Int J Biometeorol (2017) 61:487–512
DOI 10.1007/s00484-016-1228-6

ORIGINAL PAPER

A comparison and appraisal of a comprehensive range of human thermal climate indices

C. R. de Freitas [1] · E. A. Grigorieva [2]

Received: 25 April 2016 / Revised: 17 July 2016 / Accepted: 1 August 2016 / Published online: 27 August 2016

Abstract Numerous human thermal climate indices have been proposed. It is a manifestation of the perceived importance of the thermal environment within the scientific community and a desire to quantify it. Schemes used differ in approach according to the number of variables taken into account, the rationale employed, and the particular design for application. They also vary considerably in type and quality, method used to express output, as well as in several other aspects. In light of this, a three-stage project was undertaken to deliver a comprehensive documentation, classification, and overall evaluation of the full range of existing human thermal climate indices. The first stage of the project produced a comprehensive register of as many thermal indices as could be found, 165 in all. The second stage devised a sorting scheme of these human thermal climate indices that grouped them according to eight primary classification categories. This, the third stage of the project, evaluates the indices. Six evaluation criteria, namely validity, usability, transparency, sophistication, completeness, and scope, are used collectively as evaluation criteria to rate each index scheme. The evaluation criteria are used to assign a score that varies between 1 and 5, 5 being the highest. The indices with the highest in each of the eight primary classification categories are discussed. The work is the final stage of a study of the all human thermal climatic indices that could be found in literature. Others have considered the topic, but this study is the first detailed, genuinely comprehensive, and systematic comparison. The results make it simpler to locate and compare indices. It is now easier for users to reflect on the merits of all available thermal indices and decide which is most suitable for a particular application or investigation.

Keywords Thermal indices · Human climate assessment · Index evaluation

✉ C. R. de Freitas
c.defreitas@auckland.ac.nz

E. A. Grigorieva
eagrigor@yandex.ru

[1] School of Environment, The University of Auckland, Auckland, New Zealand

[2] Institute for Complex Analysis of Regional Problems, Russian Academy of Sciences, Far Eastern Branch, Birobidzhan, Russia

Introduction

Human well-being is a function of the multifaceted influence of many environmental factors, one of which is the thermal state of the environment. The latter involves the interaction of a great variety of factors such as air temperature, humidity, wind, and solar radiation and influence of the surrounds on these. There is also the human condition to consider. This includes physiological and behavioral variables such as activity level, clothing, posture, and the like. In reality, all these variables come together in a complex way. The huge number of human thermal climate indices that have been proposed over the past 100 years or so is a manifestation of the perceived importance within the scientific community of the thermal environment to society and a desire to quantify it. The index schemes used differ in approach according to the number of variables taken into account, the rationale employed, the relative sophistication of the underlying body-atmosphere heat exchange theory, and the particular design for application. They also vary considerably in type and quality, as well as many other aspects. A comprehensive overview of this range of features was undertaken to address this matter in a research project of three parts. The first part aimed to identify all indices that have been developed and create a detailed register or catalogue of these. The second part of the project set out to devise and apply a primary classification scheme that sorts indices by type. The results of these two parts of the project are reported by de Freitas and Grigorieva (2015). Those presented here are from the third and final part of the project that aims to evaluate these indices. The various stages are summarized below.

Stage 1: index register

The first part of the project was a thorough search of the literature to identify all human thermal climate indices that have been developed and reported in the scientific literature. No index was intentionally excluded. This work produced a comprehensive register of as many thermal indices as could be found, 165 in all. The definition of a human thermal index is taken to be any parameter or indicator reported in the scientific literature that purports to represent or signify the state or significance of the thermal environment for an individual or group of individuals. This includes even straightforward climate variables or terms such as wet bulb temperature, saturation deficit, etc. All cases that meet the definition were incorporated in the full index register given in de Freitas and Grigorieva (2015).

Since the initial classification work (de Freitas and Grigorieva 2015), three additional indices have been uncovered. They are added here to the previous total of 162 indices. The first is the Mahoney Scale (MS), proposed by Mahoney (1967) and cited by Ogunsote and Prucnal-Ogunsote (2003), and second the Evans Scale (ES), designed by Evans (1980) and cited by Ogunsote and Prucnal-Ogunsote (2003). Both of these indices fall into class E ("Proxy thermal stress index") and assigned for use in a warm temperature range with weather classes as an output. They incorporate both air temperature and humidity, but ES includes body-related inputs of clothing insulation and metabolic rate. The third is the adaptation strain index (ASI) for tourists by Błażejczyk and Vinogradowa (2014). The ASI belongs in class H ("Special purpose index") and is very similar to the bioclimatic contrast index (BCI) also by Blazejczyk (2011).

Stage 2: classification

The common rationale underpinning schemes to devise human thermal climate indices is to integrate the heat-related aspects of the environment and the human body in a way that gives meaning to the thermal significance of conditions. The single unifying attribute is energy exchange, or net thermal state, but proxies for this may be used. For instance, temperature equivalent is a commonly used as a proxy for the combined thermal impact on the body of several thermally relevant variables. The rationale for this is the thermal significance of any given air temperature can be imagined by most people based on their experience of various ambient conditions of heat and cold. There are many other approaches, specific references to which are given in some detail by de Freitas and Grigorieva (2015). However, the extent to which an index represents the true significance of thermal conditions depends not only on how correctly the thermal facets of the body and environment have been integrated, but also on a variety of other considerations that relate to its utility.

Many thermal index classification schemes suffer from a number of problems most often related to overlap between categories used or incomplete coverage of all index types. Robust schemes must ensure that the primary classification classes comprise a well-defined and mutually exclusive properties or characteristics of a class. Moreover, the list of primary classification classes must encompass collectively exhaustive aspects, properties, or characteristics of all indices that may exist.

De Freitas and Grigorieva (2015) point to the fact that classification schemes so far proposed suffer from a number of drawbacks most often related to overlap between categories or incomplete coverage of all index types. Robust schemes, as in faceted classification (Broughton 2001), must ensure that the primary classification classes comprise well-defined and mutually exclusive properties or characteristics of a class. Moreover, the list of primary classification classes must encompass collectively exhaustive aspects, properties, or characteristics of all indices that may exist.

The scheme introduced in the first stage of the current project is guided by these criteria. The classification scheme produced comprises of eight primary classification categories with the following letter identifiers and descriptive labels: (a) simulation device for integrated measurement, (b) single-sensor (single-parameter) index, (c) index based on algebraic or statistical model, (d) proxy thermal strain index, (e) proxy thermal stress index, (f) energy balance strain index, (g) energy balance stress index, and (h) special purpose index. Each of the 162 indices listed in Table 1 by de Freitas and Grigorieva (2015) is classified according to this schema, with the classification class identified by letters A to H from the above list and entered in the far right column of the table. The word "proxy" in C and D is used in place "empirical," the inferred meaning of which is considered too strong, as it can imply "first hand." Proxy implies "a substitute for," or "alternative to," the energy balance approach.

