Met Office

Review of heat and cold stress indices and heat-balance models

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Contents

Background

There are six basic factors that define the human thermal environment. Four of these are environmental variables: air temperature, radiant temperature, humidity and air movement (wind). The other two are behavioural factors; the metabolic heat generated by human activity, and the clothing worn. An additional human factor is the affect of acclimatisation of the individual.

As the internal temperature of the human body should remain stable, there is a heat balance between the body and its environment. The heat balance equation is:

$$M - W = E + R + C + K + S$$

The metabolic rate of the body (*M*) provides energy to enable the body to do mechanical work (*W*) and the remainder is released as heat (*M* - *W*). Heat transfer can be by conduction (*K*), convection (*C*), radiation (*R*) and evaporation (*E*). *S* is heat storage, which need to be 0 for the body to be in balance. Heat is lost from the body by convection and radiation when ambient and radiation temperatures are less than a person's skin temperature. Convective heat loss varies with wind speed. Heat loss by evaporation varies with humidity and wind speed.

Many different indices have been developed and are in use around the world. These can mainly be divided into two approaches: the human energy balance approach, and simple indices. Heat balance models quantify the exchange of heat between the body and its environment via each process individually. Heat and/or cold stress indices can be divided into rational, empirical and direct indices. Rational indices are based on calculations involving the heat balance equation. Empirical indices are based on establishing relationships with the physiological responses of human subjects. Direct indices are simple indices based on the measurement of basic environmental variables.

Existing heat balance models and heat / cold stress indices will be reviewed in this report. The aim is to select several of these models for evaluation over the coming winter in the UK. As the main concern here will be cold stress, the first indices considered model the chilling effect of the wind. However, it is hoped to eventually include both the heat and cold ends of the spectrum, and to also carry out a summer trial. With this in mind, the report goes on to review some indices that are only valid for heat stress, and then some models can be used both in hot and cold situations.

Cold Stress Indices

Wind Chill Index (WCI)

Model basis

The WCI combines the effect of air temperature and air velocity into a single index or wind chill value. It was empirically derived, originally by Siple and Passel, who conducted experiments on uninsulated cans of water in the Antarctic. There have been several attempts to improve the original formula, for example by Court in 1948 (Steadman, 1971).

Advantages

WCI is widely used throughout the world, and has been reported to give helpful results.

Disadvantages

It is only valid for cold stress situations.

WCI does not consider all relevant processes in the human heat balance. For example, the effect of radiation is not included, and it does not consider respiratory heat loss.

WCI is not valid for high wind speeds over 20 m/s.

WCI does not consider the effect of clothing, and is most applicable for unclothed parts of the body.

Weather variables required

Wind speed (adjusted to 1.5 m above ground level), air temperature.

Ease of implementation

Relatively simple to implement. The formula is in, for example, Parsons (2003), Steadman (1971).

Wind Chill Equivalent Temperature (WCT)

Model basis

The WCT was developed as an operational replacement for the WCO in North America, and was intended to address some of the weaknesses of the WCI. It is based on the effect of air temperature and velocity on a person's facial skin temperature.

Advantages

WCT is simple to implement and interpret. It is used operationally in Canada.

Disadvantages

WCT is only valid for cold stress situations.

It does not consider all relevant processes in the human heat balance.

WCT does not take account of clothing and is applicable for areas of exposed skin only.

A person's experience of wind chill is affected by their cheek thermal resistance: the empirical model is based on the 95th percentile rather than the average. Wind chill is also affected by a person's activity level and movement relative to wind direction, and this is not adjustable.

The effect of the diurnal cycle on the adjustment of wind speed from 10m to 1.5m is not considered.

Weather variables required

Air temperature, wind speed

Ease of implementation

An equation and tables of values are given in Osczevski and Bluestein (2005) – so it should be easy to implement

Required clothing insulation index (IREQ)

Model basis

This is a rational index (i.e. based on the heat balance equation) based on determining the clothing insulation required for heat balance and for comfort. This is similar in concept to the use of the required sweat index (SW_{req}) as a heat stress index. There are two levels: $IREQ_{min}$ is a minimal thermal insulation required for heat balance at a subnormal body temperature with highest acceptable strain, and $IREQ_{neutral}$ is the thermal insulation required to maintain thermal equilibrium at a normal body temperature, with no strain.

