was measured on a manikin. A re-analysis of the data reveals an interesting trend. The members of the expedition did vary their clothing insulation in response to the weather, but not continually as was expected. Instead, they varied their clothing insulation in a stepwise manner as shown in Figure 1.

The single step occurred at a temperature of about −18 °C, which is of course, zero degrees on the Fahrenheit temperature scale. On either side of the transition, the clothing insulation is, by and large, independent of the mean daily air temperature. The expedition members therefore had two basic levels of thermal protection, one for cold weather and one for "sub-zero" weather. It seems that even polar explorers do not dress for the weather to any great extent. This suggests that AT might not be appropriate, much of the time.

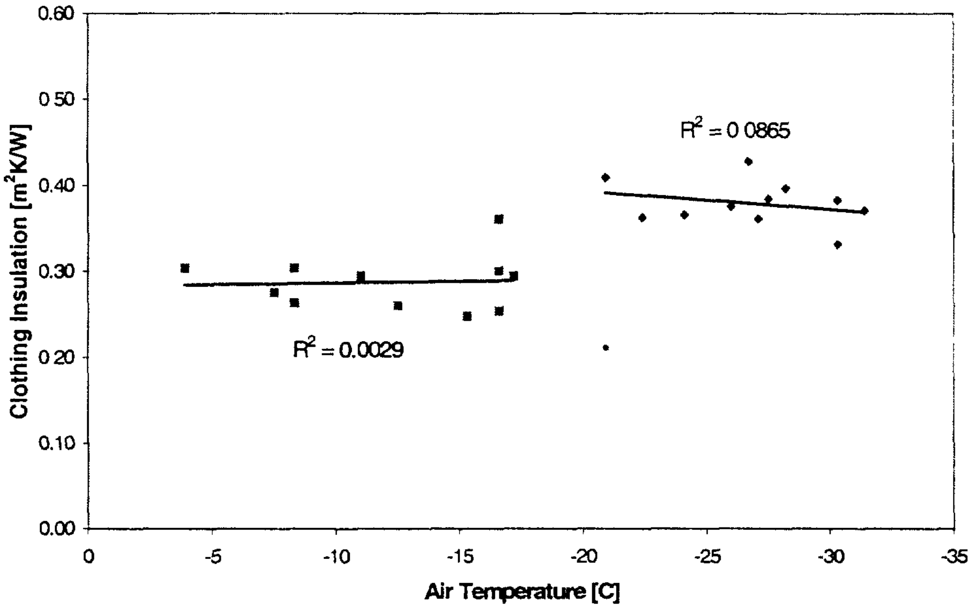

Figure 1. Clothing worn by a number of individuals on an Antarctic expedition revealing a step-wise relationship with mean daily air temperature. One point was ignored as it is clearly an anomaly.

A Test of Utility

Any index of the combined effect of cold and wind can only be said to work if it consistently has the same value in all sets of conditions that produce the same level of discomfort, hazard or sensation. Another way of stating this is to say that any value of a proposed index must be associated with one, and only one, level of discomfort. An index would not be very useful if any value could be associated with two or more different levels of hazard or sensation in cold and wind; we would not know which to expect.

In Figure 2, the Steadman AT (Quayle and Steadman 1998) and the windchill equivalent temperature, Teq, calculated from the revised facial cooling model, are presented for sets of wind and temperature that produce three different levels of sensation or hazard. Siple's windchill equation was used to find the air temperature that must be combined with any wind speed to create the windchill index associated with a particular sensation or level of hazard.

A valid index of human sensation in cold and wind should appear in Figure 2 as a horizontal line. The sensation of "Cold" has been associated with a windchill index of 750 original windchill units. At winds and air temperatures that produce this sensation, both AT and Teq are approximately the same, about 0 °C, and both are approximately constant over the range of wind speeds. AT can be calculated at lower air speeds than Teq, but below about 2 m/s (4.5 mph) AT begins to depart significantly from its nearly constant value at higher wind speeds.