Stage 3: evaluation of indices

The various index schemes proposed, to date, vary in approach according to the number of variables taken into account, the rationale employed, the relative sophistication of the scheme, and methods used to express output. Virtually, all indices have a particular "design for application" in that

Table 1 A comprehensive list of 165 human thermal bioclimatic indices with sources and indicators for evaluation

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
A. Simulation device for integrated measurement										
Black sphere actinograph	Poschmann (1932), cited by Eissing (1995)	[Unknown]	P	Surface temperature of sphere	–	Sts	Ab	No	No	Temperature equivalent (°C)
Cylinder (C) (modification of Tg as written in Brown and Gillespie 1986)	Brown and Gillespie (1986)	−15 to +38	P	Surface temperature of cylinder	–	Sts	Ab	No	No	Temperature equivalent (°C)
Ellipsoid index	Blazejczyk et al. (1998)	0,+10, +20	P	T_a,S	–	Sts	Ab	No	No	Temperature equivalent (°C)
Eupathescope (Eupatheostat)	Dufton (1929)	+20 to +38	P	T_e (T_a,T_w,v)	–	Sts	Ab	No	No	Temperature equivalent (°C)
Frigorimeter	Dorno (1928), cited by Smithson and Baldwin (1979)	[unknown]	P	Surface temperature of sphere	–	Sts	Ab	No	No	Temperature equivalent (°C)
Globe Thermometer Temperature (Tg)	Vernon (1932), Bedford and Warner (1934)	−15 to +38	P	T_g	–	Sts	Ab	No	No	Temperature equivalent (°C)
Kata thermometer	Hill et al. (1916)	+5 to +38	P	T_a,v,e,L	–	Sts	Ab	No	No	Calorific (mcal m^{-2} c^{-1})
Metal man (thermal manikin)	Pedersen (1948), cited by Eissing (1995)	[unknown]	P	T_a	–	Sts	Ab	No	No	Temperature equivalent (°C)
Resultant thermometer	Missenard (1935), cited by Eissing (1995)	[unknown]	P	T_a(e,v,S,L)	–	Sts	Ab	No	No	Temperature equivalent (°C)
Thermo-Integrator	Winslow et al. (1935)	+15 to +36	P	T_a,v,L	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Wet Globe Temperature (WGT) or Botsball	Botsford (1971), cited by Beshir and Ramsey (1988)	+10 to +50	P	T_{gw}	–	Sts	Ab	No	No	Temperature equivalent (°C)
B. Single-sensor (single-parameter) index										
Air temperature (T_a)	Macpherson (1962), Holmer (1993)	−90 to +60	P	T_a	–	Sts	Ab	No	No	Temperature (°C)
Dewpoint temperature	Bruce (1916), cited by Brüner (1959)	n/a	P	T_{dp}	–	Sts	Ab	No	No	Dewpoint temperature (°C)
Physical saturation deficit	Thilenius and Dorno (1925), cited by Eissing (1995)	n/a	P	e	–	Sts	Ab	No	No	Humidity (mmHg)
Saturation deficit	Flügge (1912), cited by Eissing (1995)	n/a	P	e	–	Sts	Ab	No	No	Humidity (mmHg)
Sultriness value	Scharlau (1943), cited by Eissing (1995)	n/a	P	e	–	Sts	Ab	No	No	Humidity (mmHg)

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Wet Bulb Temperature (Twb)	Haldane (1905)	+10 to +50	P	T_{wb}	–	Sts	Ab	No	No	Temperature equivalent (°C)
C. Algebraic or statistical model										
Air Enthalpy (AirE) or (i)	Gregorczuk (1968)	0 to +35	P	T_a,T_w,b	–	Sts	Ab	No	No	Calorific (kcal kg^{-1})
Apparent Temperature (AT)	Arnoldy (1962)	−90 to 0	P	T_a,v	–	Sts	Ab	No	No	Temperature equivalent (°C) Level of stress (points-scale)
Belgian Effective Temperature (BET or TEL)	Bidlot and Ledent (1947), cited by Graveling et al. (1988)	+27 to +35	A	T_a,T_w	–	Stn	Ab	No	Yes	Temperature equivalent (°C)
Biometeorological Comfort Index (BCI)	Rodriguez et al. (1985)	+1 to +37	A	T_a,T_w,v	–	Sts	Ab	No	No	Temperature equivalent (°C)
Bodman's Weather Severity Index (BWSI) or (S)	Bodman (1908), cited by Tikhomirov (1968)	−90 to 0	P	T_a,v	–	Sts	Ab	No	No	Descriptive 7-point scale
Comfort Vote (CmV) or (S)	Bedford (1961)	[indoors]	P	T_a,T_{mr},e,v	–	Sts	Ab	No	Yes	Thermal sensation (TSL scale)
Cumulative Discomfort Index (CumDI)	Tennenbaum et al. (1961), Sohar et al. (1962)	+15 to +35	P	T_a,T_w	–	Sts	Ab	No	No	Temperature equivalent (°C)
Discomfort Index (DI_T) or Temperature Humidity Index (THI)	Thom (1957), Thom and Bosen (1959) cited in Tromp (1966), Landsberg (1972)	+20 to +40	P	T_a,T_w	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Discomfort Index (DI_K)	Kawamura (1965), cited by Ono and Kawamura (1991)	+1 to +40	P	T_a,T_{dp}	–	Sts	Ab	No	No	Temperature equivalent (°C)
Effective Temperature (ET_M)	Missenard (1933), cited by Gregorczuk and Cena (1967)	−45 to +45	P	T_a,e	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Environmental Stress Index (ESI)	Moran et al. (2001, 2003)	+17 to +45	A	T_a,e,S	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Equatorial Comfort Index (ECI) or Singapore Index	Webb (1959)	+10 to +60 [indoors]	A	T_a,e,v	–	Sts	Ab	No	Yes	Temperature equivalent (°C) Thermal sensation (TSL scale)
Equivalent Effective Temperature (EET)	Aizenshtat and Aizenshtat (1974)	−45 to +45	P	T_a,e,v	Clo	Sts	Ab	No	No	Temperature equivalent (°C)

