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ORIGINAL PAPER

Modified wind chill temperatures determined by a whole body thermoregulation model and human-based facial convective coefficients

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Abstract Wind chill equivalent temperatures (WCETs) were estimated by a modified Fiala's whole body thermoregulation model of a clothed person. Facial convective heat exchange coefficients applied in the computations concurrently with environmental radiation effects were taken from a recently derived human-based correlation. Apart from these, the analysis followed the methodology used in the derivation of the currently used wind chill charts. WCET values are summarized by the following equation:

$$\mathrm{WCET} = 12.87 + 0.5334{*}T_o - (12.66 - 0.4414{*}T_o){*}U_{reported}^{0.1228}$$

Results indicate consistently lower estimated facial skin temperatures and consequently higher WCETs than those listed in the literature and used by the North American weather services. Calculated dynamic facial skin temperatures were additionally applied in the estimation of probabilities for the occurrence of risks of frostbite. Predicted weather combinations for probabilities of "Practically no risk of frostbite for most people," for less than 5 % risk at wind speeds above 40 km h^{-1}, were shown to occur at air temperatures above −10 °C compared to the currently published air temperature of −15 °C. At air temperatures below −35 °C, the presently calculated weather combination of 40 km h^{-1}/−35 °C, at which the transition for risks to incur a frostbite in less than 2 min, is less conservative than that published: 60 km h^{-1}/−40 °C. The present results introduce a fundamentally improved scientific basis for estimating facial skin temperatures, wind chill temperatures and risk probabilities for frostbites over those currently practiced.

Keywords Cold environments · Wind speed · Probability for frostbite · Scientific basis

Introduction

The wind chill equivalent temperature (WCET) is a well recognized and widely used cold weather indicator. It provides an estimated measure of the equivalent air temperature that would result in the same heat loss rate under calm wind conditions (Bluestein and Osczevski 2002). WCET values are tabulated in charts and expressed by equations that are based on the estimated steady-state temperatures of an exposed cheek at different combinations of air temperatures and wind speeds (NOAA 2009; Environment Canada 2011).

The concept of wind chill is credited to Siple and Passel (1945), who introduced the Wind Chill Index (WCI) as an estimate of thermal discomfort. In parts of North America, the WCI was replaced by the Wind Chill Temperature (WCT). The WCT is a calculated, or virtual, air temperature that, under the condition of "light wind" (Steadman 1971), or "calm" air movement, would result in the same WCI as would be calculated from the actual combination of dry bulb air temperature and wind speed. An alternative to WCT as a measure of the cooling intensity of the cold environment, was proposed by Brauner and Shacham (1995): (1) steady-state exposed skin temperature (EST), and, (2) maximum exposure time (MET). The EST and the WCI correlated reasonably well only for similar geometries and thermal properties.

Osczevski (1995) tested the theory that facial cooling is the primary basis for the sensation of wind chill by investigating the heat loss from a rigid polyurethane headform equipped with electrically heating elements and a thermally

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conducting, bright aluminum foil "skin". He concluded that heat transfer from an upwind looking, face-simulating object tested in a wind tunnel, is affected by wind in the same manner as heat transfer from a cylinder under similar experimental conditions. Osczevski (1995) presented a wind chill equivalent temperature (WCET), which is presumed to be the temperature at which it would feel as cold as in the absence of wind. Reported wind speed, which is usually measured at approximately 10 m above ground level, was adjusted to face level where its value is appreciably lower. The new equivalent temperatures calculated by the facial cooling model were significantly higher than the old published WCTs, especially at the low end of air temperatures and the high end of wind speeds, respectively.

Tikuisis and Osczevski (2002) developed a dynamic tissue-cooling cylindrical shell model, simulating the face, to predict transient temperature variations on its exposed surface exchanging heat by convection and radiation with the environmental air. This model formed the basis for estimating the predicted times for freezing of exposed facial skin areas that are included in NOAA's (2009) and Environment Canada's (2011) wind chill charts.

Following an internet conference of the Joint Action Group for Temperature Indices (JAG/TI) in 2000 (OFCM 2003), a decision was made to develop and implement a new WCT chart that would be more scientifically based, to be used by all North American weather services. Bluestein and Osczevski (2002) took up this task and its results were implemented by the United Stated and Canada's weather services in November 2001. Osczevski and Bluestein (2005) approximated the convective heat loss from the face exposed to wind by a steady-state electrical analog model formulated for cylindrical locations at an angle of 50° to the wind, simulating the mid cheek. The local convective heat transfer coefficients were estimated by a correlation presented by Kreith (1976), which was derived for vertical cylinders in cross flow and fits the experimental range of relevant Reynolds and Prandtl Numbers. The calculation procedure assumed a person moving through the air at walking speed. The reference still-air condition was assumed at a minimum air speed of 1.34 m s^{-1} (3 mph), which is the average street-crossing walking speed of young and old American pedestrians (Knoblauch et al. 1995). The model assumed that the person is walking into the wind, as a worst case scenario. The walking speed is therefore added to the face-level adjusted wind speed, when calculating WCT (Osczevski 1995).

