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Abstract

The Universal Thermal Climate Index (UTCI) was conceived as a thermal index covering the whole climate range from heat to cold. This would be impossible without considering clothing as the interface between the person (here the physiological model of thermoregulation) and the environment. It was decided to develop a clothing model for this application in which the following three factors were considered: 1: typical dressing behaviour in different temperatures, as observed in the field, resulting in a model of the distribution of clothing over the different body segments in relation to the ambient temperature, 2: the changes in clothing insulation and vapour resistance caused by wind and body movement, and 3: the change in wind speed in relation to the height above ground. The outcome was a clothing model that defines in detail the effective clothing insulation and vapour resistance for each of the thermo-physiological model's body segments over a wide range of climatic conditions. This paper details this model's conception and documents its definitions.

Keywords: clothing insulation, cold, heat, wind, vapour resistance

Introduction

This special issue of IJB is dedicated to the development of the Universal Thermal Climate Index (UTCI) based on an advanced thermo-physiological model of human temperature regulation. With the goal for UTCI of achieving a climate index that can be applied from extreme heat to extreme cold, it is evident that clothing needs to play an important role in its development as it forms the interface between the human and his or her environment. In the conceptual phase of the index/model development four options for dealing with clothing were considered:

1: To work with fixed reference clothing. While this is not uncommon in climate indices (e.g. ISO 7243 (1989), Wet Bulb Globe Temperature, WBGT) this is usually done where a single climate type (for WBGT: heat) is studied. Especially in the heat, where clothing will be limited (except where protective clothing is required) this is feasible. For UTCI, this would however be unrealistic as the span of climates is too large to work with a single clothing insulation level.

2: To use the clothing needed for thermal equilibrium, as defined by the model calculations, as an index value. This technique, with a heat balance model rather than a physiological model, is used in the Required Clothing Insulation Index (IREQ, ISO 11079-2007). This is a cold stress index and hence clothing will always be required. For the warm and hot side,

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clothing required would become minimal, and even without clothing, equilibrium may not be achievable. Hence this approach cannot be used as it would not cover the whole climate range.

3: To calculate the clothing needed for equilibrium as in option 2, but now not using the clothing insulation itself as an index, but instead look at the change in physiological response for a certain ambient temperature when the other conditions (wind, radiation, humidity) are changed from reference to actual conditions, without changing the clothing insulation. Clothing levels used would be defined as a function of ambient temperatures, each combined with the reference values for the other climatic parameters. The selection of the clothing worn in the reference situations could be based on thermal equilibrium (as in IREQ) where possible. Then wind, humidity and radiation situations different from the reference would translate in higher or lower strain.

Several problems were identified with this approach. Firstly, in the reference condition equilibrium would always be achieved by definition, and thus physiologically, reference conditions for different temperatures would be the same, not providing any meaningful info to the user. Secondly, the amounts of clothing estimated for very cold conditions is unrealistically high and thus would produce an attenuated effect of e.g. wind compared to realistic conditions.

4: Defining clothing insulation as function of ambient temperature, as in 3, but to use clothing insulation values based upon actual observations of people's clothing behaviour in the field. This would imply that the strain simulated by the model would be realistic in terms of the clothing effect, and that the impacts of radiation, wind etc. would also be deduced from realistic conditions.

This last approach was chosen for the UTCI development and its implementation is the topic of this paper. This paper will describe the model developed and the data it is based on. Where no, or limited data were available, arbitrary decisions were made based on discussions between the experts on clothing insulation that were involved in the project. These arbitrary decisions are also described in the paper.

Defining clothing insulation

As different definitions of clothing insulation appear in the literature and this paper, it is relevant to provide a brief description of the context. Figure 1 shows a schematic drawing of clothing covering the body. The insulation provided by the clothing including the enclosed and surface air layers is called I_T. This total insulation is often split in the insulation of the external air layers (I_a) and that of the clothing with its included air layers (I_{cl}). The latter is

called the 'intrinsic clothing insulation'. Due to the increased surface area of the clothing relative to the skin it covers, a surface area correction (f_{cl}) is needed to separate I_T into I_a and I_{cl}:

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} \qquad \textbf{(1)}$$

With f_{cl}= *surface area clothed body/surface area nude body.*

_____

Fig. 1 about here

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A model of clothing behaviour

The adjustment of clothing insulation is a powerful behavioural response to changing climatic conditions. In UTCI it was therefore considered appropriate to adjust clothing insulation to the ambient temperature based on real world observations of clothing behaviour. Thereby, the philosophy for UTCI was to consider seasonal clothing adaptation habits based on available data from field surveys in order to obtain a more realistic representation of this behavioural action that notably affects the human perception of the outdoor climate.

Various publications are available that provide information regarding the thermal insulation of clothing actually worn at various environmental air temperatures in different countries. The background of most of these studies is in the area of cold related mortality. Donaldson et al. (1998) studied clothing behaviour in Yekaterinburg, Russia; Donaldson et al. (2001) and Keatinge et al. (1997) collected outdoor clothing data from 6583 people across Europe (Northern Finland, Southern Finland, The Netherlands, Greater London, Baden Wurttemberg in Germany, Northern Italy and Palermo in the south, and finally in Athens, Greece) in relation to the prevailing outdoor weather conditions as part of the 'Eurowinter' study. These studies used local market-survey companies to collect data on outdoor clothing worn during the first excursion of the day lasting longer than 10 min for 6583 individuals. They calculated total dry insulation of these garments using ISO 9920 (1994), using the summation method of individual garments' insulation based on the tables provided in ISO 9920.
Goodwin et al. (2000) studied clothing during brief trips outdoors in the UK. Clothing insulation was assessed from tables according to the method of Sprague and Munson (1974) following careful inspection of subjects' indoor and outdoor clothing ensembles, in both seasons. ISO 9920, used by the studies above closely resembles Sprague and Munson's methodology; Mäkinen et al. (2006) studied winter clothing behaviour in Finland; and finally

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Lindner (2010) reports clothing habits of young people in Poland during the spring and summer seasons at air temperature ranged from 5 to 32ºC. The main origin of these data is European. The most critical point is that most of the authors (except Lindner's paper) used only general information regarding air temperature (e.g. mean monthly or seasonal values) to establish a relation with clothing worn.