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Equivalent Warmth (EqW)	Bedford (1936), cited by Auliciems and Szokolay (2007)	+20 to +38 [indoors]	A	T_a,T_{mrt},e	T_s	Sts	Ab	No	Yes	Temperature equivalent (°C)
Humidex (HD)	Masterson and Richardson (1979)	+21 to +49	P	T_a,e(T_{dp})	–	Sts	Ab	No	No	Temperature equivalent (°C)
Humisery	Weiss (1982)	+20 to +45	P	T_a,e,v,el	–	Sts	Ab	No	No	Temperature equivalent (°C)
Humiture	Hevener (1959), Lally and Watson (1960), Winterling (1979)	+20 to +45	P	T_a,T_w	–	Sts	Ab	No	No	Temperature equivalent (°C)
Increment Temperature Equivalent to Radiation Load (ITER)	Lee and Vaughan (1964)	+40 to +50	A	T_a,v,S	Clo,w	Sts	Ab	No	Yes	Temperature equivalent (°C)
Index of thermal sensation (ITSN)	Rohles and Nevin (1971), Rohles et al. (1975)	+16 to +37 [indoors]	A	T_a,e	Clo,M	Sts	Ab	No	Yes	Thermal sensation (TSL scale)
Insulation Predicted index (Iclp)	Blazejczyk (2011)	−20 to +5	A	T_a,v	M	Sts	Ab	No	No	Clothing required for comfort (°C m^2 W^{-1})
Modified Discomfort Index (MDI)	Moran et al. (1998a)	+15 to +35	A	T_a,T_w	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Oxford Index (OxI) or Wet-Dry Index (WD)	Lind and Hellon (1957)	+30 to +55	A	T_a,T_w	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Perceived Temperature (PT_L) Gefühlte Temperatur	Linke (1926), cited by Eissing (1995)	[unknown]	P	T_a,v,L	–	Sts	Ab	No	No	Temperature equivalent (°C)
Relative Humidity Dry Temperature (RHDT)	Wallace et al. (2005)	+20 to +50	P	T_a,T_w	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Resultant Temperature (RT) or Net Effective Temperature (NET)	Missenard (1948), cited by Givoni (1969); Landsberg (1972)	−45 to +45	P	T_a,T_{we},v	Clo	Sts	Ab	Yes	Yes	Temperature equivalent (°C)
Severity Rating (S)	Osokin (1968)	−90 to 0	P	T_a,ΔT_a,e,v	–	Sts	Ab	No	No	Descriptive 7 −point scale
Subjective Temperature (ST)	McIntyre (1973)	+10 to +35 [indoors]	A	T_a,T_{mrt},v	Clo,M	Sts	Ab	No	No	Temperature equivalent (°C) Thermal sensation (TSL scale)
Summer Simmer Index (SumSI)	Pepi (1987, 1999)	+20 to +40	P	T_a,e	–	Sts	Ab	No	No	Temperature equivalent (°C)
Temperature Humidity Index (THI_S)	Schoen (2005)	0 to +60	P	T_a,T_{dp}	–	Sts	Ab	No	No	Temperature equivalent (°C)
Temperature-Wind Speed-Humidity Index (TWH)	Zaninović (1992)	−45 to +45	P	T_a,e,v	–	Sts	Ab	No	No	Calorific (kJ kg^{-1})

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Thermal-insulation Characteristics of Clothing (TICC)	Kondratyev (1957), cited by Rusanov (1981)	−30 to +20	P	T_a,v	M	Sts	Ab	No	No	Clothing required for comfort (°C m^2 W^{-1})
Tropical summer index (Tsi)	Bureau of Indian Standards (1987), cited by Auliciems and Szokolay (2007)	+15 to +40	A	$T_a(T_g)$,T_w,v	–	Sts	Ab	No	Yes	Temperature equivalent (°C) Comfort scale (points)
Wet Bulb Globe Temperature (WBGT)	Yaglou and Minard (1957), cited by Kerslake (1972)	+10 to +50	P	T_a,T_g,T_{we}	–	Sts	Ab	No	Yes	Temperature equivalent,(°C)
Wet-bulb dry temperature (WBDT)	Wallace et al. (2005)	+20 to +50	P	T_a,T_w	–	Sts	Ab	No	Yes	Temperature equivalent (°C)
Wet Kata Cooling Power by Hill (WKCP) (H_w)	Hill and Hargood-Ash (1919)	−40 to +30	P	T_a,e,v	–	Sts	Ab	No	No	Calorific (W m^{-2})
Wind Chill Equivalent Temperature (WCTwc) (Twc)	Falconer (1968)	−90 to +33	A	T_a,v,S	–	Sts	Ab	No	No	Temperature equivalent (°C)
Wind Chill Index (WCI)	Siple and Passel (1945)	−60 to 0	P	T_a,v	–	Sts	Ab	No	No	Calorific (kcal m^{-2} hr^{-1})
D. Proxy thermal strain index										
Cold Strain Index (CSI)	Moran et al. (1999), Pandolf and Moran (2001), Rissanen and Rintamäki (2007)	−33 to +10	A	No	T_s,T_r	Stn	Ab	No	Yes	Level of strain (points-scale)
Cumulative Heat Strain Index (CHSI)	Frank et al. (1996)	+40 to +45	A	No	T_r,Hr	Stn	Ab	No	Yes	Level of strain (units)
Index of Physiological Effect (IPhysE) or (Ep)	Robinson et al. (1945)	+23 to +50	A	T_a,e	Clo,M,Hr,T_r,T_s,W	Stn	Ab	No	Yes	Level of strain (points-scale)
Index of Thermal Stress (ITS_K) (N)	Kondratyev (1957), cited by Rusanov (1981)	−30 to +20	P	T_a,v	Clo,M	Stn	Ab	No	No	Level of strain (points−scale)
Integral Index of Cooling Conditions (IICC)	Afanasieva et al. (2009)	−55 to 0	A	T_a,v	Clo,M	Stn	Ab	No	Yes	Level of strain (points−scale)
Mean Equivalence Lines (MEL)	Wenzel(1978)	+15 to +57	A	T_a,e	M	Stn	Ab	No	Yes	Level of strain (points−scale)
Perceptual Hyperthermia Index (PHI)	Gallagher et al. (2012)	+33 to +40	A	No	T_c,Hr	Stn	Ab	No	Yes	Level of strain (points−scale)
Perceptual strain index(PeSI)	Tikuisis et al. (2002)	+40	A	T_a,e	T_c,Hr	Stn	Re	No	Yes	Level of strain (points−scale)
Physiological Heat Exposure Limit (PHEL) Chart	Dasler (1977)	+20 to +50	A	T_a,T_g,T_{we},v	M	Stn	Ab	No	Yes	Survival time (min)
	Hall and Polte (1960)	+37 to +70	P	No	T_r,W,Hr	Stn	Ab	No	Yes	