The effective cheek internal thermal resistance was estimated from human experiments conducted by Brjakovic and Ducharme (2004). Six adult male and 6 female subjects walked for 30 min at 1.34 m s^{-1} on a treadmill facing winds of 2, 5 and 8 m s^{-1} directed at face level with air temperatures of +10, 0 and −10 °C. Cheek thermal resistances were calculated from heat flux and skin temperature sensors after they had reached a steady-state. The thermal resistance of 0.091 m^2 K W^{-1} used in the model represented the 95th percentile value of the experiments, as a worst case (Osczevski and Bluestein 2005).

Shitzer (2006) used a simple, steady-state, one-dimensional hollow cylindrical model, assuming only radial conduction, to demonstrate the dependence of convective heat transfer correlations used in previous wind chill studies, on physical and environmental parameters such as air temperature, wind speed, dimensions of the heat exchanging object, air thermal properties, etc. Variability of calculated surface temperatures was demonstrated to exceed 15 %, being significantly larger for slender body parts, e.g., fingers. He concluded that the WCT is very sensitive to the choice of the specific correlation used to express the convective heat exchange coefficient. Shitzer (2007) quantified the effects of blood perfusion that elevates skin surface temperatures and thus decreases WCETs due to the enhancement of heat exchange with the environment.

The above cited studies used one-dimensional heat exchange models, all lacking the essential physiological control mechanisms, to simulate human cheeks' responses to cold/windy environments. Nor do most of these studies consider the cold weather insulation worn and the effects of blood perfusion on the estimated WCETs. Furthermore, these models invariably employed convective heat exchange coefficients that were derived by inanimate objects, to estimate WCTs. These fundamental deficiencies render the currently calculated WCT values physiologically inadequate and physically inaccurate.

The purpose of this study was to recalculate wind chill equivalent temperatures (WCETs) by a detailed whole body thermoregulation model, in which physiological control functions, effects of cold weather insulation worn and blood perfusion are expressed explicitly (Fiala et al. 2001, 2012). The calculations are additionally based on convective heat transfer coefficients between the exposed human face and its surrounding environment, which were estimated from experiments with human subjects under cold and windy conditions (Ben Shabat and Shitzer 2012). The results indicate consistently higher WCETs and consistently lower facial skin temperatures than currently estimated. Higher air temperatures at which frostbites may occur, are also indicated above −30 °C.

Materials and methods

Methods

The main utility of the concept of "wind chill" is in its applicability as an index and indicator of the combined effects of cold and windy environments and in assessing the potential for incurring frostbites of bare skin surfaces.

This index typically applies to persons "wearing appropriate winter clothing" (Steadman 1971) who transition from a thermo-neutral indoor environment to walk outdoors. Closer-to-realistic simulation of humans' responses under these conditions should be based on a rather detailed thermoregulation model that considers physiological control mechanisms, the application of appropriate cold-weather clothing and thermal effects of blood perfusion on body temperatures. An additional improvement in the calculation procedure is the application of a heat convection correlation that was derived from human experiments (Ben Shabat and Shitzer 2012).

Whole body thermoregulation model

The comprehensive UTCI-Fiala thermoregulation model (Fiala et al. 2012) was updated to include both an adaptive clothing section and a human experiment-based facial convection heat exchange coefficient to simulate the whole body and the resulting local responses to cold exposure. Model-predicted facial temperatures were used subsequently to estimate the WCETs and risks to incur frostbites for combinations of wind speeds and air temperatures.

The model passive system

The model incorporates two interacting systems of thermoregulation: the controlled passive system and the controlling active system. The passive system is a multi-segmental, multi-layered representation of an average person 73.4 kg in weight and 1.73 m in height (Fiala et al. 2012). In this version of the model the body was divided into a total of 12 compartments: 10 cylindrical, or semi-cylindrical, elements simulating the neck, shoulders, thorax, abdomen, upper and lower arms, hands, upper and lower legs and feet. The face and head were depicted by a three-dimensional, multi-layered and multi-nodal combination of a semi-cylindrical element, 15.6 cm in diameter and 9.84 cm in height, coupled with a semi-spherical element, 20.8 cm in diameter. Tissue composition, thermal and basal physiological properties of these two and other body elements are listed in Fiala et al. (1999). This combination renders the geometry used for this body region fundamentally differently than that of the simple, one-dimensional cylindrical geometries used in the earlier models listed above. Each body segment consisted of multiple annular concentric layers representing the different tissue layers (bone, muscle, fat, skin, etc.), each with its characteristic thermo-physical properties and physiological functions. Tissue layers were further subdivided into sectors in the angular direction (anterior, posterior and inferior) to facilitate the simulation of asymmetrical removal of body heat, and into individual tissue nodes in the radial direction. The face was subdivided laterally into anterior and superior sectors and the head into a posterior sector and the forehead. The sizes and composition of the body elements, including the thicknesses and characteristics of each of the tissue layers, were stored in a data file, facilitating the modeling of different body characteristics. Similarly, the regions of the body covered by clothing, comprising local thermal and evaporative characteristics of individual garments, were also stored in a data file and enabled various clothing ensembles to be composed and simulated.