Activity levels during these outdoor excursions were not defined, but for daily activities like shopping these are expected to be close to the reference condition used in UTCI, i.e. walking at 4 km/hr.

Data were extracted from the studies mentioned above, and combined with results of surveys conducted in Poland (Blazejczyk and Twardosz, 2002, 2006 and Blazejczyk 2004) and Sweden (Gavhed and Holmér, 1989) made available by members of the COST 730 Work Group. The experimental data set from Poland is based on direct observations carried out in the spring and summer seasons. The participants (N=50) were exposed outdoors for 4 hours to different, naturally occurring, weather conditions (air temperatures ranged from 3 to 32ºC). Participants chose clothing they expected to be adequate for actual weather conditions. During the exposure they reported their thermal sensations during light outdoor activity (Metabolic activity=90-120 W/m^2 compared to 135 W/m2 for UTCI reference conditions). They also listed clothing items used. Total insulation of clothing ensembles were calculated according to ISO 9920. The ISO9920 approach, used in most studies discussed here, uses the following equation:

$$I_{cl} = 0.161 + 0.835\sum I_{clu} \tag{2}$$

With I_{clu} being the insulation provided by each clothing item. Insulation of clothing used varied from 0.1 clo (briefs only) to 1.43 clo (multilayer clothing). For the present analysis we have used only those data when subjects reported thermal sensations: "cool", "comfortable" and "warm". The data point obtained from Gavhed and Holmér was measured on a static thermal manikin, while the relation between insulation chosen and actual temperature was based on tests with and activity level of 175 W/m^2 compared to 135 W/m2 for UTCI ref conditions (Gavhed and Holmér 1989).

The data are presented in Figure 2.

This figure clearly reveals the overall intrinsic clothing insulation I_{cl} to be a function of the ambient air temperature, best described by a third order polynomial:

$$Icl = 1.372 - 0.01866 \cdot T_a - 0.0004849 \cdot T_a^2 - 0.000009333 \cdot T_a^3 \tag{3}$$

Figure 2 about here

The coefficient of determination is 0.85, i.e. 85% of the variance in clothing insulation is explained by ambient temperature, with a standard error of 0.16 clo (p<0.01).

The relation covers the kind of clothing worn by Europeans who are adapted to their local climates for light activity conditions. Though metabolic rates in some studies were slightly higher and in others slightly lower than UTCI reference conditions (135 W/m^2) as a whole the data can be regarded as representative for the type of activity used as reference (walking 4 km/hr). When comparing the observed values to those determined by the Required Clothing Insulation Index (ISO11079 2007) for the same temperature range and activity (I_{req} is defined below 10ºC), and considering that the observed clothing insulation shows only a small increase below zero degrees Celsius, the results (Figure 2) suggest that from the thermo-physiological point of view, people would tend to *'under-dress'* for steady state exposure to a given cool (<5ºC) outdoor climate. As a characteristic behaviour, this should be accounted for by the UTCI model as the under dressing will make people more sensitive to the effect of wind.

As a general approach, the empirical clothing model of Figure 2 can be used in UTCI for the reference condition. The philosophy for UTCI is also that insulation is adjusted based solely on ambient temperature, thus allowing effects of wind, humidity and radiation to modulate the physiological response at a certain ambient temperature, without the clothing being altered.

Local versus whole body insulation

The above field observations provided information on the global thermal clothing insulation for the human body as a whole. For use with the UTCI-Fiala model which is a multi-segmental representation of the human body (Fiala et al., 1999, 2001, 2010, 2011 this issue), clothing data are required for each of the simulated body segments. For this purpose, a 'local' clothing model is developed that takes into account the non-uniformity of clothing ensembles in different temperature environments, i.e. from partial body coverage (uneven insulation distribution) in the heat to almost full body coverage (more even distribution of insulation) in the extreme cold. The derivation of local insulation values is based on observations of the percentage of people wearing individual items such as hats, gloves, overalls, etc. as provided in the work by Donaldson et al. (1998, 2001) and Goodwin et al. (2000). For modelling purposes, this information was converted to the 'probable' local insulation values of the corresponding items, as shown for the example of wearing a hat and gloves in Figure 3. In the model, this probability was translated in an increasing insulation value at that segment with decreasing temperature up to a saturation point.

Figure 3 about here

The converted local insulation values (in m²K/W) obtained for items covering the head, hands, and legs are shown together with estimated local insulation values obtained for feet and the torso (including upper/lower arms) in Figure 4. The I_{cl}-values for the feet were estimated based on footwear data provided in ISO 9920 (2009). After assigning local insulation values for head, hands, feet, lower arms and legs, the I_{cl}-values for the torso and arms were subsequently defined to reproduce the overall I_{cl}-values as observed in field studies (Fig. 2). The whole body insulation values resulting from local quantities discussed above are plotted together with the corresponding observed data over ambient temperature in Figure 5.

The equations implemented in the model for this purpose are shown below as equations (4) to (10). The general form is that of an exponential function to achieve the dependency on T_a. This clothing model is based on observed clothing behaviour data for ambient temperatures down to -20°C. For extreme cold conditions, however, it seems reasonable (Tikuisis, personal communication regarding Canadian clothing behaviour in extreme cold) to assume that people would increasingly use special protective clothing rather than using ordinary clothing (I_{cl} remaining below 0.3 m²K/W (2 clo)) when temperature gets very low. To account for this, the final local insulation of the torso, arms, hands and head is therefore weighted by a second exponential function to gradually increase the local thermal resistance starting at about -10°C ambient temperature, illustrated in Figure 6. This factor is represented in the equations as 'w'. The weighting factors w were derived/modelled to obtain overall (resultant) total clothing resistances (still air) of 0.47 m²K/W (3 clo) for T_a < -26°C. The overall resistance continues rising (very gradually) for further decreasing T_a's, reaching an I_T of 0.527 m²K/W (3.4 clo) at about -50°C.