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Physiological Index of Strain (Is)										Level of strain (points−scale)
Physiological Strain Index (PSI)	Moran et al. (1998b), Moran (2000)	+20 to +50	A	No	T_r,Hr	Stn	Ab	No	Yes	Level of strain (points−scale)
Predicted Four−hour Sweat Rate (P4SR)	McArdle et al. (1947), cited by Givoni (1969)	+27 to +55	A	$T_a(T_g),T_w$,v	Clo,M accl	Stn	Ab	No	Yes	Sweat rate (litres)
Skin Temperature (SkT) or (tsk)	Mehnert et al. (2000)	+20 to +60	A	T_a,T_{mrt},e,v	Clo,M,T_r	Stn	Ab	No	Yes	Skin temperature (°C)
Skin wettedness (SkW)	Gonzalez et al. (1978)	+25 to +50	A	T_a,T_w	–	Stn	Ab	No	Yes	Skin wettedness (%)
E. Proxy thermal stress index										
Bioclimatic Index of the Severity of Climatic Regime (BISCR)	Belkin (1992)	−90 to +60	P	T_a,e,v,b,el	–	Sts	Ab	No	No	Comfort (points −scale)
Classification of Weather in Moments (CWM)	Rusanov (1973)	−50 to +35	P	T_a,e,v,n	–	Sts	Ab	No	Yes	Weather types
Comfort Index (CI)	Terjung (1966, 1968)	−40 to +40	P	T_a,e	–	Sts	Ab	No	No	Thermal sensation (TSL scale)
Corrected Effective Temperature (CET)	Vernon and Warner (1932), Bedford (1964)	+1 to +43	A	T_g,T_w,v	Clo	Sts	Ab	No	Yes	Temperature equivalent (°C)
Daily Weather Types (DWT)	Lecha (1998)	+5 to +35	P	T_a,e,v,n,pr	–	Sts	Ab	No	Yes	Weather types
Effective Temperature (ET)	Houghten and Yagloglou (1923), cited by Givoni (1969)	+1 to +45	P	T_a,T_w,v	Clo	Sts	Ab	No	Yes	Temperature equivalent (°C)
Index of Pathogenicity of Meteorological Environment (IPME)	Latyshev and Boksha (1965)	−30 to +30	P	$T_a,\Delta T_a$,e,v,n,S,Δb	–	Sts	Re	No	Yes	Level of strain (points−scale)
Index of Sultriness Intensity (ISI)	Akimovich and Balalla (1971)	+16 to +40	P	T_a,e	–	Sts	Ab	No	No	Level of sultriness (points−scale)
Evans Scale (ES)	Evans (1980), cited by Ogunsote and Prucnal-Ogunsote (2003)	+5 to +35	A	T_a,e	Clo,M	Sts	Ab	No	No	Weather types
Mahoney Scale (MS)	Mahoney (1967), cited by Ogunsote and Prucnal-Ogunsote (2003)	+5 to +35	P	T_a,e	–	Sts	Ab	No	No	Weather types
Meteorological Health Index (MHI)	Bogatkin (2006)	−30 to +40	P	$T_a,\Delta T_a$,e,v,b,n,pr,Δb	–	Sts	Re	No	No	Level of stress (points)
Modified Effective Temperature (MET)	Smith (1952), cited by Graveling et al.	+1 to +43	A	T_g,T_w,v	Clo,M	Sts	Ab	No	Yes	Temperature equivalent (°C)

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
	(1988)									
Spatial Synoptic Classification (SSC)	Kalkstein et al. (1996), Sheridan (2002)	−90 to +60	A	T_a,ΔT_a,e,v,n	–	Sts	Ab	No	Yes	Weather types
Summer Severity Index (SSI) or (I_o)	McLaughlin and Shulman (1977)	+20 to +40	P	T_a,ΔT_a,e,pr,S	–	Sts	Ab	No	No	Thermal sensation (TSL scale)
Thermal Sensation Index (TSNI), (S)	de Paula Xavier and Lamberts (2000)	+15 to +30 [indoors]	A	T_a,T_{mrt},e,v	Clo,M	Sts	Ab	No	Yes	Thermal sensation (TSL scale)
Wind Effect Index (WEI)	Terjung (1966)	−40 to +30	P	T_a,v,S	–	Sts	Ab	No	No	Calorific (kcal m^{-2} h^{-1})
F. Energy balance strain index										
Body–atmosphere Energy Exchange Index (BIODEX)	de Freitas and Ryken (1989)	−15 to +32	A,P	T_a,e,v, S(optional)	Clo,M	Stn	Ab	Yes	Yes	Body core temperature (°C)
Body Temperature Index (BTI)	Dayal (1974)	+30 to +42	A	T_a,T_g,e,v	Clo,M,accl	Stn	Ab	Yes	Yes	Body temperature (°C)
Effective Heat Strain Index (EHSI)	Kamon and Ryan (1981)	+27 to +36	A	T_a,T_w,T_g,v	Clo,M	Stn	Ab	Yes	No	Level of strain (points–scale)
Equilibrium Rectal Temperature (ERT) or(T_{rec})	Givoni and Goldman (1972)	+25 to +49	A	T_a,e,v	Clo,M,accl	Stn	Ab	Yes	Yes	Body temperature (°C)
Exposed Skin Temperature (EST)	Brauner and Shacham (1995)	−60 to +10	A	T_a,v,S	M	Stn	Ab	Yes	No	Skin temperature (°C) Comfort scale (points)
Heart Rate Index (HRI_G)	Givoni and Goldman (1973a)	+25 to +50	A	T_a,e,v	Clo,M	Stn	Ab	Yes	Yes	Heart rate (min^{-1})
Heart Rate Index (HRI_D)	Dayal (1974)	+30 to +42	A	T_a,T_g,e,v	Clo,M,accl	Stn	Ab	Yes	Yes	Heart rate (min^{-1})
Heat Strain Decision Aid Model (HSDA)	Cadarette et al. (1999), Santee and Wallace (2003)	+18 to +43	A	T_a,T_w,T_g,e,v	Clo,M	Stn	Ab	Yes	Yes	Body temperature (°C)
Heat Stress Index – Belding and Hatch (HSI_{BH})	Belding and Hatch (1955)	+27 to +35	A	T_a,T_g,e,v	Clo,M	Stn	Ab	Yes	Yes	Level of stress (points–scale) with strain equivalence given
Heat Stress Prediction Model (HSPM) or Heat Strain Model	Pandolf et al. (1986), Cadarette et al. (1999)	+18 to +43	A	T_a,e,v,S	Clo,M	Stn	Ab	Yes	Yes	Body temperature (°C)
Heat Tolerance Limits (HTL)	Vogt et al. (1982)	+20 to +60	A	T_a,T_{mrt},e,v	Clo,M	Sts	Ab	Yes	Yes	Heat tolerance limits (chart lines)
Index of Thermal Stress (ITS)	Givoni (1969)	+20 to +55	A	T_a,e,v,S,L	Clo,M	Stn	Ab	Yes	Yes	Sweat rate (kcal hr^{-1})
Maximum Exposure Time (MET)	Brauner and Shacham (1995)	−60 to +10	A	T_a,v,S	M,T_s	Stn	Ab	Yes	No	Skin temperature (°C)