The energy balance within the body was formulated by the Pennes (1948) bio-heat equation that includes the effects of blood perfusion. This equation was applied in all 187 tissue nodes by the appropriate material constants and geometrical particulars and was solved by a finite-difference scheme. At the body surface the model energy balance considered environmental heat exchange components for each sector including free and forced convection, long- and short-wave radiation and the evaporation of moisture from the skin.

The model active system

The active system simulates the regulatory responses of shivering, sweating and peripheral vasomotion (Fiala et al. 2012). This system was developed by means of statistical regression analysis using measured data obtained from numerous physiological experiments covering steady-state and transient cold, cool, moderate, warm and hot stress conditions, and activity levels of up to heavy exercise (Fiala et al. 2001).

Development and implementation of an adaptive clothing model

Fiala's multi-segmental model employs a clothing model that uses local thermophysical and geometrical clothing characteristics for each body region and calculates the global clothing insulation applied. The local clothing factors may be user-defined or estimated by a recently developed and implemented adaptive clothing model (Ben Shabat 2010). This model is based on field observations of European people's clothing behavior and habits, who are adapted to their local climates during light outdoor activities, over a wide range of climatic conditions (Havenith et al. 2012). The model, which is based on the statistical probability approach, allows for the adjustment of local and overall clothing insulation solely to the ambient conditions. For the head the model assumes local insulation values I_{cl} to vary between 0.8 clo and 1.1 clo for ambient temperatures between 0 °C and −40 °C. The facial area is assumed to be exposed. Further details are given by Havenith et al. (2012).

The sensitivity of Fiala's modified model to changes in clothing insulation was examined for the following conditions: air temperature=−10 °C, wind speed 6 m s^{-1}, activity level=1.2 met, mean radiant temperature (MRT) = T_{air} and relative humidity=60 %. Clothing insulation values were set at three different levels: 0.62 (low), 1.54 (close to model-applied value at −10 °C air temperature), and 2.55 clo (high, typical for exposure to much lower air temperatures).

Calculations show that the body's mean skin temperatures ($\overline{T}_{sk}$) level off at approximately 25 °C and 20 °C, for the 2.55 and 1.54 clo, respectively, after about 3 h of exposure to these conditions. At the lower clothing insulation value, mean skin temperatures attained progressively lower values, as expected. These clothing insulation levels were shown to have practically negligible effects on exposed facial temperatures. However, wind speed does affect facial temperatures, as shown in Fig. 1.

Validation of the whole body thermoregulation model

The UTCI-Fiala thermoregulation model (Fiala et al. 2012) has been validated extensively recently by Psikuta et al. (2012). Model predicted temperatures were compared to a variety of measured data sets showing very good conformity. Specifically relevant to this study is the comparison of measured and predicted cheek skin temperature during a combination of a sudden decrease in air temperature accompanied by increases in air velocity. Figure 10 on page 456 in Psikuta et al. (2012) plots cheek temperature variations due to changes from a 60-min exposure to a 20 °C/0.2 m s^{-1}environment followed by 30 min exposures to −10 °C air temperature and two air speeds: 1 and 5 m s^{-1}, respectively. This figure demonstrates that in both cases, model predictions follow the measured data closely. It is additionally noted that cheek temperatures do not seem to have reached a thermal steady-state in either case after 30 min of exposure to cold and windy conditions. This is in clear contrast to the above noted suggestion by Tikuisis and Osczevski (2002). An additional face-area parameter—forehead temperature—is also compared to measured data with resulting excellent conformity and a similar trend of continued decline after 30 min (Fig. 9, Psikuta et al. 2012, p. 456).

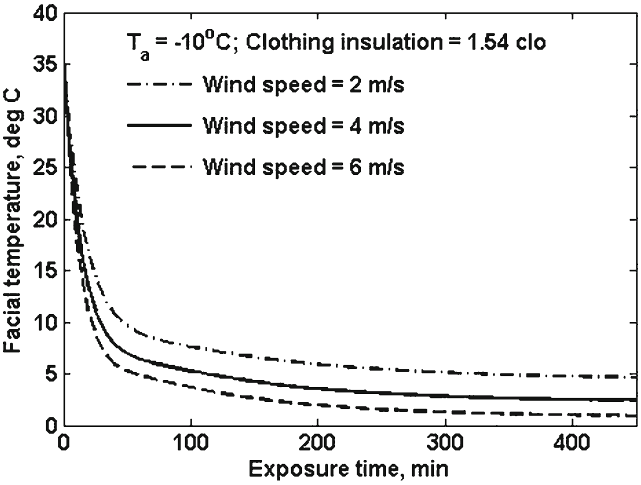


Fig. 1 Facial skin temperature variations with wind speed

Results

Facial skin temperatures calculated by the whole body thermoregulation model

As noted above, the whole body thermoregulation model (Fiala et al. 2012) considers both convection and radiation (Kubaha et al. 2004) heat exchange effects with the environment. In the present study the facial convective heat transfer coefficients were replaced separately by either two correlations:

(1) A correlation applied in the development of the currently used wind chill chart (Osczevski and Bluestein 2005) derived from experiments with cylinders in cross flow (Kreith 1976):

$$h = 1.14\frac{k_{\mathrm{air}}}{\mathrm{D}}\mathrm{Re}^{0.5}\mathrm{Pr}^{0.4}\left[1-(\omega/90)^3\right] \qquad (1)$$

where k_{air} is the thermal conductivity of air, W m^{-1} K^{-1}; Re = U*D/υ is Reynolds number where U is wind speed, m s^{-1} and υ is air kinematic viscosity, m^2 s^{-1}; Pr=υ/α is Prandtl number where α is air thermal diffusivity, m^2 s^{-1}; and ω is the windward angle at which the heat transfer coefficient is evaluated.

(2) A modified correlation, having the same functional form of Eq. (1), that is based on a series of experiments conducted with human subjects exposed to cold and windy conditions (Ben Shabat and Shitzer 2012):

$$h = 0.869\frac{k_{\mathrm{air}}}{D}\mathrm{Re}^{0.5765}\mathrm{Pr}^{0.4}\left[1-(\omega/90)^3\right] \qquad (2)$$

In the following calculations, effective wind speeds were adjusted to face level with the addition of a constant value representing pedestrians' average walking speed into the wind, following the methodology used in the derivation of the currently used wind chill chart (Osczevski and Bluestein 2005):

$$U_{effective} = \frac{2}{3}U_{reported} + 1.34 \qquad (3)$$

The whole body model was run to simulate 450 min of exposure, to ascertain the attainment of a thermal steady state, which occurs in a shorter time span in practice. Tikuisis and Osczevski (2002) have suggested that a thermal steady state is achieved in about 70 min of exposure to a relatively "mild" environment of 0 °C and 3 m s^{-1} wind speed. This is apparently unsupported by their own comparison of measured and calculated data as the latter values do not capture the *continued declining trend* after about 20 min established by the experimental data (ibid, Fig. 3, p. 1245). Figure 2 shows steady-state facial skin temperatures calculated with the human experiments-based correlation, Eq. (2), for combinations of wind speeds and air temperatures. Figure 3 compares results derived with Eq. (2) to those calculated with the correlation applied in the currently used wind chill chart, Eq. (1), for two air temperatures: −10 and −40 °C. The results clearly differ significantly in that the human experiment-based convective heat exchange correlation, Eq. (2), yields *lower* steady state facial temperatures. The gap between the two sets widens as air temperature is lowered but lessens somewhat as wind speed increases. This implies that wind chill equivalent temperatures estimated by the new Eq. (2) would be *higher* than those currently in use since the skin-to-air temperature differences would become smaller, implying less heat loss to the environment.

Table 1 lists facial temperatures, rounded to the full digit, over relevant ranges of air temperatures and reported wind speeds, as calculated by the whole body model and Eq. (2). This table also shows ranges of probabilities for sustaining frostbites from “practically no risk” (facial temperature>−4.8 °C, indicated by no shading), to “imminent risk in less than 2 min,” highlighted by dark shading.

Wind chill equivalent temperatures calculated by the whole body thermoregulation model

UTCI-Fiala modified whole body model (Fiala et al. 2012) was applied to calculate WCETs. Both convective heat exchange coefficients—the human experiment-based, Eq. (2), and Kreith’s (1976) Eq. (1)—were applied separately in the calculations. Figure 4, which is plotted for an air temperature of −10 °C, shows that values calculated with Eq. (2) yield WCETs that are *higher* than the published values (NOAA 2009; Environment Canada 2011), as indicated above. Values calculated by the whole body model and Krieth’s correlation, Eq. (1), are seen to almost coincide with those published values for this air temperature. For other air temperatures, these two quantities deviate from each other.

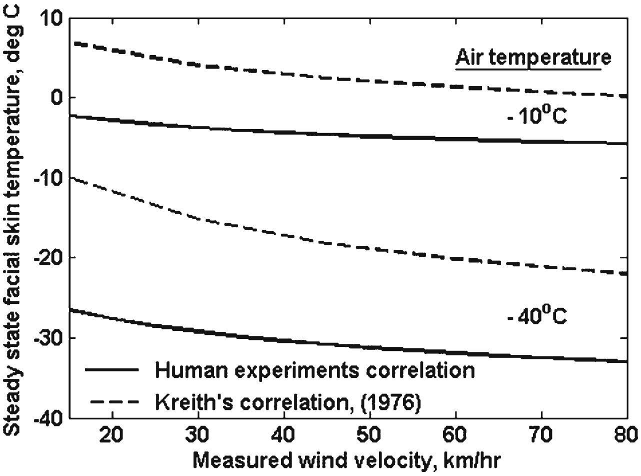


Fig. 3 Steady-state facial skin temperatures calculated by the whole body model and by two convective heat exchange correlations