Advantages

It has been implemented as an international standard ISO 11079.

Disadvantages

IREQ is only valid for cold stress.

It is likely to be difficult to implement.

Weather variables required

Air temperature, radiant temperature, relative humidity, wind speed

Ease of implementation

There is a web form for calculation of the index here:

http://www.eat.lth.se/fileadmin/eat/Termisk_miljoe/IREQ2009ver4_2.html

The index is complex and requires radiant temperature and metabolic rate to be estimated. Details and algorithms are provided in Holmer (1988).

Heat Stress Indices

Discomfort Index (DI)

Model basis

This direct index is a weighted combination of wet and dry-bulb temperature. The parameters have been developed empirically, and the model has no physiological basis. There are several slightly different formulas.

Advantages

A simple model to implement.

Disadvantages

DI does not take account of the effect of thermal radiation.

It does not allow activity level or clothing to be variable.

It is only applicable to heat stress – not cold stress.

Weather variables required

Wet-bulb temperature, dry-bulb temperature

Ease of implementation

Easy: formulas are in Epstein and Moran, 2006.

Wet Bulb Globe Temperature (WBGT)

Model basis

A weighted combination of three temperature variables. The parameters have been developed empirically, and the model has no physiological basis. The evaluation of thermal stress is performed by comparing the WBGT index values with reference values, which are a function of the metabolic rates and can be varied for different applications.

Advantages

- The most widely used heat stress index worldwide – it has been found to be useful for example military heat casualties (Parsons, 2003).
- It has been adopted as an ISO standard (ISO 7243, 1989).

Disadvantages

- Black-globe temperature is not routinely measured by meteorological stations. However, Gaspar and Quintela (2009) have developed a model to predict the WBGT index from meteorological parameters.
- WBGT can only be used for heat stress, not cold stress.
- Some authors have identified discrepancies between the index and thermal physiological strain (Gaspar and Quintela, 2009). For example, it underestimates the effect of increased convection in hot humid conditions (Maloney and Forbes, 2010).

Weather variables required

Wet-bulb temperature, dry-bulb temperature, black-globe temperature.

Ease of implementation

A very simple algorithm (Parsons, 2003), but difficult to obtain black-globe temperature.

Environmental Heat Stress Index (ESI)

Model basis

This model was developed empirically in order to be a more usable index than the WBGT, with which it correlates well. The usability comes from avoiding the use of the black globe temperature, and instead using the commonly observed relative humidity and solar radiation.

Advantages

The ESI uses only commonly available meteorological parameters.

Disadvantages

The ESI is only valid in hot situations and can not be used for cold stress.

It does not model all relevant process in the human heat balance.

Weather variables required

Air temperature, relative humidity, solar radiation

Ease of implementation

Implementation should be easy, with the formula given in Moran and Epstein (2006).

Required Sweat Rate (SW_{req})

Model basis

Based on a comparison of sweating required to maintain heat balance with the maximum that is physiologically possible and acceptable in humans. This model is a development of the Heat Stress Index (HSI) and the Index of Thermal Strain (ITS).

Advantages

SW_{req} has been accepted as an international standard ISO 7933, 1989.

Disadvantages

The index is only used to predict heat stress.

Mean radiant temperature is not measured directly, but can be estimated using the RayMan model (Matzarakis et al, 2007).

Several studies have found that SWreq has limitations in validity and usability, and have found differences between predicted and actual responses (Parsons, 2003). Some of these limitations concern the effect of clothing and movements.

Weather variables required

Mean radiant temperature, air temperature, vapour pressure, wind speed.

Ease of implementation

A complex series of equations, including values required for metabolic rate and clothing insulation (Parsons, 2003). The estimation of mean radiant temperature is also complex.