Figure 4 about here

Figure 5 about here

Figure 6 about here

Equations for local insulation values ($I_{cl,local}$-values, in [m²K/W]):

   1. Head excl. face (hat)

$$I_{cl,head} = \frac{C_1}{1+\exp(a \cdot T_a + b)} \cdot w \quad with \quad w = \frac{0.8}{1+\exp(0.2T_a + 6)} + 1 \qquad \textbf{(4)}$$

2. Torso (incl. neck) + upper arms

$$I_{cl,torso+upper\ arms} = \left[\frac{C_1}{1+\exp(g \cdot T_a + h)} + a \cdot T_a + C_2 \right] \cdot w \quad with \quad w = \frac{0.8}{1+\exp(0.2T_a + 4)} + 1 \qquad (5)$$

3. Lower arms

$$I_{cl,lower\ arms} = \left[\frac{C_1}{1+\exp(g \cdot T_a + h)} + a \cdot T_a + C_2 \right] \cdot w \quad with \quad w = \frac{0.8}{1+\exp(0.2T_a + 4)} + 1 \qquad (6)$$

4. Hands (gloves)

$$I_{cl,head} = \frac{C_1}{1+\exp(a \cdot T_a + b)} \cdot w \quad with \quad w = \frac{0.3}{1+\exp(0.2T_a + 6)} + 1 \qquad (7)$$

5. Upper legs

$$I_{cl,upper\ legs} = \frac{C_1}{1+\exp(a \cdot T_a + b)} + C_2 \qquad (8)$$

6. Lower legs

$$I_{cl,lower\ legs} = \frac{C_1}{1+\exp(a \cdot T_a + b)} + \frac{C_2}{1+\exp(g \cdot T_a + h)} \qquad (9)$$

7. Feet (shoes)

$$I_{cl,feet} = \frac{C_1}{1+\exp(a \cdot T_a + b)} + C_2 \qquad (10)$$

8. Whole body insulation

$$I_{cl,\ whole\ body} = \frac{\overline{t_{sk}} - \overline{t_{cl}}}{H_{sk}} = \frac{\sum \alpha_i . t_{sk,i} - t_{cl,i}}{\sum (\alpha_i . H_i)} = \frac{\sum \alpha_i . t_{sk,i} - \sum \alpha_i . t_{cl,i})}{\sum (\alpha_i . H_i)} \qquad (11)$$

$$\text{with } \alpha_i = \frac{surface\ area\ of\ segment\ i}{total\ surfacearea\ of\ manikin}$$

$$\overline{t_{sk}} = \text{average skin temperature}$$

$$\overline{t_{cl}} = \text{average clothing surface temperature}$$

$$t_{sk,i} = \text{skin temperature of segment } i$$

$$t_{cl,i} = \text{local clothing surface temperature}$$

$$H_i = \text{heat loss of segment } i$$

The coefficients for the equations are listed in Table 1.

Table 1 about here

The effect of wind and body movement on clothing insulation

Both clothing insulation and the insulation of surface air layers are heavily influenced by changing wind speed and body movement (Havenith et al. 1990[a,b], 2002, 2008, Holmér et al., 1999, Havenith and Nilsson, 2004, 2005, Nielsen et al. 1985, Nilsson et al. 2000). Wind and movement will therefore also influence the clothing effect on the physiological responses of the person and thus these effects need to be incorporated in the model. To consider these effects a model of the effect of wind and motion on intrinsic clothing insulation was developed based on the equations by Holmér et al. (1999) and Havenith and Nilsson (2004, 2005), as they were summarised in ISO 9920 (2009) and ISO 11079 (2007)

A practical problem is that the correction equations provided are all based on correcting total insulation I_T, while the UTCI-model works with (local) I_{cl} values. This therefore requires 1: a transfer of the model's static I_{cl} values to static I_T values, then 2: a correction of this I_T value for movement and wind, followed by 3: a back calculation to a correction factor for the I_{cl} value which is then applied to all individual body segments:

1: The total static insulation of the clothing (without wind or body movement), I_T, is calculated from the static clothing insulation I_{cl}, the static air insulation, I_a, and the clothing area factor f_{cl} as follows:

$$I_T = I_{cl} + \frac{I_{a,STATIC}}{f_{cl}} \tag{12}$$

Where $I_{a,\ static}$ = 0.0853 m^{2}KW^{-1} (ISO 11079-2007)

and

$$f_{cl} = 1,00 + 1,81 \times I_{cl} \quad [\,I_{cl} \text{ expressed in } m^2 \cdot K/W\,]$$

(McCullough & Jones, 1984; Olesen et al., 1982; Oliviera et al., 2005; ISO 9920, 2009)