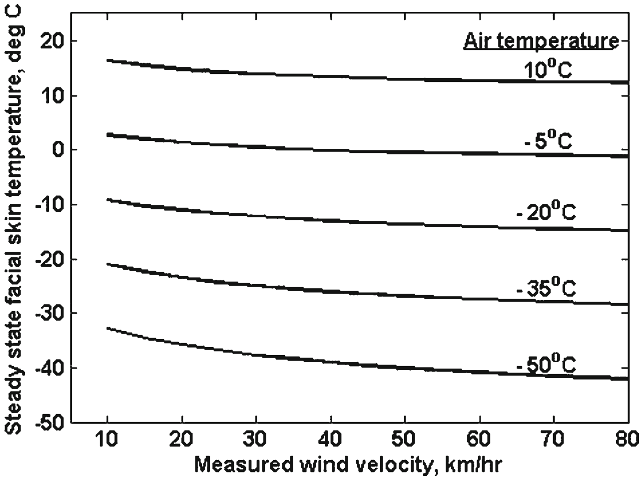


Fig. 2 Steady-state facial skin temperature changes with air temperature and wind speed calculated by the whole body model and Eq. (2)

Finally the whole body model, coupled with the extrapolated human experiments-based correlation, Eq. (2), is used to calculate WCETs for air temperatures from +10 °C to −50 °C and measured wind speeds from 4.8 to 80 km h^{-1}. Results shown in Fig. 5 are compared to published data (NOAA 2009; Environment Canada 2011). At the highest air temperature considered, the published values are seen to be slightly above those calculated by the whole body model. However, as air temperature is lowered, presently calculated values are progressively becoming higher than the published ones. This clear trend is intensified with increased wind speeds. Step-like portions of the curves, seen in Fig. 5 at the lower end of wind speeds, are the consequences of the limitation that wind chill temperatures are currently calculated for wind speeds higher than 5 km h^{-1} (Bluestein and Osczevski 2002).

WCETs, rounded to the full digit, are listed in Table 2 for relevant ranges of air temperatures and reported wind speeds, as calculated by the whole body model and Eq. (2). WCETs listed in Table 2 are least-square approximated by Eq. (4), which retains the same format of the equation used to calculate WCTs by Environment Canada (2011):

$$\mathrm{WCET} = 12.87 + 0.5334 * T_o - (12.66 - 0.4414 * T_o) * \mathrm{U}_{\mathrm{reported}}{}^{0.1228} \quad (4)$$

where T_o is environmental temperature, °C, and $\mathrm{U}_{\mathrm{reported}}$ is reported wind speed measured at 10 m above ground, km h^{-1}. Equation (4) presents WCET values in degrees Celsius to

Table 1 Whole body model calculated facial skin temperatures, °C (rounded) as functions of reported wind speed and air temperature. Predicted times for a 5 % risk of frostbite (skin temperature below − 4.8 °C) are indicated by shaded regions (see legend below)

Reported Wind Speed, km/hr	Air Temperature, Deg C												
	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
10	16	11	7	3	-1	-5	-9	-13	-17	-21	-25	-29	-33
15	15	11	6	2	-2	-6	-10	-14	-18	-22	-27	-31	-35
20	15	10	6	1	-3	-7	-11	-15	-19	-24	-28	-32	-36
25	14	10	5	1	-3	-8	-12	-16	-20	-24	-29	-33	-37
30	14	9	5	0	-4	-8	-12	-17	-21	-25	-29	-33	-38
35	14	9	5	0	-4	-8	-13	-17	-21	-26	-30	-34	-38
40	13	9	4	0	-4	-9	-13	-17	-22	-26	-30	-35	-39
45	13	9	4	0	-5	-9	-13	-18	-22	-26	-31	-35	-40
50	13	8	4	-1	-5	-9	-14	-18	-22	-27	-31	-36	-40
55	13	8	4	-1	-5	-9	-14	-18	-23	-27	-32	-36	-41
60	13	8	4	-1	-5	-10	-14	-19	-23	-27	-32	-36	-41
65	13	8	3	-1	-5	-10	-14	-19	-23	-28	-32	-37	-41
70	12	8	3	-1	-6	-10	-15	-19	-23	-28	-32	-37	-42
75	12	8	3	-1	-6	-10	-15	-19	-24	-28	-33	-37	-42
80	12	8	3	-1	-6	-10	-15	-19	-24	-28	-33	-38	-42

□	Practically no risk	▒	Risk between 4 and 8 min	█	Risk less than 2 min
░	Risk greater than 8 min	▓	Risk between 2 and 4 min		

within ±0.9 °C with an overall root mean square error (RMSE) of 0.285 °C.