Predicted Heat Strain (PHS)

Model basis

A development of SW_{req} to address some of its weaknesses. New models for the effect of clothing and the prediction of mean skin temperature were developed, and all of the algorithms used were reviewed. The model was validated using a database of 909 laboratory and field experiments

Advantages

Considers all relevant processes in the human heat balance.

Derived following collaborative research by European experts in the field, and adopted as an international standard.

Extensive validation showed that the model provides reasonably accurate predictions, which were more reliable than SW_{req} or WBGT (Malchaire et al, 2001).

Disadvantages

Difficult to implement.

Weather variables required

Air temperature, radiant temperature, vapour pressure, wind speed

Ease of implementation

A complex set of equations is provided in Parsons (2003). Metabolic rate is required and can be derived from ISO 8996.

Kata Thermometer

Model basis

This is a model based on a thermometer which measures the cooling or warming power of the atmosphere. It can either operate as a dry bulb, including only heat loss by convection and radiation, or can operate as a wet bulb, in which case it also includes the evaporative power of the atmosphere. Algorithms have been developed to estimate these values from standard meteorological variables. The effect of clothing has to be estimated (a 30% reduction in heat loss).

Advantages

Reasonably accurate predictions verified against empirical data.

Disadvantages

Under-estimated limits when humidity was low (< 30%).

Weather variables required

Dry-bulb temperature, wind speed, relative humidity and solar radiation.

Ease of implementation

Algorithms are provided in Maloney and Forbes (2010). Although the algorithms are relatively complex, there shouldn't be any problems with implementation.

MANMO ('man model')

Model basis

This is a physiological heat balance model which quantifies the exchange of heat via each process individually.

The model has terms to quantify short-wave radiant heat input, long-wave radiant heat balance, convective heat balance, respiratory heat loss, and evaporative heat loss. Assumptions can be made about clothing. The model solves for equilibrium skin temperature, and sweating rate is included as a skin wettedness factor, being linearly related to skin temperature from 33°C to 37°C.

Advantages

The environmental data required are often available.

Reasonably accurate predictions verified against empirical data.

Disadvantages

There is no upper bound on sweating rate in the original model – so the evaporative heat loss will be overestimated when the evaporative potential of the environment exceeds the maximum sweat rate of an individual. An upper bound can be put on the sweating rate, but this provides a conservative estimate of the ability to achieve heat balance.

The model over-estimated limits when humidity was low (< 50%).

The model may not perform well on cloudy days, as radiation is assumed to follow a standard annual cycle.

The model does not seem to have been used to predict cold stress, and has been tailored specifically to perform well on hot days.

Weather variables required

Dry-bulb temperature, relative humidity, wind speed

Ease of implementation

Algorithms are provided in Maloney and Forbes (2010). Although the algorithms are relatively complex, there shouldn't be any problems with implementation.

Combined Heat and Cold Stress Indices

Net Effective Temperature (NET)

Model basis

Developed from effective temperature to include the effect of relative humidity. In hot weather, NET increases as temperature and/or RH increases, but decreases with increasing winds. In cold weather, NET decreases with temperature, and with increasing RH and winds. A large positive value implies high heat load, while a large negative value represents large heat loss.

Advantages

NET is applicable in both hot and cold situations.

It is relatively simple to compute and interpret.

The index is consistent with common human perceptions.

Leung et al (2008) found statistically significant negative-lagged correlations between the daily minimum NET and winter mortality in Hong Kong, attributed to circulatory and respiratory diseases.

Disadvantages

Doesn't model all relevant processes, for example solar radiation is not considered.

Weather variables required

Air temperature, wind speed, relative humidity

Ease of implementation

The simple formula is in Li and Chan (2000).

Weather Stress Index (WSI)

Model basis

WSI is calculated by calculating an apparent temperature and determining to what extent it deviates from the mean value for that location. Thus it takes into account the acclimatisation of humans to the environment in which they live. A threshold (e.g. 0.99) is set for the proportion of days with apparent temperature lower or higher than the day under consideration. The NET (see previous section) can be used as the apparent temperature.

Advantages

WSI is applicable for use in both hot and cold scenarios.

It takes account of acclimatisation.