2: The resultant total insulation of the clothing (affected by wind and body movement), $I_{T,r}$, is calculated from the walking speed, v_w, and the relative wind speed, v_{ar}, to which the person is exposed. Although several equations are available in the literature to calculate $I_{T,r}$ for a limited range of I_T (summer or winter garments), no single equation covers the whole range used in UTCI. By using equation 6 from Havenith and Nilsson (2004, 2005), derived for cold insulation clothing (with $I_T > 2$ clo), and setting the wind permeability, p, equal to unity (representing typical cold clothing with an impermeable outer layer) a reduction factor, corr-I_T, is defined as follows:

$$CORR \; I_T = e^{\left[-0,0512 \times (v_{ar}-0,4) + 0,794 \times 10^{-3} \ast (v_{ar}-0,4)^2 - 0,0639 \times v_w\right]}$$
(13)

with:

v_{ar} = wind speed relative to the person $(m \cdot s^{-1})$; from 0,4 $m \cdot s^{-1}$ to 18 $m \cdot s^{-1}$

v_w = walking speed $(m \cdot s^{-1})$; from 0 to 1,2 $m \cdot s^{-1}$

v_{ar} = v_w + (wind speed at 1m above ground)

if $v_{ar} > 18 \; m \cdot s^{-1} \; v_{ar} = 18 \; m \cdot s^{-1}$ and

if $v_w > 1.2 \; m \cdot s^{-1} \; v_w = 1.2 \; m \cdot s^{-1}$

This correction factor was found to give reasonable values of $I_{T,r}$ (with $I_{T,r}$ always less than I_T) over the range clothing insulations (I_{cl} = 0.4 to 3.0 clo) and wind speeds at 10 m above the ground (meteorological wind speed; 0 to 30 m/s), giving significant reduction in insulation for higher wind speeds.

The local air velocity, v_{ar} [m/s], can be calculated in the model (used for developing UTCI) from meteorological wind speed measurement at 10m height above ground applying a logarithmic wind profile approach as approximation (which is intrinsically valid only for neutral stratification):

$$v_a = v_{Zr} \frac{\log(Z/z0)}{\log(Zr/z0)}$$

(14)

where Z [m] is the height of the body element (centre) above ground, Zr [m] is the reference height of the meteorological measurement, i.e., 10 m, and z0 [m] is the roughness length, assumed to be 0.01 m in this case (e.g. a short cut meadow or street).

3: Using this correction factor for I_T, the correction factor to be used on I_{cl} was arbitrarily based on the relationships at the upper bound of insulation of 2.5 clo (I_T=2.82 clo):

$$corr\, I_{cl} = \frac{\left(\dfrac{I_{T,r} - I_{a,r}}{f_{cl}}\right)}{2.5} \tag{15}$$

calculated for $I_{T,static}$=2.82 clo; $I_{cl,static}$=2.5 clo.

with

$$I_{T,r} = I_T \cdot corr\, I_T = 2.82 \cdot corr\, I_T \tag{16}$$

This is then applied to all Icl values:

$$I_{cl,r} = I_{cl} \cdot corr\, I_{cl} \tag{17}$$

The resultant air insulation, $I_{a,r}$, is calculated using a corrected form of equation A.13 of ISO 11079 (2007) as follow:

$$I_{a,r} = I_{a,static} \cdot \left(0.92 \cdot e^{(-0.15 v_{ar} - 0.22 v_w)} - 0.0045\right). \tag{18}$$

where the value 0.092 (as given in the standard) is corrected to 0.92 (Holmér 2009, personal communication).

In order to be able to use the above approach for calculating the impact of wind and walking speeds on the resultant insulation values, the local equivalents referring to the global I_{cl}-value used above, are 'mapped' on individual body parts

It should be noted that, in the model, the local resultant wind speed, v_{ar}, is calculated separately for each body element as a composite of the walking speed and the corresponding (local) wind speed to which the body element is exposed to:

$$v_{ar} = \sqrt{\left[\left(v_w - v_a \cdot \cos(\alpha)\right)^2 + \left(v_a \cdot \sin(\alpha)\right)^2\right]} \tag{19}$$

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with

v_a = air speed at 1 m height $(m \cdot s^{-1})$,

v_w = walking speed $(m \cdot s^{-1})$,

α = angle between walking and air speed (0 if in same direction).

This equation is integrated and averaged numerically in the model to obtain a direction-independent expression as described in ISO 9920 (2009). The resultant global insulation for different values of wind speed based on the clothing model developed above is illustrated in Fig. 7 for four different wind speeds.

Figure 7 about here

Calculation of vapour resistance

The impact of the walking and wind speeds on the clothing's resultant evaporative resistance is dealt with using the equation derived by Havenith for ISO 9920 (2009) based on Havenith et al. (1999, 2002):

$$R_{eT,r} = e^{(-0,468 \times (v_{ar} - 0,15) + 0,080 \times (v_{ar} - 0,15)^2 - 0,874 v_w + 0,358 v_w{}^2)} \times R_{eT} \qquad (20)$$

with:

$R_{eT,r}$ =resultant total vapour resistance (m²kPa/W)

R_{eT} =total vapour resistance (m²kPa/W)

v_{ar} = wind speed relative to the person $(m \cdot s^{-1})$; from 0,15 $m \cdot s^{-1}$ to 3.5 $m \cdot s^{-1}$

v_w = walking speed $(m \cdot s^{-1})$; from 0 to 1,2 $m \cdot s^{-1}$

v_{ar} = v_w + (wind speed at 1m above ground)

if v_{ar} > 3.5 $m \cdot s^{-1}$ v_{ar} =3.5 $m \cdot s^{-1}$ and

if v_w > 1.2 $m \cdot s^{-1}$ v_w =1.2 $m \cdot s^{-1}$

Clothing static vapour resistance was calculated as:

$$R_{e,cl} = 0,06 \times \frac{I_{cl}}{i_{m,cl}} \quad \left(in \ m^2 \cdot kPa / W \right) \qquad (21)$$

with:

$R_{e,cl}$ =intrinsic clothing vapour resistance (m²kPa/W)

I_{cl} =intrinsic clothing insulation (m²K/W)

$i_{m,cl}$ =clothing vapour permeability index (n.d.)

based on a vapour permeability index ($i_{m,cl}$) of most permeable one- or two-layer clothing ensembles of 0,34 (ISO 9920, 2009), while $R_{e,T}$ is calculated as:

$$R_{e,T} = R_{e,cl} + \frac{R_{e,a}}{f_{cl}}$$
(22)

With the air layer vapour resistance::

$$R_{e,a} = \frac{0,06}{h_c}$$
(23)

according to ISO 9920 (2009) (modified to ensure the fcl-factor is included only once) using the model's local convective heat transfer coefficients, h_c.