Discussion

This study presents the application of a whole body thermoregulation model of an average clothed person to predict WCETs and risks of incurring frostbite. An additional key improvement is the use of facial convective heat exchange coefficients estimated from human experiments. These two key features of the present analysis differ fundamentally from those that have been practiced in previous related studies, all of which were based on rather simple, one-dimensional models of the human cheek coupled with convective coefficients based on experiments with inanimate objects, typically cylinders (Kreith 1976). These common practices, on which current WCT values are based, leave open

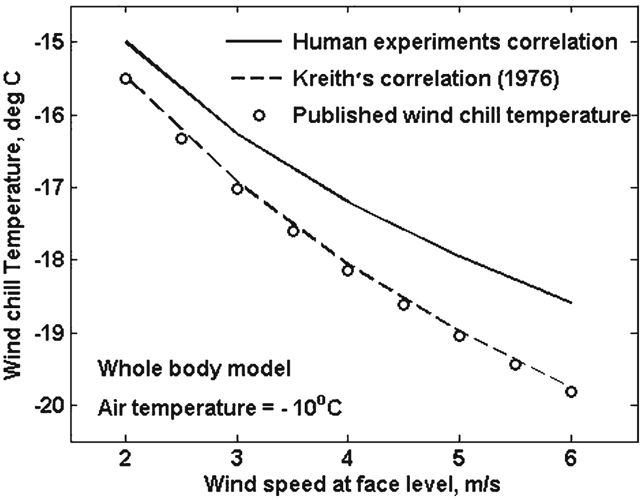


Fig. 4 Wind chill equivalent temperatures (WCETs) vs wind speed at facial level calculated by the whole body model

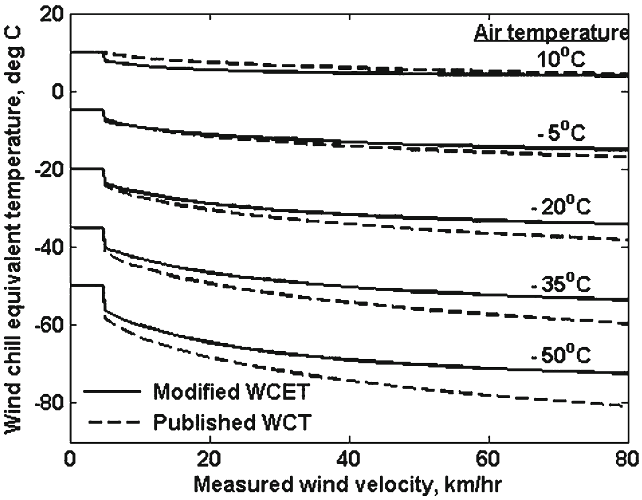
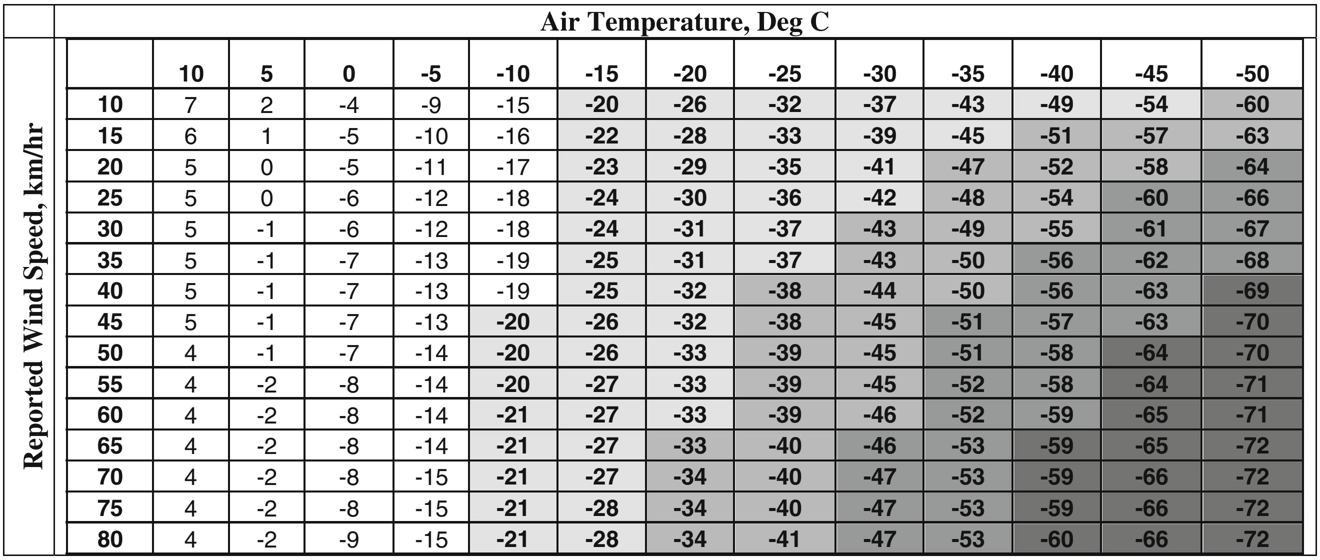


Fig. 5 WCETs calculated by the whole body model compared to published values (NOAA 2009; Environment Canada 2011)

Table 2 Whole body model calculated wind chill equivalent temperatures (WCETs), °C (rounded) as functions of reported wind speed and air temperature. Predicted times for a 5 % risk of frostbite (skin temperature below − 4.8 °C) are indicated by shaded regions (see legend below)