The index is used operationally in Hong Kong to alert the public to stressful weather (Li and Chan, 2000).

Disadvantages

WSI doesn't model all relevant processes, for example solar radiation is not considered.

Weather variables required

Air temperature, wind speed, relative humidity, including climatology of these variables.

Ease of implementation

Relatively easy, but site-specific climatologies need to be generated.

Perceived Temperature (PT)

Model basis

The Klima-Michel model is a human heat budget model, which incorporates Fanger's comfort equation to calculate perceived heat and cold, leading to estimation of the perceived temperature (PT). The model is based on the assumption of an average male, assumed to be walking at 4 km per hour and wearing appropriate clothing. Thresholds of PT for different levels of stress are given in Jendritsky et al (2000).

Advantages

The model accounts for all process in the heat-balance equation, and only uses input variables available from synoptic stations. If available, short-wave and long-wave radiation from model forecasts can replace cloud information.

Perceived temperatures have been shown to correlate with excess mortality in South Korea (Kim et al, 2009).

PT is used operationally in Germany for forecasts and warnings, and for a range of applications.

Disadvantages

The physiological and behavioural assumptions made may not be valid, so the results expressed in °C may be misleading.

Weather variables required

Air temperature, relative humidity, wind speed, cloud amount and height.

Ease of implementation

May need to get algorithms or code from Deutscher Wetterdienst.

Physiological Equivalent Temperature (PET)

Model basis

PET is defined as the temperature at which, in a typical indoor setting, the heat budget of the human body is balanced in the same way as in the complex outdoor conditions to be assessed. The calculation of the PET is based on the Munich energy-balance model for individuals (MEMI). PET increases with solar radiation in the summer and decreases with wind speed in the winter. PET is highly correlated to PT, with the main differences occurring due to different assumptions about clothing, and the PET's fixed value of vapour pressure.

Advantages

It considers the influence of all thermally relevant climate parameters in a thermophysiologically relevant way.

It can be used for the assessment of both hot and cold conditions.

Easy to interpret by the general public.

Disadvantages

Variations in clothing and activity are not accounted for, as the index is based only on climatic parameters.

Mean radiant temperature is not routinely measured.

Weather variables required

Air temperature, mean radiant temperature, wind speed, humidity.

Ease of implementation

Radiant temperature needs to be derived, and the complex algorithms implemented.

Universal Thermal Climate Index (UTCI)

Model basis

An advanced model of human thermoregulation was validated and extended. This was integrated with a clothing model. UTCI follows the concept of an equivalent temperature, with climate conditions being compared to a reference environment. The UTCI equivalent temperature for a given combination of wind, radiation, humidity and air temperature is defined as the air temperature of the reference environment which produces the same physiological response. A strain index was calculated to model the physiological response.

Advantages

Developed under a European COST action, and proposed for adoption as an ISO standard.

This index aims to be valid for use in a wide range of climates and applications, including both hot and cold ends of the scale. It has plausible reactions to humidity and radiation in warm environments and wind in the cold.

Disadvantages

Weather variables required

Air temperature, solar radiation, relative humidity, wind speed.

Ease of implementation

Although this is a complex model, software source code and an executable program are available at the project's website www.utci.org.

Conclusion and Recommendations

This review has presented a description and assessment of 15 indices and models which are used for quantifying cold stress and / or heat stress.

The models vary in complexity. The more complex indices, which model the human heat balance equation, include the effects of thermal radiation. Consequently they are likely to give more precise results, especially when a person is exposed directly to the sun. However, they are also difficult to implement and apply practically, as the required measurements are not usually available to have to be derived from developed relationships.

The more complex models also include the effects of a person's clothing and metabolic rate. This is very useful when applying to particular situations such as a work environment. However, the requirement here is for an index to be mapped over the entire country for general use or for correlation with excess mortality. This means that the inclusion of these factors is not necessarily going to be helpful.