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Maximum Recommended Duration of Exercises (MRDE)	Young (1979)	+10 to +50	A	T_a,e,S	M	Stn	Ab	Yes	No	Level of strain (points−scale)
Physiological Strain(PhS)	Blazejczyk (2005), Blazejczyk, Matzarakis (2007)	−40 to +40	A	T_a,e,v,n,S,(L),b	Clo,M	Stn	Ab	Yes	Yes	Level of strain (points−scale)
Physiological Subjective Temperature (PST)	Blazejczyk, Matzarakis (2007)	−40 to +40	A	T_a,e,v,n,S,(L),b	Clo,M	Stn	Ab	Yes	No	Temperature equivalent (°C) Thermal sensation (TSL scale)
Predicted Heat Strain (PHS)	Malchaire et al. (2001)	+25 to +50	A	T_a,T_{mrt},e,v	Clo,M	Stn	Ab	Yes	Yes	Sweat rate (g h^{-1}) Body temperature (°C)
Reference Index (RI)	Pulket et al. (1980)	+30 to +40	A	T_a,e,v,L	Clo,M	Stn	Ab	Yes	Yes	Level of strain (points−scale)
Relative Heat Strain (RHS)	Lee and Henschel (1966)	0 to +60	A	T_a,T_w,e,v	Clo,M	Stn	Ab	Yes	No	Comfort scale (points)
Required Sweat Rate (Req SR)	Vogt et al. (1981, 1982)	+20 to +60	A	T_a,T_g,e,v	Clo,M	Stn	Ab	Yes	Yes	Sweat rate (g m^{-2} s^{-1})
Respiratory Heat Loss (RHL) (Qr)	Rusanov (1989)	−90 to +37	A,P	T_a,e,b,el	M	Stn	Ab	Yes	Yes	Calorific (W)
Skin Temperature Energy Balance Index (STEBIDEX)	de Freitas (1985, 1986, 1987)	−25 to +35	A,P	T_a,v,e,L,S	Clo,M	Stn	Ab	Yes	Yes	Skin temperature (°C)
Subjective Temperature Index (STI)	Blazejczyk (2005)	−40 to +40	A	T_a,e,v,n,S,(L),b	Clo,M	Stn	Ab	Yes	Yes	Temperature equivalent (°C) Thermal sensation (TSL scale)
Survival Time Outdoors in Extreme Cold (STOEC)	de Freitas and Symon (1987)	−40 to +10	A,P	T_a,v,S	M	Stn	Ab	Yes	No	Survival time (hrs)
Thermal Acceptance Ratio (TAR)	Ionides et al. (1945), cited by Graveling et al. (1988)	+27 to +35	A	T_a,T_{mrt},e	M	Stn	Ab	Yes	Yes	Level of strain (points−scale)
Thermal Discomfort (DISC)	Gagge et al. (1986)	+10 to +50 [indoors]	A,P	T_a,v,e,L	Clo,T_s	Stn	Ab	Yes	No	Level of strain Thermal sensation (TSL scale)
Thermal Strain Index (TSI)	Lee (1958)	0 to +65	A	T_a,e,v	Clo,M	Stn	Ab	Yes	No	Comfort scale (points)
Thermal Work Limit (TWL)	Brake and Bates (2002)	+36 to +40	A,P	T_a,T_g,e,v,b	Clo,M,accl	Stn	Ab	Yes	Yes	Calorific (W m^{-2})

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
G. Energy balance stress index										
Air Cooling Power (ACP)	Mitchell and Whillier (1971) McPherson (1992)	+20 to +43	A	T_a,T_w,T_g,v,b	Clo,M,T_s	Sts	Ab	Yes	No	Calorific (W m^{-2})
Apparent Temperature (AT) or Heat Index (HI)	Steadman (1979, 1984)	+20 to +60	A	T_a,e,S	Clo,M	Sts	Ab	Yes	No	Temperature equivalent (°C)
Climate Index (CLIM)	Becker (2000)	−40 to +40	A,P	T_a,e,v,S,L,n	Clo,M	Sts	Ab	Yes	No	Thermal sensation (TSL scale)
Clothing Insulation (Ic)	Mount and Brown (1982, 1985)	−20 to +20	P	T_a,v,S,n,pr	–	Sts	Ab	Yes	No	Clothing required for comfort (°C m^2 W^{-1})
Clothing Thickness (Clo)	Steadman (1971)	−40 to 0	P	T_a,v,S	–	Sts	Ab	Yes	No	Clothing required for comfort (mm)
Comfort Chart (CmCh)	Mochida (1979)	+15 to +32	A	T_a,T_{mr},e,v	Clo,M	Sts	Ab	Yes	No	Comfort chart giving lines of equal temperature sensation
Heat Budget Index (HEBIDEX)	de Freitas (1985, 1986, 1987)	−25 to +35	A,P	T_a,v,e,L,S	Clo,M	Sts	Ab	Yes	Yes	Calorific (W)
Heat Stress Index (HSI_{WK})	Watts and Kalkstein (2004)	+20 to +60	A	T_a,e,v,n	Clo	Sts	Re	Yes	Yes	Thermal sensation (TSL scale)
Humid Operative Temperature (HToh)	Nishi and Gagge (1971), Gagge et al. (1971)	+10 to +40	A,P	T_a,T_{mrt},e,v	Clo,M	Sts	Ab	Yes	Yes	Temperature (°C)
Index of Clothing Required for Comfort (CLODEX)	de Freitas (1986, 1987)	−25 to +35	A,P	T_a,v,e,L,S	Clo,M	Sts	Ab	Yes	No	Clothing required for comfort (clo)
Modified (Reduced) Temperature (MTTR) or (T_{np})	Adamenko and Khairullin (1972)	−60 to 0	A	T_a,v,S	–	Sts	Ab	Yes	Yes	Temperature equivalent (°C)
Natural Wet Bulb Temperature (NWBT) or (Tn)	Maloney and Forbes (2011)	−40 to +30	P	T_a,e,v,S	–	Sts	Ab	Yes	Yes	Temperature equivalent (°C)
New Effective Temperature (ET*)	Gagge et al. (1971)	+10 to +40	A,P	T_a,T_{mrt},e,v	Clo,M	Sts	Ab	Yes	Yes	Temperature equivalent (°C) Comfort scale (points)
New Wind Chill Temperature Index (NWCI or WCET)	OFCM (2003), Osczevski and Bluestein (2005)	−40 to +10	A	T_a,v	–	Sts	Ab	Yes	Yes	Temperature equivalent (°C)
Operative Temperature (OpT) or (To)	Winslow et al. (1937), Winslow and Herrington (1949)	+5 to +40	P	T_a,T_{mrt},v	M	Sts	Ab	Yes	Yes	Temperature equivalent (°C)