Conclusion

Using real life data for clothing behaviour, a model was developed to determine the insulation and vapour resistance of the clothing worn for individual body segments in relation to ambient temperature. The model incorporates a shift to more specialised cold weather clothing for extreme cold, and includes corrections of the clothing insulation and vapour resistance required to represent the impact of wind and movement on the clothing properties. This clothing model is integrated with the UTCI-Fiala model of thermoregulation (Fiala et al., 2011, this issue) to define the heat transfer properties between the human skin and the environment.

Considering how it was deduced, the clothing model may be considered to represent the clothing behaviour of European and North American urban populations. The most important feature of this clothing behaviour is that people do not adjust their clothing to the climate requirements completely and seem to 'under-dress' in the cold. The approach followed here requires further validation, though first results presented in this issue indicate that it may also be applicable to a urban areas in other continents (Bröde et al. 2011). The principles derived in this action allow the extension to e.g. the working population wearing special clothing for safety and protection, or to populations with different clothing habits (Al-ajmi et al. 2008).

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Table 1: Equation coefficients for the estimation of local insulation in relation to ambient temperature.

	a	b	g	h	C1	C2
Head	0.20430	-0.94440			0.17050	
Hands	0.21550	-0.01010			0.25110	
Upper legs	0.18560	-1.64420			0.31620	0.10080
Lowerlegs	0.18560	-1.64420	1.09740	-33.04490	0.31620	0.10080
Feet	0.09120	0.60090			0.58130	0.03880
Upper body	-0.00135		0.40900	-8.34300	0.10000	0.11240
Lower arms	-0.00135		0.47370	-10.44580	0.16000	0.05240
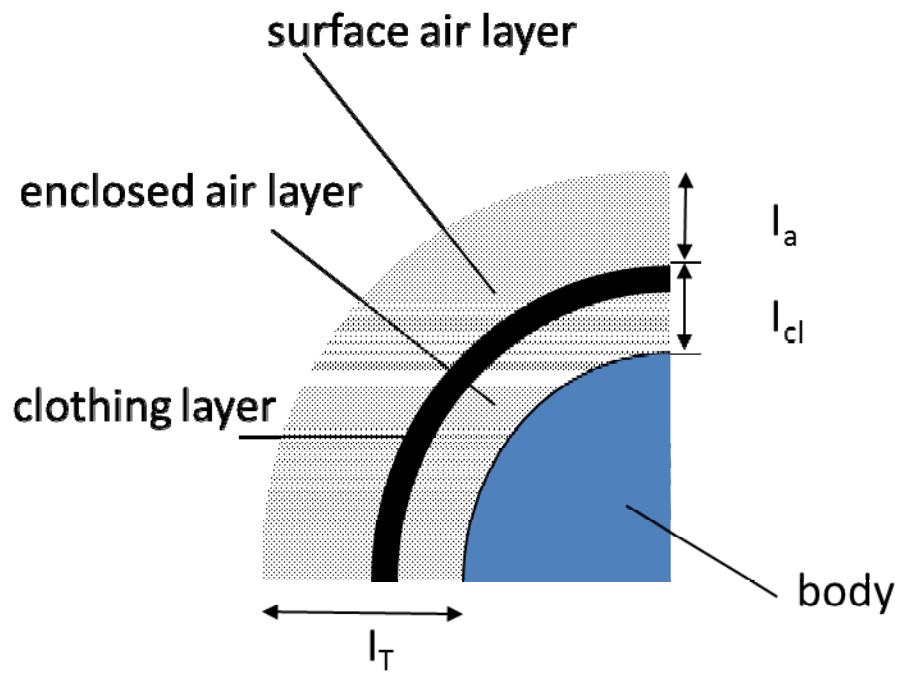
Figure 1, schematic drawing of clothing covering the body with the enclosed and adjacent air layers, indicating the symbols for the insulation of different parts of the package.
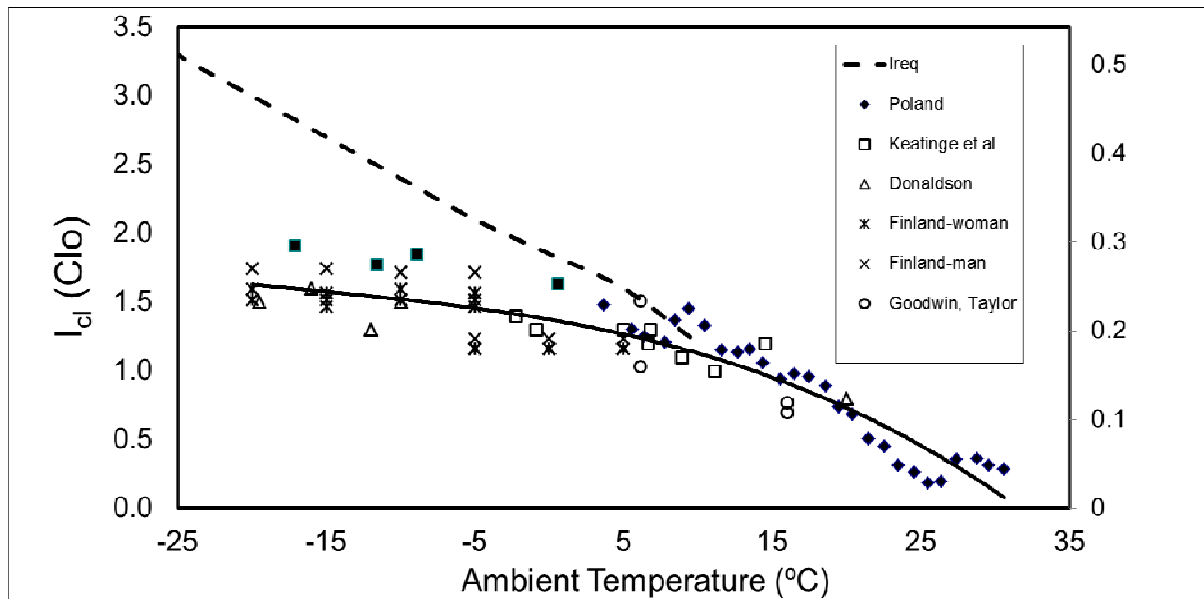
