THE NEW WIND CHILL EQUIVALENT TEMPERATURE CHART

BY RANDALL OSCZEVSKI AND MAURICE BLUESTEIN

Reasons for revising the wind chill equivalent temperature chart in 2001 as well as the theory and assumptions behind the new calculation and weaknesses in the Wind Chill Equivalent Temperatures (WCT) concept are outlined.

A new formula for expressing the combined effect of wind and low temperature on the cooling of exposed skin was introduced in North America in November 2001. This formula is largely based on established engineering correlations of wind speed and convective heat transfer. The formulation it replaced was based on the results of an impromptu experiment that Paul Siple and Charles Passel carried out during the United States Antarctic Expedition, 1939–41. Although the resources available on the expedition limited the sophistication of their experiment, it became the best-known result of a century of Antarctic research. Siple and Passel (1945) simply measured the time it took to freeze water in a small plastic bottle suspended from a post on the roof of the expedition building. From these observations, they derived the Wind Chill Index (WCI), a three- or four-digit number representing the rate of heat loss of the cylinder per unit surface area.

Since its publication in 1945, several researchers, notably Molnar (1960), pointed out flaws in the original experiment. The major faults include the great variability in the data points, the small size of the cylinder, the apparent neglect of its internal thermal resistance, and the assumption of a constant surface temperature when calculating the WCI. Critics pointed out that the equation selected to represent the scattered data points, a parabola, was physically inappropriate because beyond the range of the experimental data, it predicted that wind chill would decrease with increasing wind speed instead of increasing gradually to some limiting value defined by the internal thermal resistance. These errors were compounded when the WCI was routinely calculated from the wind speed reported by the local weather station at a height of 10 m. Wind speeds measured high above the ground are significantly greater than those at lower levels (Steadman 1971).

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Despite these shortcomings, the WCI proved to be a useful number that seemed to reflect the human experience of cold and the risk of facial frostbite (Burton and Edholm 1955). Osczevski (1995b) showed that the heat flux in wind from a small cylinder like the one used in the original experiments was not greatly different from the heat loss per unit area of the face of a thermal manikin facing the wind. He mathematically modeled wind chill as facial heat loss and showed that sets of wind and temperature data that combined to produce any particular value of the WCI produced only a narrow range of skin temperatures in his model. Since skin temperature defined thermal sensation, this explained why the apparently flawed WCI could work as a predictor of consistent human sensations.

The WCI survived unchanged in some parts of North America until the twenty-first century. However, by the mid-1970s, Wind Chill Equivalent Temperatures (WCT) had supplanted the Wind Chill Index in most of North America. The WCT is a calculated air temperature that, in the absence of wind, would result in the same WCI value as would be calculated from the actual conditions of dry bulb temperature and wind speed. When first adopted by the military in the 1960s, the absence of wind was presumed to mean just that—zero air movement. The equivalent temperatures calculated from this assumption greatly exaggerated the effect of wind. For example, a wind speed of 40 km h^{-1} combined with an air temperature of –1°C was said to be equivalent to –40°C in still air (Strategic Air Command 1964). Eagan (1964) realized that neither people, nor air, are ever perfectly still. He defined the absence of wind to mean a minimum wind speed of 1.78 m s^{-1}, probably because that was about the minimum measurable wind speed with a cup anemometer. This change raised all WCTs to more reasonable levels. For example, it increased the problematic WCT for the combination of –1°C and 40 km h^{-1} from –40° to –18°C. However, many still believed that WCT exaggerated the effect of the wind. These included Bluestein (1998), Elsner and Bolstad (1963), Kessler (1993), Milan (1961), Osczevski (1995a, 1995b, 2000), and Steadman (197), among others.

As result of an Internet conference on wind chill, hosted by the Canadian Weather Service in 2000 (Maarouf and Bitzos 2000), Environment Canada (EC) and the U.S. National Weather Service (NWS) convened a group of interested parties and researchers to evaluate the state of the art in WCT determination and to recommend a better approach. This group, called the Joint Action Group for Temperature Indices (JAG/TI) included members of the NWS and the EC and had as its first objective a WCT chart that would be easy to understand, could be utilized by all North American weather services, and would be scientifically valid. The group concluded that the alternative proposals published by Osczevski (1995b) and Bluestein and Zecher (1999), using the same heat transfer principles but different geometries, offered the best opportunity for a more accurate WCT chart. Osczevski and Bluestein, both members of the group, were designated by the JAG/TI to work together to develop a new WCT chart to be ready for the 2001–02 winter season. This was accomplished and implemented in the United States and Canada in November 2001.