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Outdoor Apparent Temperature (OAT)	Steadman (1984, 1994)	−40 to +50	A	T_a,e,v,S	Clo,M	Sts	Ab	Yes	No	Temperature equivalent (°C)
Outdoor Thermal Environment Index (OTEI) or (ETVO)	Nagano and Horikoshi (2011)	−90 to +60	A,P	T_a,e,v,S,L	Clo,M	Sts	Ab	Yes	No	Temperature equivalent (°C)
Perceived Temperature (PT_J)	Jendritzky et al. (2000), Staiger et al. (2012)	−40 to +50	A	T_a,e,v,S,L	Clo,M	Sts	Ab	Yes	No	Temperature equivalent (°C)
Physiological Equivalent Temperature (PET)	Mayer and Höppe (1987)	−50 to +50	A	T_a,T_{mrt},e,v	Clo,M	Sts	Ab	Yes	Yes	Temperature equivalent (°C)
Predicted Mean Vote – indoors (PMV)	Fanger (1970)	+15 to +45 [indoors]	A	T_a,v,e,L	Clo,M	Sts	Ab	Yes	Yes	Thermal sensation (TSL scale)
Predicted Mean Vote – outdoors (PMV*)	Gagge et al. (1986)	0 to +50	A	T_a,v,e,S,L	Clo,M,T_s	Sts	Ab	Yes	No	Thermal sensation (TSL scale)
Predicted Mean Vote – Fuzzy (PMV_F)	Hamdi et al. (1999)	−10 to +32	A	T_a,v,e,L	Clo,M	Sts	Ab	Yes	No	Thermal sensation (TSL scale)
Predicted Mean Vote – outdoors (PMVo)	Jendrizky and Nübler (1981)	−40 to +40	A,P	T_a,v,e,S,L	Clo,M	Sts	Ab	Yes	No	Thermal sensation (TSL scale)
Predicted Percentage Dissatisfied (PPD) Index	Fanger (1970)	+15 to +45 [indoors]	A	T_a,v,e,L	Clo,M	Sts	Ab	Yes	Yes	Predicted percentage dissatisfied (%)
Qs Index	Rublack et al. (1981), cited by Graveling et al. (1988)	+18 to +50	A	T_a,e,v,L	Clo,M,T_s	Sts	Ab	Yes	Yes	Calorific (W m^{-2})
Quotient of Heat Stress ($Q_{dif,H}$)	Hubac et al. (1989)	+20 to +60	A	T_g,e,v	Clo,M,Hr	Sts	Re	Yes	Yes	Calorific
Radiation Equivalent Effective Temperature (REET)	Sheleihovskyi (1948), cited by Rusanov (1981)	0 to +50	A,P	T_a,e,v,S	–	Sts	Ab	Yes	No	Temperature equivalent (°C)
Required Clothing Insulation (I_{req})	Holmer (1984, 1988)	−35 to +10	A	T_a,T_{mrt},e,v	M,T_s,sw	Sts	Ab	Yes	Yes	Clothing required for comfort (clo)
Standard Effective Temperature (SET*)	Gonzalez et al. (1974)	0 to +50	A,P	T_a,T_{mrt},e,v	Clo,M	Sts	Ab	Yes	Yes	Temperature equivalent (°C) Thermal sensation (TSL scale)
Standard Effective Temperature for Outdoors (OUT_SET*)	Pickup and de Dear (2000)	−90 to +60	A,P	T_a,T_{mrt} (L,S),e,v	Clo,M	Sts	Ab	Yes	Yes	Temperature equivalent (°C)
Standard Operative Temperature (To´)	Gagge (1941), cited by Kerslake (1972)	−10 to +50	P	T_a,T_{mrt},v	T_s	Sts	Ab	Yes	Yes	Temperature equivalent (°C)
Still Shade Temperature (SST)	Burton and Edholm (1955)	−20 to +5	A	T_a,v,S	M	Sts	Ab	Yes	No	Temperature equivalent (°C)

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Thermal Balance (ThBal) (Q_s)	Rusanov (1981)	−90 to +37	A,P	T_a,e,v,S,L	M	Sts	Ab	Yes	Yes	Calorific (W)
Thermal Insulation of Clothing (TIC_A)	Aizenshtat (1964)	−40 to +30	A	T_a,e,v,S,L,n	–	Sts	Ab	Yes	Yes	Clothing required for comfort (clo)
Thermal Insulation of Clothing (TIC_B)	Budyko and Cicenko (1960), Liopo and Cicenko (1971)	−55 to +34	P	T_a,v,S	M	Sts	Ab	Yes	Yes	Clothing required for comfort (clo)
Thermal Insulation of Clothing (TIC_R)	Rusanov (1981)	−40 to +30	A,P	T_a,e,v,S,L	M	Sts	Ab	Yes	No	Clothing required for comfort (clo)
Thermal Insulation of Protective Clothing (TIPC)	Afanasieva (1977)	−60 to +10	P	T_a,v	M	Sts	Ab	Yes	Yes	Clothing required for comfort (°C m^2 W^{-1})
Thermal Resistance of Clothing (TRC)	Jokl (1982)	−40 to +20	A	T_a,T_g,v	–	Sts	Ab	Yes	Yes	Clothing required for comfort (K m^2 W^{-1})
Thermal Sensation (TSGIV)	Givoni et al. (2003)	+1 to +35	A	T_a,T_{gr},e,v,S	Clo,M	Sts	Ab	Yes	Yes	Thermal sensation (TSL scale)
Total Thermal Stress (TTS)	Auliciems and Kalma (1981)	−40 to +40	P	T_a,e,v,S,L	–	Sts	Ab	Yes	No	Calorific (W)
Universal Thermal Climate Index (UTCI)	Jendritzky et al. (2009, 2012)	−90 to +60	A	T_a,e,v,S,L	Clo,M	Sts	Ab	Yes	Yes	Temperature equivalent (°C) Thermal sensation (TSL scale)
Wind Chill Equivalent Temperature (WCET)	Steadman (1971)	−40 to +15	P	T_a,v	–	Sts	Ab	Yes	No	Temperature equivalent (°C) Calorific (cal $m^{-2}s^{-1}$)
H. Special purpose index										
Adaptation Strain Index (ASI)	Błażejczyk and Vinogradowa (2014)	−40 to +40	A	T_a,e,v,n,S, (L),b	Clo,M	Stn	Re	Yes	No	Thermal strain categories
Acclimatization Thermal Strain Index (ATSI)	de Freitas and Grigorieva (2009)	−90 to +37	A,P	T_a,e,v,b,el	M	Stn	Re	Yes	Yes	Level of strain (%)
Bioclimatic Contrast Index (BCI)	Blazejczyk (2011)	−40 to +40	A	T_a,e,v,n,S, (L),b	Clo,M	Stn	Re	Yes	No	Bioclimatic contrasts (points) Adaptation intensity (points–scale)
Bioclimatic Distance Index (BDI)	Mateeva and Filipov (2003), cited by Blazejczyk (2011)	−40 to +30	A,P	T_a,e,v,S,L	M	Sts	Re	Yes	No	Clothing required for comfort (clo)