Figure 2, Relationship between intrinsic clothing insulation as observed in field observations and air temperature. Values are presented in clo (left axis) and m^2KW^{-1} (right axis); (1 clo=0.155m^2KW^{-1}). Hashed line represents required clothing insulation for the respective temperatures to be thermo-neutral according to ISO 11079-2007.
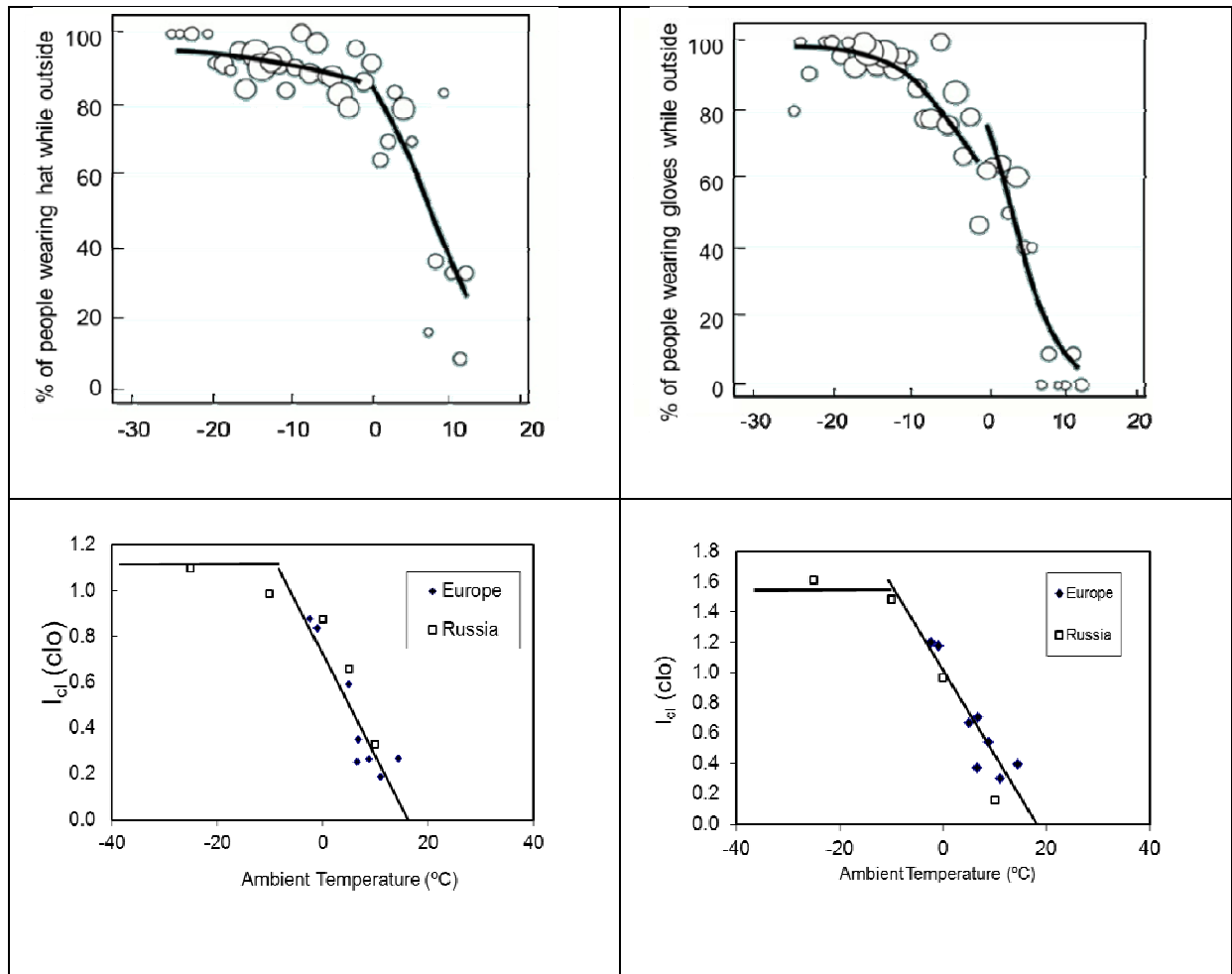
Figure 3, top panel: Observed percentages of clothing items worn outdoors (Adapted by permission from BMJ Publishing Group Limited, Donaldson et. al. 1998) and bottom panel: the corresponding 'probable' local I_{cl}-values as a function of the mean daily outdoor temperature (1 clo=0.155m^{2}KW^{-1}). Left: Hat, Right: gloves.
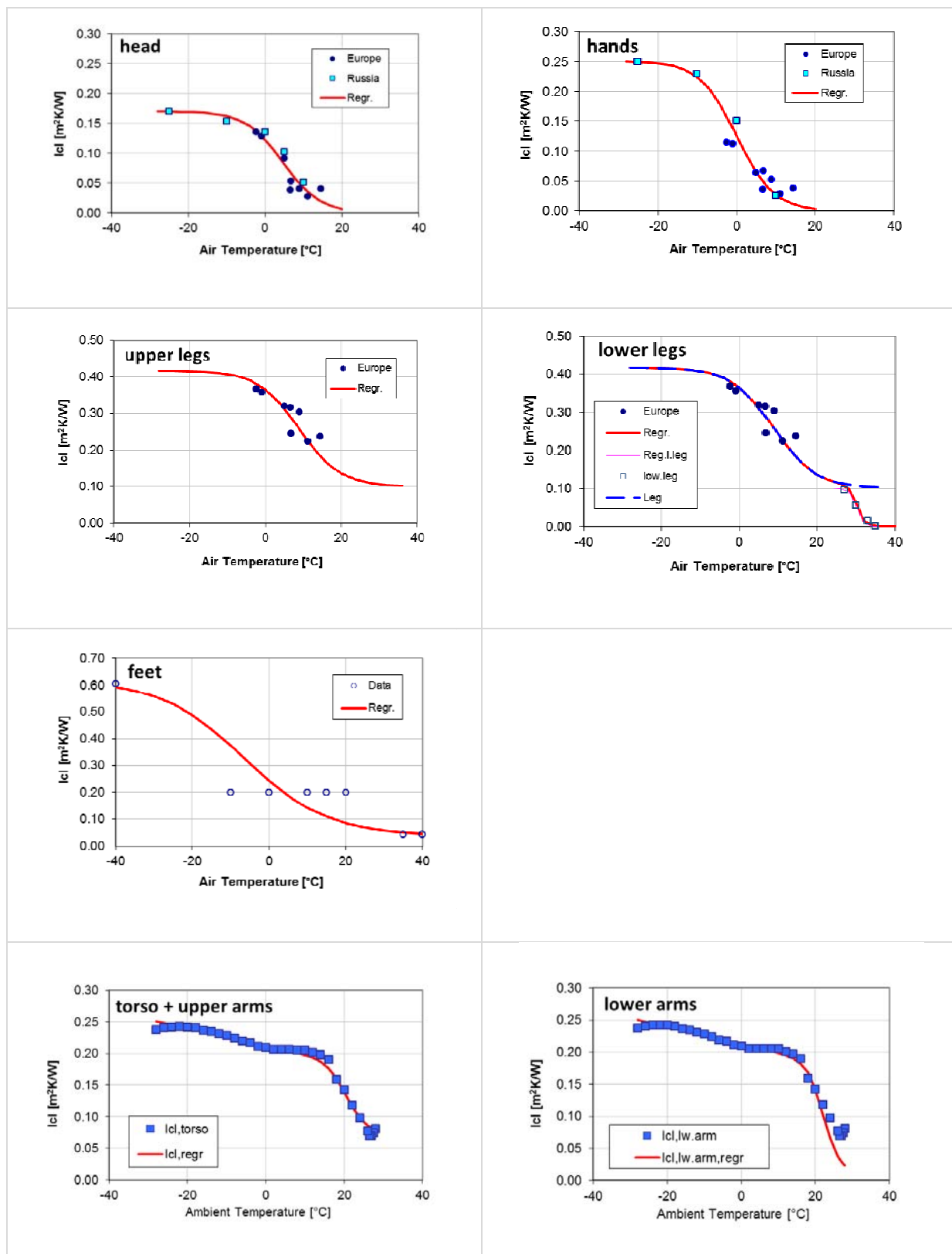
Figure 4, Local clothing insulation values (in m^{2}K/W) for clothing items covering: a) the head, b) hands, c) upper legs, d) lower legs, e) feet, f) torso/upper arms, and g) lower arms.
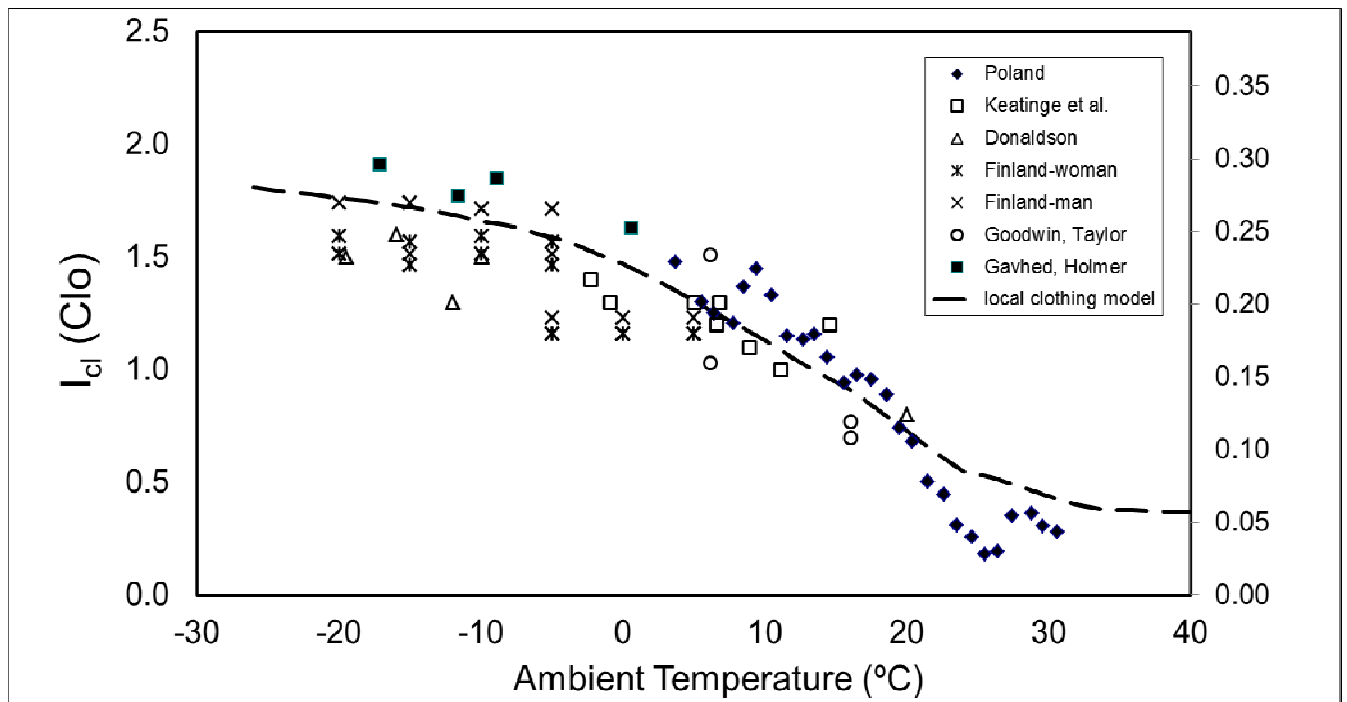
Figure 5, Global thermal insulation values resulting from local quantities as a function of the ambient temperature (1 clo=0.155m^{2}KW^{-1}).
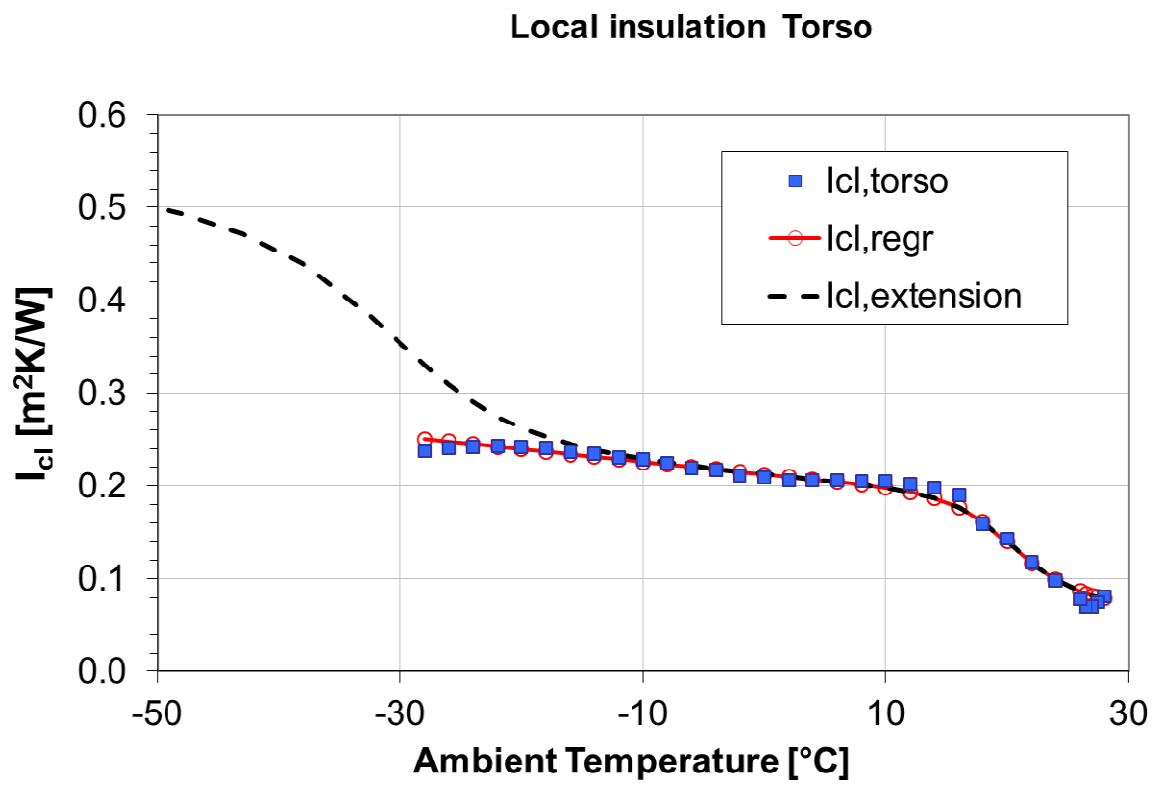
Local insulation Torso