ASSUMPTIONS. We decided to concentrate on areas of exposed skin. In winter, the face is the most exposed area. The success of the old WCI as an index of thermal discomfort and its close relationship to facial skin temperature suggested that facial cooling might be key to the sensation of wind chill. We approximated the convective heat loss from the face in wind by calculating the convective heat flow from the upwind side of a vertical cylinder in cross flow. The diameter of this cylinder was assumed to be 18 cm. Heat transfer was calculated at cylinder locations that are 50° to the wind, equivalent to midcheek. Here the convective heat transfer rate is about equal to the average over the front 160° of the cylinder. The face would be facing into the wind in the worst-case scenario. Kreith (1976) gives the local convective heat transfer coefficient (h) at a point on the curved surface of a cylinder of diameter D that makes a central angle of θ° to the wind as

$$h = 1.14\mathrm{Re}^{0.5}\mathrm{Pr}^{0.4}[1-(\theta \times 90^{-1})^3)]kD^{-1},$$

where k is the thermal conductivity of air. This equation fits the range of Reynolds numbers (Re) and Prandtl numbers (Pr) encountered.

The rate of heat loss by radiation is a function of the temperatures of the cylinder surface and the air as defined in Incropera and DeWitt (1996). The cylinder exchanges radiant heat with both the sky and the ground. The ground surface temperature is assumed to equal the air temperature except in still air with a clear sky, when it is assumed to be colder than air temperature by 2.5°C (Geiger 1971). The apparent emissivity of the sky depends on the square root of the water vapor pressure at screen height according to an empirical equation (Monteith 1973). We made the untested assumption that the equation could be used

at much lower temperatures than its empirical base, which is limited to temperatures above the freezing point. Even in still air, radiant heat transfer to the cold sky is only about 20% of the total heat transfer. We also assumed perfectly dry air and a clear sky when calculating radiant heat loss in the reference condition of no air movement. Thus, the apparent emissivity was a constant for all WCT calculations.

The 2001 calculation is for a person moving through the air at walking speed. For the reference still-air condition, the calculation assumes a minimum air speed of 1.34 m s^{-1}, which is the average walking speed of American pedestrians, young and old, crossing intersections in studies of traffic light timing (Knoblauch et al. 1995). When there is wind, it is assumed that the adult is walking into the wind (worst case) and so the walking speed is added to the wind speed at face level when calculating the WCT.

Finally, the wind speed at face level was assumed to be two-thirds of that measured at the 10-m height of the weather stations. This was based on an analysis by Steadman (1971) and refers to the ratio of wind speeds in an open field. The ratio in an urban area could be considerably smaller. This ratio must depend on the stability of the lower atmosphere, being smaller at night and early morning than in the afternoon; however, no correction for time of day was included in the model. Ideally, wind speeds for public consumption would be measured at the lower height (1.5 m).

Each resistance element in Fig. 1 represents a resistance to heat transfer. From the core temperature of 38°C to the skin there is an effective internal resistance of (R_1). It is an effective resistance, as heat not only flows through the body tissues by conduction from the warmer body core but also by blood circulation. From the skin to the outside air are two parallel resistances—convection (R_2) and radiation (R_3). Resistances are in units of squared meters times kelvins per watt. In the steady state, heat transfer from the body core to the skin must equal that from the skin to the air via the parallel paths of convection and radiation. Note that any incoming solar radiation was not considered, as it was not part of the JAG/TI mandate at this point. Calculating the heat exchanges is complicated as one needs to know the skin temperature to calculate the heat flow rates, but the skin temperature cannot be calculated until one knows these rates. An iterative calculation procedure is therefore required, the details of which are reported elsewhere (Bluestein and Osczevski 2002). All calculations were carried out in an Excel spreadsheet, which lends itself to multiple iterations.