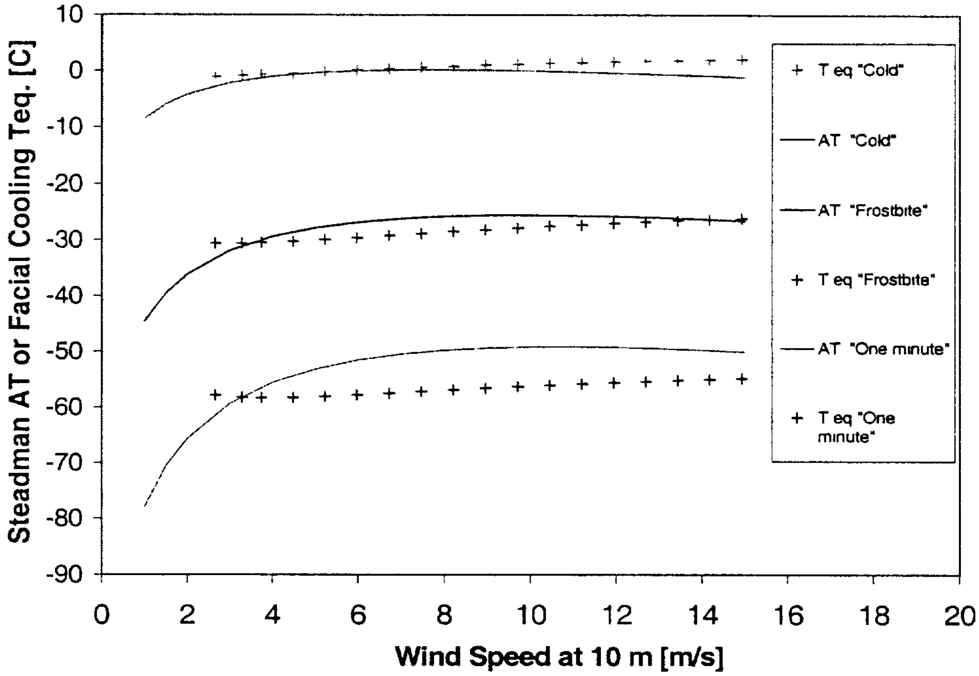

Figure 2. A test of AT and Teq

In conditions that Siple associated with the risk of frostbite, Teq has a fairly constant value of –28 °C ± 2 °C (S. D.). However, AT only has an approximately constant value at wind speeds above about 5 m/s (10 mph). The problem with AT is even more obvious in conditions where frostbite would occur in one minute. AT fails the test at wind speeds below about 6 m/s (13 mph). In contrast, Teq remains relatively constant at –57 °C ± 1 °C over this range of wind speeds.

Theoretical Considerations

Conditions that feel the same should always be described by the same number, whatever index is being used. This is true whether the sensation has been produced by high winds and a relatively warm temperature, or nearly calm winds and a much lower temperature. Elementary theoretical considerations suggest that an index based on clothed, whole body heat loss, such as AT, cannot pass this test in the cold.

For example, on a windy day, at a temperature above freezing, a fleece track suit covered by a windproof nylon jacket and trousers might be adequate clothing. However, the same windchill index can also be produced by a much lower temperature and almost no wind. Although a windproof nylon layer provides very good protection against heat loss when it is windy, it has very little protective value when it is almost calm.

Conditions that produce the same windchill index feel about the same, as Siple and decades of general use have shown. These two situations should therefore feel the same. Teq would be almost the same for the two conditions and the exposed skin would be cooled to the same temperature. However at the lower air temperature with little wind, the individual would probably have to wear thicker clothing beneath his or her windproof layer to limit the heat loss to the same value. This means that the Apparent Temperature would be much lower. Thus conditions that feel the same can have different Apparent Temperatures and conditions with the same Apparent Temperature can feel different. This would be confusing.

Unless the index values form perfect horizontal lines in Figure 2, any y-axis value will be associated with more than one level of discomfort. For Teq, calculated from the revised facial cooling model, the lines are almost horizontal so that only a narrow range of sensation or hazard is associated with any value of Teq. If intermediate sensation lines had been plotted in Figure 2, it would be apparent that any value of AT can be associated with more than one level of discomfort or hazard. This is easier to see in the next example, in Figure 3.