Reported Wind Speed, km/hr	Air Temperature, Deg C												
	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50
10	7	2	-4	-9	-15	-20	-26	-32	-37	-43	-49	-54	-60
15	6	1	-5	-10	-16	-22	-28	-33	-39	-45	-51	-57	-63
20	5	0	-5	-11	-17	-23	-29	-35	-41	-47	-52	-58	-64
25	5	0	-6	-12	-18	-24	-30	-36	-42	-48	-54	-60	-66
30	5	-1	-6	-12	-18	-24	-31	-37	-43	-49	-55	-61	-67
35	5	-1	-7	-13	-19	-25	-31	-37	-43	-50	-56	-62	-68
40	5	-1	-7	-13	-19	-25	-32	-38	-44	-50	-56	-63	-69
45	5	-1	-7	-13	-20	-26	-32	-38	-45	-51	-57	-63	-70
50	4	-1	-7	-14	-20	-26	-33	-39	-45	-51	-58	-64	-70
55	4	-2	-8	-14	-20	-27	-33	-39	-45	-52	-58	-64	-71
60	4	-2	-8	-14	-21	-27	-33	-39	-46	-52	-59	-65	-71
65	4	-2	-8	-14	-21	-27	-33	-40	-46	-53	-59	-65	-72
70	4	-2	-8	-15	-21	-27	-34	-40	-47	-53	-59	-66	-72
75	4	-2	-8	-15	-21	-28	-34	-40	-47	-53	-59	-66	-72
80	4	-2	-9	-15	-21	-28	-34	-41	-47	-53	-60	-66	-72

⬜	Practically no risk	▒	Risk between 4 and 8 min	█	Risk less than 2 min
░	Risk greater than 8 min	▓	Risk between 2 and 4 min		

the question of the validity and applicability of results thereof to humans.

The use of a whole body model to predict WCTs introduces a number of fundamental improvements that are inherently lacking in the simple, one-dimensional cheek models:

(1) It facilitates the estimation of exposed facial cheek temperatures, and those of other body regions, as integral components of the entire human body and its response to environmental exposure.
(2) It includes the effects of the modeled thermoregulatory control system and, in particular, the effects of the blood circulatory system, on body heat loss, e.g., vasoconstriction.
(3) It includes a consideration and local variations of individual components of the human environmental heat exchange including surface convection, long- and short-wave radiation, as well as evaporation of sweating which is known to potentially increase the risk of frostbite in physically active subjects.
(4) It facilitates the consideration of the overall activity level, typically level walking, as expressed by the metabolic rate, thus reflecting the body's actual thermal state.
(5) It facilitates the adjustment of clothing insulation worn according to weather conditions.
(6) It may facilitate consideration of specific anthropometric data for individual representation and of adaptation to climatic conditions, etc. (features not applied in the present study).

As noted above, the whole body thermoregulation model used in this study accounts for several fundamental changes in the modeling approach in an effort to obtain more realistic predictions of WCTs. Nevertheless, other important factors still remain subject to future work. Among these, the effects of long-term adaptation to climatic conditions that may alter the values of predicted WCTs. Another factor may be behavioral responses directed to mitigate the effects of exposure to cold wind that may alter facial temperatures. However, the role of such responses is currently difficult to quantify and implement in simulation models, due mainly to lack of adequate experimental data.

The application of human-based convective coefficients further reinforces the applicability of the results of this study over those derived by coefficients that bear no direct relevance to humans (Shitzer and Tikuisis 2012). It is noted, however, that the presently used convective coefficients, Eq. (2), were derived for a limited range of wind speeds at facial level, from 0.2 to 6 m s^{-1} [converting to 0.3 to 9 m s^{-1}, or 1 to 32 km h^{-1}, measured wind speeds, according to the first term on the right of Eq. (3)] and air temperatures down to only −10 °C (Ben Shabat and Shitzer 2012). These limits reflect the available experimental data and safety considerations exercised in exposing human subjects to environmentally stressful conditions. This limitation necessitated the extrapolation of these results to cover wider ranges of wind speeds and air temperatures (Ben Shabat and Shitzer 2012). Extrapolated values predicted by Eq. (2), were demonstrated to follow trends consistent with those given by Eq. (1) over the entire range of relevant wind speeds and were between 60 to 100 % higher, as given by Eq. (5):

$$\frac{\text{Equation (2) estimated h}}{\text{Equation (1) estimated h}} = 1.582\ \mathrm{U}^{0.0765} \tag{5}$$

where U, is air velocity, m s^{-1}, D=0.18 m and υ (air kinematic viscosity)=12.852 $m^2\ s^{-1}$ at an air temperature of −10 °C. This observation lends confidence to the application of the derived convective values in the computations although further verification, over wider experimental ranges, is still required.

Results of this study indicate that the modified whole body model, coupled with the human-based convective correlation, predicts consistently lower facial skin temperatures than those calculated by the correlation that is used presently by the weather services in the US (NOAA 2009) and Canada (Environment Canada 2011), as seen in Fig. 5. This is to be expected due to the intensification of heat loss to the environment caused by the higher resulting convective coefficients indicated by Eq. (5). Whole body model calculated facial skin temperatures, listed in Table 1, were additionally compared to those published by Tikuisis and Osczevski (2003) and were also found to be consistently lower. Examples are at 15 km h^{-1}/−10 °C for which the present facial temperature is −2 °C compared to +6.9 °C; and at 75 km h^{-1}/−45 °C it is presently estimated at −37 °C compared to −25.3 °C.