Table 1 (continued)

(a) Index	(b) Reference	(c) Hot (H), cold (C) and design range (°C)	(d) Active (A), passive (P)	(e) Variable atmosphere-related inputs	(f) Variable body-related inputs	(g) Stress (Sts), strain (Stn)	(h) Relative (Re), absolute (Ab)	(i) Heat exchange	(j) Validated	(k) Output
Draught Risk Index (DRI) or (PD)	Fanger et al. (1988)	+23 [indoors]	A	T_a,v	–	Sts	Ab	No	Yes	Percent dissatisfied (%)
Grade of Heat Strain (GHSI) (HRI_H)	Hubac et al. (1989)	+20 to +60	A	T_g,e,v	Clo,M,Hr	Stn	Re	Yes	Yes	Level of strain (points–scale)
Heat Tolerance Index (HTI)	Hori (1978)	+30 [indoors]	A	–	Clo,T_r,W,S_a	Stn	Ab	No	Yes	Level of strain (by grouping)
Integral Load Index (ILI)	Matyukhin and Kushnirenko (1987)	−90 to +60	P	T_a,ΔT,e,Δe,v,S	–	Stn	Re	No	Yes	Level of strain (points–scale)
Predicted effects of heat acclimatization (PEHA)	Givoni and Goldman (1973b)	+49 [indoors]	A	T_a,e	M,T_r,Hr	Stn	Ab	No	Yes	Heart rate (min^{-1}) Rectal temperature (°C)
Weather Stress Index (WSI)	Kalkstein and Valimont (1986, 1987)	−90 to +60	A	T_a,e,v	Clo,M	Sts	Re	Yes	No	Comfort scale (%)
Weather–Climate Contrasts (WCC)	Rusanov (1987)	−40 to +30	A,P	T_a,e,v,S,L	M	Stn	Re	Yes	Yes	Level of strain (points–scale)

T_a air temperature, T_w wet bulb temperature, T_{we} temperature of wet bulb exposed, T_g globe temperature, T_{mrt} mean radiant temperature (integration of T_g and v), T_{gw} wet globe temperature, T_e temperature of eupatheostat, T_{dp} dew point temperature, T_{gr} ground surface temperature, *e* humidity, *v* wind, *S* solar radiation, *L* LW rad, *b* ambient barometric pressure, *n* cloud cover, *pr* precipitation, *el* elevation, *M* metabolic rate, *clo* clothing, *Hr* heart rate, T_s temp of skin, T_r rectal temp, *sw* skin wettedness, *w* water loss, *W* rate of sweating, S_a salt loss, *accl* relevant to acclimatized person, *n/a* not applicable there is a purpose or reason for the index, usually related to thermal comfort, physical well-being, or environmental risk. They vary considerably in type and quality, as well as many other aspects. The aim in the third and final stage of the project is to evaluate the indices in each of the eight classification categories described above by grading them according to the extent to which they meet the various evaluation criteria.

Background to the evaluation scheme

Given the great variety of thermal indices that exist, it is clear that there is not a single unifying technique to evaluate all indices across all eight primary classification categories. Even within each index class, it is not a straight forward matter to assess the quality of a specific index. The evaluation method used here was informed by the work of Graveling et al. (1988), Ott and Thom (1976), Keller and Kuvakin (1998), and Keyantash and Dracup (2002). Graveling et al. (1988) consider evaluation schemes devised for assessing thermal conditions or workers in hot conditions in mining. They report on the work by the US National Institute for Occupational Safety and Health (NIOSH, 1986) that proposed the following criteria should be satisfied by any thermal index being considered for industrial use: (a) applicability should be proven in industrial use, (b) all important factors should be incorporated in the index scheme, (c) measurements and calculations required should be simple, (d) included factors should have a valid weight in relation to total physiological strain, and (e) usable for setting regulatory limits.

Ott and Thom (1976) provide a critical review of air pollution index systems in the USA and Canada. They report that the criteria for a uniform air pollution index should possess the following desirable features: (a) The meaning of the index should be easily understood by the public. (b) The index should transform the atmospheric concentration units of each pollutant into a non-dimensional number which is also easily understood by the public. (c) The index should include all major pollutants. (d) The index should be capable of being calculated in a simple manner using reasonable assumptions. (e) The index should be based on a reasonable scientific premise.

By way of background, Keller and Kuvakin (1998) put forward the following diagnostic criteria for the assessment of an index used for characterizing the impact of the physical environment on human health: (a) confidence of metric or index scoring method, (b) its variability in time and space, (c) the possibility of extrapolating and comparing the resulting (observable) index values, (d) the extent to which separate indices may be combined or summed and the nature and significance of changes of meaning, and (e) the logistical, financial, and other difficulties in obtaining index values.

Along similar conceptual lines, Keyantash and Dracup (2002) developed a scheme for the climatic evaluation of indices of drought. They devise a set of six weighted evaluation criteria and assigned values (1 to 5, 5 being the highest) to each of the indices. The criteria were decided based on desirable properties that a drought index should ideally possess, namely robustness, tractability, transparency, sophistication, extendibility, and dimensionality.