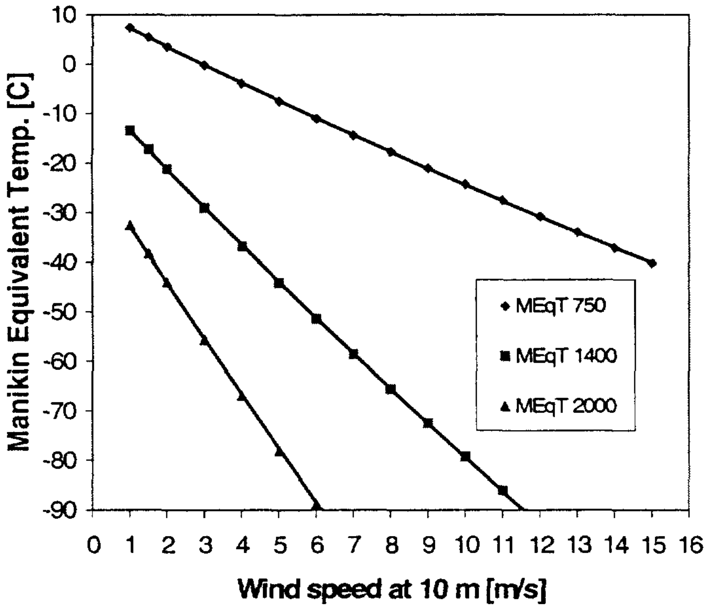

Figure 3. Manikin windchill equivalent temperatures do not correspond with constant levels of human sensation in cold winds.

Equivalent temperatures derived from experiments with a heated manikin wearing average outdoor clothing (Wyon 1989) are presented in Fig. 3 for the same three discomfort or hazard levels. Wyon's manikin windchill index clearly fails the test, for the lines of constant sensation are not even close to being horizontal. Each level of discomfort or hazard is represented by a wide range of values of the equivalent temperature on the y-axis. Conversely, each manikin equivalent temperature can describe many sensations. For example, a manikin equivalent temperature of –35 °C could be produced by the combinations of wind and temperature that produce windchill index values of 750, 1400, or 2000. These combinations produce very different levels of sensation and hazard in human beings, but not in thermal manikins that maintain a constant skin temperature.

Conclusion

The facial cooling model suggests that the classic windchill index works because combinations of wind and temperature that produce consistent values of the index also result in consistent skin temperatures on the exposed face. Facial skin temperature and overall thermal comfort seem to be intimately related. Wind erodes the boundary air layer adjacent to the skin and increases convective heat transfer. This reduces the temperature of exposed skin and creates the sensation that the air temperature is lower than the thermometer says it is.

Although the sensation of windchill is largely an effect of exposed skin temperature, the temperature of the skin beneath clothing may play a role when the face is protected from the wind and the focus of discomfort awareness is transferred to the legs or some less well protected area.

Although calculations of total body heat transfer in cold weather are important in assessing the risk of hypothermia and in estimating survival times in cold conditions, they do not relate directly to the sensation of windchill.

Because people tend to dress for the season rather than the weather, an index of windchill such as AT that assumes that adequate clothing is always being worn might not apply much of the time. Theory suggests that it is not possible to derive a useful index of windchill based on heat transfer through normal outdoor winter clothing. Such an index cannot consistently and uniquely correspond to levels of human sensation, which it would have to, at least approximately, to be useful.

An index or an equivalent temperature derived from Siple's windchill index, or from the DCIEM facial cooling model will pass this test. Either can be used as they are associated with narrow ranges of human thermal sensation in cold winds. However, some changes to the way wind speed is measured or used in the calculation of the windchill index would be required

Ideally wind speed should be measured at a height between 1.5 and 2 metres above the ground when it is to be used to assess the impact of the wind on human thermal comfort. Wind is normally measured at 10 metres. It must be corrected to some more human scale for use in windchill calculations. This has not been the standard practice in North America and much of the rest of the world. The correction should take into account the stability of the lower 10 m of the atmosphere.

Further work should be done to relate human sensation to windchill in non-sedentary conditions and to elucidate the relationship between skin temperature and skin thermal resistance at skin temperatures at or below 0 °C. The facial cooling model might be further improved by relating wind speed to the local heat transfer from areas on the midline of the face, where cooling should be highest when facing the wind.

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