These differences in facial temperatures are reflected immediately in the predicted wind speed/air temperature combinations for which the exposure times for a 5 % probability of a frostbite risk are predicted. This risk is currently assumed to occur when facial skin temperature reaches −4.8 °C (Keatinge and Cannon 1960; Danielsson 1996). Table 1 predicts frostbite risks of less than 5 % for any exposure times to prevail for all weather combinations of air temperatures equal or above −5 °C and all listed wind speeds and additionally for wind speeds below 45 km h^{-1} when the air temperature equals −10 °C. Tikuisis and Osczevski (2003), on the other hand, predict this risk level to apply at air temperatures equal or higher than −12.5 °C and wind speeds up to 150 km h^{-1} gradually extending to an air temperature of −30 °C for a 15 km h^{-1} wind speed. Similarly, the highest air temperature in Table 1 for which imminent frostbite risk is expected in less than 2 min is −40 °C and a wind speed of 65 km h^{-1}, whereas Tikuisis and Osczevski (2003) set this temperature at −32.5 °C coupled with a much higher wind speed of 150 km h^{-1}.

The WCETs listed in Table 2 were compared to those published by the weather services in the US (NOAA 2009) and Canada (Environment Canada 2011). Present values were found to be consistently higher than those published. Examples for the above environmental combinations, are: at 15 km h^{-1}/−10 °C the present WCET is −16 °C compared to the published −17 °C and at 75 km h^{-1}/−45 °C the present value is −66 °C compared to −73 °C. Tikuisis and Osczevski (2003) list WCT values that are identical to those published by the above weather services.

The wind chill chart published by Environment Canada (2011) also includes a frostbite guide. At or above air temperatures of −10 °C, and for any reported wind speed up to 80 km h^{-1}, all environmental combinations are characterized as: “Low risk of frostbite for most people.” The transitions from this risk level to the next, which is defined as: “Increasing risk of frostbite for most people within 30 min of exposure,” is set at a wind speed of 40 km h^{-1} and T_a=−15 °C extending to 10 km h^{-1} for T_a=−20 °C. Tikuisis and Osczevski (2003) list the transitions to the next risk level of “risk greater than 8 min” at 45 km h^{-1}/−20 °C extending to 5 km h^{-1}/−45 °C. In Table 1 the transition from “Practically no risk” to “risk greater than 8 min” occurs at a wind speed of 40 km h^{-1} and T_a=−10 °C. The highest listed frostbite risk level is: “High risk for most people in 2 min of exposure, or less.” Environment Canada’s (2011) frostbite guide lists the first occurrence of this risk level at 40 km h^{-1}/−35 °C, Tikuisis and Osczevski (2003) at 65 km h^{-1}/−45 °C and Table 2 at 60 km h^{-1}/−40 °C.

These comparisons point to the following observations:

1. At the highest range of air temperatures, the more conservative weather combination for the predicted frostbite risk to occur (low risk for most people), is due to the present study (transition at: 40 km h^{-1}/−10 °C).
2. At the lowest range of air temperatures, the more conservative weather combination for predicted frostbite risk to occur (risk in less than 2 min for most people) is due to Environment Canada (2011) (transition at: 40 km h^{-1}/−35 °C).

Finally, it is noted that the estimation of WCETs in the present study followed the basic methodology and assumptions by which the published WCT charts were calculated. Certain aspects of this methodology were discussed and criticized recently by Shitzer and Tikuisis (2012). Two of the main points addressed in the present study were: (1) the use of a whole body thermoregulation model that includes blood perfusion effects, responses of the active control system, metabolic heat generation rates, effects of clothing worn; and (2) the application of a human-based convective heat exchange correlation. Among other aspects that remained unchanged, but still require consideration in future studies, are: (1) reevaluation of the appropriate value and physical/physiological meaning of “calm” wind conditions, (2) the applicability of the assumption of a steady-state for which facial skin temperatures and WCTs are estimated, and (3) the implications of the “worst case scenario” in the determination of the effective wind speed for which the analysis is performed.

Conclusion

This study proposes a more comprehensive and relevant approach using a whole body thermoregulation model to replace the simple, one-dimensional models used heretofore in the estimation of WCETs and probabilities for risk of the occurrence of frostbite. The proposed approach additionally applies human-based convective heat exchange correlations, in contrast to the currently applied correlations, which are all based on experiments with inanimate objects. The results indicate consistently higher WCETs and consistently lower facial skin temperatures than currently estimated. Higher air temperatures at which frostbites may occur, are also indicated above −30 °C. These results, which are more scientifically based, and are generally more conservative than the currently practiced recommendations to the public, should be considered to form the basis of a modified and more realistic wind chill chart to be communicated to the public in the relevant cold regions of the world.

Based on the above analysis and results it becomes apparent that Osczevski and Bluestein's (2005) statement: "*It seems unlikely that another half century will go by before wind chill is again upgraded*" was evidently correct.

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