Figure 6, Extension of the adaptive clothing model for local I_{cl}-values of torso/arms for extreme cold conditions.
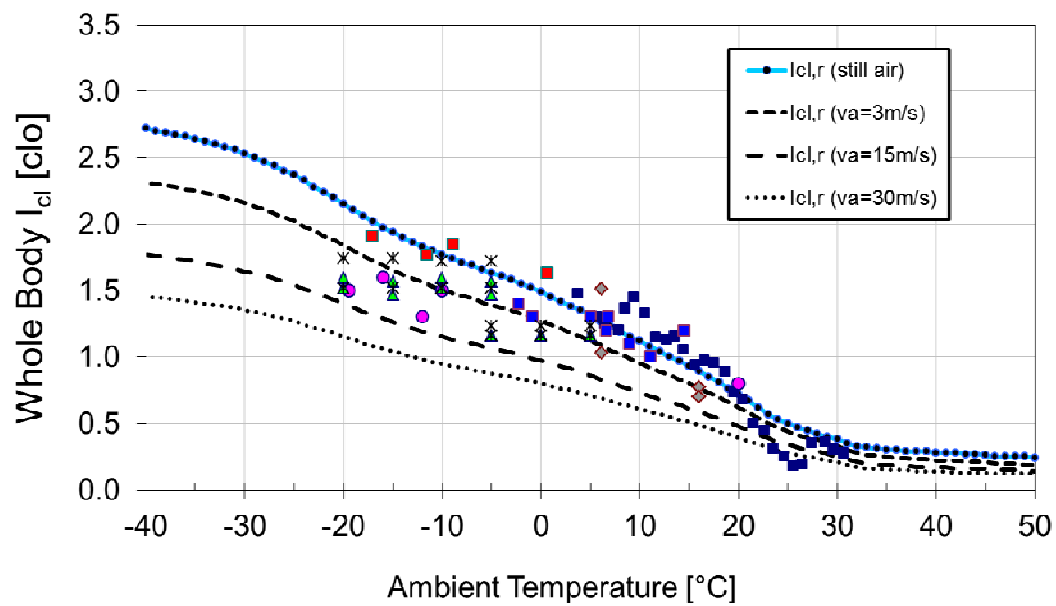
Figure 7, Global thermal insulation values based on the combined UTCI clothing model in relation to ambient temperature for different values of wind speed (referring to meteorological wind speed as measured 10 m above the ground).