Experiments with human volunteers were conducted by Ducharme et al. (2002) in a test chamber

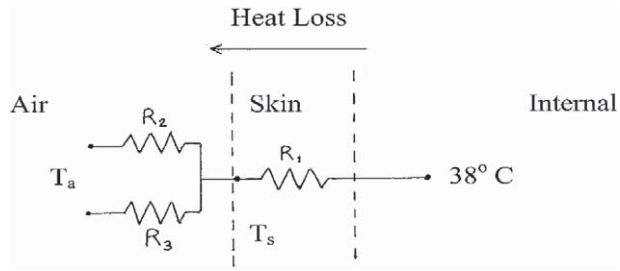

Fig. 1. Electrical analog for heat transfer path.

at the Defence and Civil Institute of Environmental Medicine in Canada [now Defence R & D Canada (DRDC) Toronto]. This study has been described as a verification of the accuracy of the model (Nelson et al. 2002), however, this is a misconception; its primary purpose was to determine a numerical value for R_1. Except for one limited study (Osczevski 1994), no values for the thermal resistance of the cheek existed in the literature. For Ducharme's study, 12 adult volunteers, male and female, aged 22–42 with a mean of 33 years, were instrumented for skin and rectal temperatures. Heat flux sensors (RdF Micro-Foil HFS 20455-3) were applied to their cheeks with surgical tape. Rectal thermistors probes were used to measure body core temperature. The subjects, who were dressed for thermal neutrality, were asked to walk on a treadmill at 1.34 m s^{-1} facing winds of approximately 2, 5, and 8 m s^{-1} at face level, at each of three air temperatures, +10°, 0°, –10°C. Test periods were 90 min long, with each experiment lasting 30 min before the wind speed was changed. We calculated individual values of R_1 from experiments in which the heat flux and skin temperatures reached approximately steady states. Here, R_1 is the ratio of the difference between the skin and core temperatures

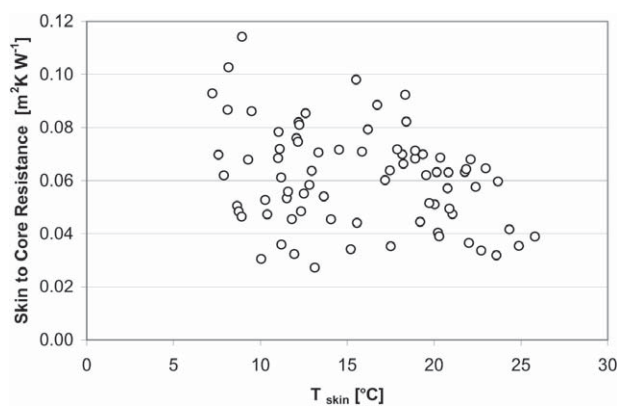

Fig. 2. Steady-state thermal resistances between the core and skin of the cheek derived from unpublished data (M. Ducharme et al. 2001, personal communication).

and the heat flux from the skin. Figure 2 illustrates the wide range of effective cheek thermal resistance, particularly at low skin temperatures. We chose the 95th percentile value of resistance, 0.091 m^2 K W^{-1}, to calculate WCT chart for the worst case. Siple and Passel's cylinder had an internal resistance of only about 0.02 m^2 K W^{-1} (Osczevski 1995b).

The calculation of WCT assumes an internal body temperature of 38°C, which was the average core temperature in the experiments mentioned above. Except in extreme circumstances, internal body temperature is a function of metabolic rate, not environmental temperature.

RESULTS. WCTs were found for the range of 40° to –45°F and 5 to 60 mph^{-1} in increments of 5 units, and a range of 10° to –50°C and 10 to 80 km h^{-1} in SI units. The results were submitted to the JAG/TI in the summer of 2001.

The results were acceptable to the NWS, but the service was unable to utilize the iterative procedure in their computers. We used the spreadsheet to calculate 800 values of WCT for combinations of wind speed and air temperature that might be encountered in the real world, and then carried out a multiple linear regression to obtain best-fit equations, following the mathematical form suggested by Quayle and Steadman (1998). These equations were then used to calculate WCT over the desired ranges of wind speed and temperature in the final WCT charts, which are shown in Tables 1 and 2. The equations are given with the tables. They should not be used at very low wind speeds, that is, less than 3 mph or five km h^{-1}. WCT is a steady-state descriptor. It is the equivalent temperature after the skin has cooled to its lowest point, which can take 20 min (Tikuisis and Osczevski 2002). The charts assume a critical skin temperature of –4.8°C for a 5% risk of frostbite, as indicated by Danielsson (1996). In the steady state, a skin temperature of –4.8°C is reached at an equivalent WCT of –27°C.