The trial should include a range of indices from simple to complex. Obviously for the winter trial, indices which are not valid for cold stress should be discounted. The recommended simple indices are WCT and NET. NET could be used as a relative index (WSI) if spatial climatologies can be derived, as it has been shown that acclimatisation has a significant effect on people's thermal perception and comfort. The recommended complex models are UTCI and IREQ. UTCI and IREQ have both been accepted as international standards, so despite their complexity it should be possible to implement them. PT and PET are also candidates for inclusion, but they have possibly been superseded by UTCI. PT and PET have similar approaches and results, but PT would be preferred as it doesn't make use of mean radiant temperature.

The timescales, presentation and communication of the indices will need to be carefully considered. If indices are calculated hourly or 3-hourly then daily maximum values could be presented. However, persistence of heat and cold stress could also be important over timescales of one to several days. The diurnal cycle of exceedances above a threshold of stress could also be useful to enable people to adjust their behaviour during the part of the day when the risk is greatest.

References

Bröde P, Jendritzky G, Fiala D, Havenith G. 2010. The Universal Thermal Comfort Index UTCI in operational use. Proceedings of conference: Adapting to Change: new thinking on comfort, Windsor, April 2010.

Budd GM. 2008. Wet-bulb globe temperature (WBGT) – its history and its limitations. *Journal of Science and Medicine in Sport* **11:** 20-32.

Epstein Y, Moran DS. 2006. Thermal comfort and the heat stress indices. *Industrial Health* **44:** 388-398.

Gaspar AR, Quintela DA. 2009. Physical modelling of globe and natural wet bulb temperatures to predict WBGT heat stress index in outdoor environments. *International Journal of Biometeorology* **53:** 221-230.

Gulyas A and Matzarakis A. 2009. Seasonal and spatial distribution of physiologically equivalent temperature (PET) index in Hungary. *Idöjárás* **113:** 221-231.

Holmer I. 1988. Assessment of cold stress in terms of required clothing insulation – IREQ. *International Journal of Industrial Ergonomics* **3:** 159-166.

Holmer I. 1993. Work in the cold: review of methods for assessment of cold exposure. *International Archives of Occupational Health* **65:** 147-155.

Höppe P. 1999. The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. *International Journal of Biometeorology* **43:** 71-75.

Jendritsky G, Staiger H, Bucher K, Graetz A, Laschewski G. 2000. The Perceived Temperature: the method of Deuscher Wetterdienst for the assessment of cold stress and heat load for the human body. Internet Workshop on Windchill, Environment Canada, 23pp, available from www.utci.org

Kim J, Kim KR, Choi B, Lee D, Kim J. 2009. Regional distribution of perceived temperatures estimated by the human heat budget model (the Klima-Michel model) in South Korea. *Advances in Atmospheric Sciences* **26:** 275-282.

Leung YK, Yip KM, Yeung KH. 2008. Relationship between thermal index and mortality in Hong Kong. *Meteorological Applications* **15:** 399-409.

Li PW, Chan ST. 2000. Application of a weather stress index for alerting the public to stressful weather in Hong Kong. *Meteorological Applications* **7:** 369-375.

Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, Den Hartog E, Holmer I, Parsons K, Alfano G, Griefahn B. 2001. Development and validation of the predicted heat strain model. *Annals of Occupational Hygiene* **45:** 123-135.

Maloney SK, Forbes CF. 2010. What effect will a few degrees of climate change have on human heat balance? Implications for human activity. *International Journal of Biometeorology.*

Matzarakis A, Rutz R, Mayer H. 2007. Modelling radiation fluxes in simple and complex environments – application of the RayMan model. *International Journal of Biometeorology* **51:** 323-334.

Moran DS, Epstein Y. 2006. Evaluation of the Environmental Stress Index (ESI) for Hot/Dry and Hot/Wet Climates. *Industrial Health* **44:** 399-403.

Osczevski R, Bluestein M. 2005. The new wind chill equivalent temperature chart. *Bulletin of the American Meteorological Society* **86:** 1453-1458.

Parsons KC. 2003. Human thermal environments: the effects of hot, moderate, and cold environments on human health, comfort and performance. 2nd edition, Taylor & Francis.

Steadman RG. 1971. Indices of windchill of clothed persons. *Journal of Applied Meteorology* **10:** 674-683.

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