With this new model for wind chill, the problematic combination of –1°C and 40 km h^{-1} mentioned in the beginning, which was at first supposed to be equivalent to –40°C, and with Eagan's improvements became –18°C, has now risen to –9°C.

DISCUSSION. The value chosen for the internal thermal resistance of the body tissues is important. As shown in Fig. 3, had we chosen a value of 0.07 m^2 K W^{-1} (about the average of the subjects in the chamber experiments when the skin is cold), WCTs in the chart would have been a few degrees colder than those calculated by assuming the 95th percentile value of 0.091 m^2 K W^{-1}.

We calculated WCT for the segment of the population having the highest R_1 (95th percentile) and therefore the coldest exposed facial skin. They should feel the cooling power of any given combination of wind and temperature more keenly and have a higher risk of frostbite than almost anyone else. As Fig. 3 shows, the WCT calculated for this segment looks less severe than it would have had we chosen the average R_1 of the people in the laboratory study.

Table 1. The new Wind Chill Temperature (WCT) chart, with air temperature in °F and wind speed in mph. Here, WCT = $35.74 + 0.6215T - 35.75V^{0.16} + 0.4275TV^{0.16}$. Shading indicates temperatures at which frosbite can occur.

Wind Speed (mph) \ Temperature (°F)	Calm	40	35	30	25	20	15	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45
5	36	31	25	19	13	7	1	–5	–11	–16	–22	–28	–34	–40	–46	–52	–57	–63
10	34	27	21	15	9	3	–4	–10	–16	–22	–28	–35	–41	–47	–53	–59	–66	–72
15	32	25	19	13	6	0	–7	–13	–19	–26	–32	–39	–45	–51	–58	–64	–71	–77
20	30	24	17	11	4	–2	–9	–15	22	–29	–35	–42	–48	–55	–61	–68	–74	–81
25	29	23	16	9	3	–4	–11	–17	–24	–31	–37	–44	–51	–58	–64	–71	–78	–84
30	28	22	15	8	1	–5	–12	–19	–26	–33	–39	–46	–53	–60	–67	–73	–80	–87
35	28	21	14	7	0	–7	–14	–21	–27	–34	–41	–48	–55	–62	–69	–76	–82	–89
40	27	20	13	6	–1	–8	–15	–22	-29	-36	–43	–50	–57	–64	–71	–78	–84	–91
45	26	19	12	5	–2	–9	–16	–23	–30	–37	–44	–51	–58	–65	–72	–79	–86	–93
50	26	19	12	4	–3	–10	–17	–24	–31	–38	–45	–52	–60	–67	–74	–81	–88	–95
55	25	18	11	4	–3	–11	–18	–25	–32	–39	–46	–54	–61	–68	–75	–82	–89	–97
60	25	17	10	3	–4	–11	–19	–26	–33	–40	–48	–55	–62	–69	–76	–84	–91	–98

Table 2. The new Wind Chill Temperature (WCT) chart, with air temperature in °C and wind speed in km h^{-1} Here, WCT (°C) = 13.12 + 0.6215T – 11.37$V^{0.16}$ + 0.3965$TV^{0.16}$. Shading indicates temperatures at which frostbite can occur.

Wind Speed (km h^{-1}) \ Air Temperature (°C)	Calm	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45	–50
10	9	3	–3	9	–15	–21	**–27**	**–33**	**–39**	**–45**	**–51**	**-57**	**–63**
15	8	2	–4	–11	–17	–23	**–29**	**–35**	**–41**	**–48**	**–54**	**–60**	**–66**
20	7	1	–5	–12	–18	–24	**–31**	**–37**	**–43**	**–49**	**–56**	**–62**	**–68**
25	7	1	–6	–12	–19	–25	**–32**	**–38**	**–45**	**–51**	**–57**	**–64**	**–70**
30	7	0	–7	–13	–19	–26	**–33**	**–39**	**–46**	**–52**	**–59**	**–65**	**–72**
35	6	0	–7	–14	–20	–27	**–33**	**–40**	**–47**	**–53**	**–60**	**–66**	**–73**
40	6	–1	–7	–14	–21	**–27**	**–34**	**–41**	**–48**	**–54**	**–61**	**–68**	**–74**
45	6	–1	–8	–15	–21	**–28**	**–35**	**–42**	**–48**	**–55**	**–62**	**-69**	**–75**
50	6	–1	–8	–15	–22	**–29**	**–35**	**–42**	**–49**	**–56**	**–63**	**–70**	**–76**
55	5	–2	–9	–15	–22	**–29**	**–36**	**–43**	**–50**	**–57**	**–63**	**–70**	**–77**
60	5	–2	–9	–16	–23	**–30**	**–37**	**–43**	**–50**	**–57**	**–64**	**–71**	**–78**
70	5	–2	–9	–16	–23	**–30**	**–37**	**–44**	**–51**	**–59**	**–66**	**–73**	**–80**
80	4	–3	–10	–17	–24	**–31**	**–38**	**–45**	**–52**	**–60**	**–67**	**–74**	**–81**

Consideration of those individuals at the other end of the distribution of R_1, that is, those having lower-than-average R_1 values, points up the paradox of WCT. These people would have higher-than-average rates of heat loss in any given combination of wind and temperature because they have less internal insulation. Because WCT is based on the rate of heat loss, they would experience a personal WCT that is a more severe number than the one in the chart. However, they are able to transfer heat more easily to the exposed skin and therefore would have a higher cheek skin temperature than the average person. Because their cheeks are warmer, it should not feel as cold to them as it would to the 95th percentile person on whom the chart is based.

Unlike the old wind chill, there is no minimum wind speed below which WCT cannot be calculated, as even in zero wind there is a relative air movement equal to the walking speed.

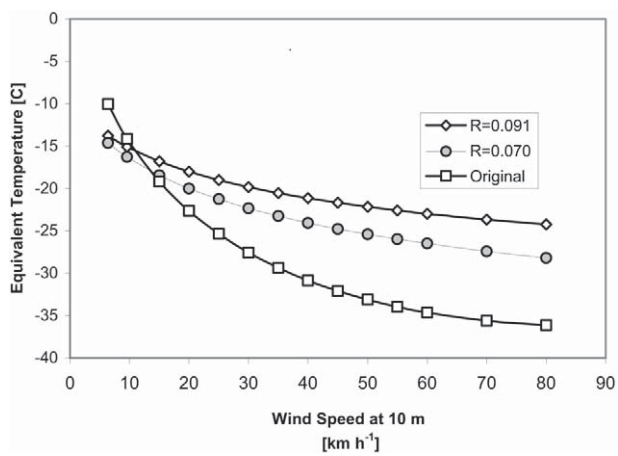

Fig. 3. The 2001 Wind Chill Model at T air = –10°C with the 95th and 50th percentile values of R_1, compared to the original WCT based on Siple and Passel's (1945) Wind Chill Index.

CONCLUSION. Wind chill is not a neat and simple package. A person's exposure to wind is determined by their surroundings and their activity relative to the wind direction. Time of day affects the lapse rate and the ratio of the wind at 10 m to the wind at face level, and physiology affects how they react to it. Because one's experience of the equivalent temperature depends on facial skin temperature, which varies from person to person because cheek thermal resistances vary widely, WCT is not an ideal way to express the combined effect of wind and low temperature. Ideally, an index of wind chill should be invariant with respect to individual differences or stated so that it can be individually calibrated with experience, as was the original three- or four-digit Wind Chill Index that Siple and Passel (1945) created. However, the public seems to have a strong preference for the equivalent temperature format (Maarouf and Bitzos 2000), a deceptive simplification that only seems to be easier to understand.

Wind chill is an evolving concept. Wind chill equivalent temperature charts might someday include

solar heating effects; improved prediction of time to frostbite and more sophisticated time-dependent models of skin cooling in wind. The short-term effects of wind chill are of interest, as many people in the modern world are not exposed to the wind for long enough to reach a steady-state skin temperature. Consideration might also be given to modifying the assumed value of internal thermal resistance to tailor the chart more directly to the average person. An upward adjustment of the steady-state core temperature and minimum wind speed could result in a chart that applies more directly to people engaged in tasks that have moderately high rates of energy expenditure, such as recreational cross-country skiers or runners. Another niche calculation might be a marine wind chill chart, incorporating the cooling effects of fog or spray. It seems unlikely that another half century will go by before wind chill is again upgraded.

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