Method

The rationale underpinning index evaluation schemes is that the various indices should be compared with like indices. Hence, the evaluations reported here are for indices within each one of eight primary classification categories. Based on the work described above (Graveling et al. 1988, Ott and Thom 1976, Keller and Kuvakin 1998, Keyantash and Dracup 2002), we suggest six criteria in no particular order of importance, namely comprehensiveness, scope, sophistication, transparency, usability, and validity. No particular merit is assigned to when an index was developed. Clearly, the list of criteria may be condensed or expanded, but we consider these six criteria provide a reasonable framework for the evaluation of thermal indices without excessive complication. Within each of the six sets of evaluation criteria, there are pointers that guide the scoring process, as follows:

Comprehensiveness A comprehensive index would include all major factors contributing to thermal stress or strain, such as air temperature, humidity (for heat), air movement (for both heat and cold), metabolic rate, solar heat load, mean radiant temperature, and clothing. Frequently, in statistical modeling, there is conscious attempt to approximate thermal conditions using variables that make calculations as simple as possible, but not at the expense of completeness. The simplicity in approach is accounted for in the "Usability" criterion below. However, the usefulness of an index will depend on its accuracy. In energy balance modeling, for example, a common assumption is that the more variables accounted for in the index scheme, the better the index, but inevitably, there are errors in each one and the computational procedure is more complex. Collectively, the errors for each node and group of variables could be large. Say the indices give the net energy balance of the body. How do you know what the true energy balance of the body is? You will only know this if you monitor a human body (or mannequin) in a controlled setting. This is accounted for in the "Validity" criterion below.

Scope Scope, or extendibility, refers to the range of environmental conditions over which the index may be used. It is the degree to which an index may be extended to apply across time to a variety of scenarios, or environmental exposure limits. For instance, an index may apply to cool or cold conditions, rather than the full range of hot to cold. Likewise, an index may be suitable for use in low wind speeds, or for people with a single (steady) metabolic rate or clothing state. This does not mean that a particular index, such as the wind chill index, is "poor"; only that it is designed specifically for cold or cool conditions, thus is not extendable across the full range of thermal environmental conditions.

Sophistication Sophistication reflects the conceptual merits of an approach. It would include an index scheme that is theoretically sound and grounded in well-established bioclimatic processes. Theoretical sophistication should incorporate empirically tested methods that are backed by research findings reported in the relevant scientific literature.

Transparency Transparency considers the clarity of and justification for the rationale behind the index. For example, a mysterious algebraic function added to the computational procedure for deriving the index would make that rationale for the index ambiguous. That is not to say deterministic models are better than empirical models, or vice versa; rather that the reasoning underpinning the model is both clear and justifiable. A classic example of a climatic index that lacks transparency is Thornthwaite's equation for calculating potential evapotranspiration (Thornthwaite 1948; Thornthwaite et al. 1957).

Usability Usability, or tractability, is concerned with how easily the index scheme can be applied. It represents the practical aspects of the index. For example, a tractable index does not require high-level numerical computing and the actual stages of the computation should not be particularly complicated. An intractable index would require non-standard data or data that is collected especially for use in the index scheme or one that does not need a wide-ranging historical database for its computation. Usability also includes the ease with which index values (or output) can be interpreted. Ideally, the meaning of the index should be easily understood by a layperson.

Validity The validity of an index is related to how well or reliably the index value mirrors the actual heat stress to which the human body is subjected or how that relates to thermal strain. Validation and testing in the derivation of an index are most often undertaken through laboratory or field studies.

The strengths and weaknesses of the various human thermal indices and how those characteristics relate to the evaluation criteria were considered in the assignment of the scores for all indices within each the eight index classification categories. The six evaluation criteria are used to assign a score that varies between 1 and 5, 5 being the highest, and "0," when a particular evaluation criterion is not offered (or does not appear). The question arises as to whether or not to assign weightings to criteria to reflect the relative importance of each evaluation criterion. This was the approach adopted by Keyantash and Dracup (2002). In the present circumstances, the decision was made to assign equal weightings to each of the six evaluation criteria. This is because it can be convincingly argued that each of the criteria cover attributes of thermal indices that could be individually of equivalent importance.

Scoring procedure

The scoring process presents challenges, but consistency is a key concern. The use of index performance indicators assists in this. They are embodied in the six evaluation criteria and guide the scoring process. The performance indicators shown in Table 1 include: (a) the thermal conditions (or temperature range) across which the index is deemed to apply, (b) whether the index is designed for "passive" or "active" metabolic states or both, (c) listing of variable atmosphere-related inputs to the index scheme, (d) variable body-related inputs such as metabolic rate and clothing, (e) units used to express the index. Further indicators include assessments of whether or not the index is: (f) an index of thermal environmental stress or an index of thermophysiological strain, (g) an absolute or relative measure of thermal conditions, (h) based on biophysical body-atmosphere heat (energy) budgets, and (i) has been experimentally tested and validated.

Several of the performance indicators have already been employed via the classification scheme of de Freitas and Grigorieva (2015). For instance: (h) "based on biophysical body-atmosphere heat (energy) balance" is taken into account by placing such indices within classes (F) and (G) of the classification scheme and (f) "thermal environmental stress or thermophysiological strain" is taken into account by sorting indices into either classes (D) and (F) or classes (E) and (G), respectively, in the classification scheme.

Additionally, questions guide the scoring within each of the six evaluation criteria, as follows:

Comprehensiveness How many variables contributing to thermal stress or strain are included in the index scheme? (for example, air temperature, humidity, air movement, metabolic rate, solar heat load, mean radiant temperature, clothing).

Scoring: "1" for each variable, and "5" for five variables or more.

Scope Over what range of environmental conditions may index be used?

Scoring: "1" for narrow range, "3" for broad range, "4" if index covers both cold and cool conditions (for example, indices for clothing insulation), and "5" if index covers both hot and cold conditions.

Sophistication What are conceptual merits of the approach?

Scoring: “5” for all indices in the classification Classes (F) and (G), “4” for all indices in Classes (D) and (E), “3” for Class (C) indices, and “2” for indices in Classes (A) and (B). Special Purpose Class (H) indices to be scored depending on methods (A to G) used.

Transparency Are the use of all terms in the index scheme justified?

Scoring: “5” for all justified, “3” for most cases, “2,” or “1” for poorly; “0” for none justified.

Usability How easily the index scheme can be applied? (a) Computational procedure is straightforward. (b) Requires only standard data. (c) Output easy to interpret.

Scoring: “5” if (a) and (b) and (c) are present; “3” if only two of (a), (b), or (c) are present; “1” if only one of (a), (b), or (c) are present; “0” if none of (a), (b), or (c) is present.

Validity Has the index been developed from or tested with empirical laboratory of field-based data?

Scoring: “5” for indices derived from or tested with laboratory or field-based empirical data; “4” if index is compared against more than one fully validated index; “3” if index is compared against one fully validated index; “2” if using a “rational scheme” but has not been validated; and “0” if not validated. “Rational indices” are those that are based on body-atmosphere energy exchange approximations, or those that predict well-established thermophysiological parameters; for example, those that predict sweat rate, body core temperature or change in core temperature, heart rate, or those that predict a combination of two or more of these physiological parameters.

Results

The index evaluation procedure described above is consistent in that it addresses each of the performance indicator questions in turn to direct the scoring in all of the six evaluation criteria. Where a particular score is uncertain, the benefit of doubt is given and the higher score option is chosen. To provide supporting information, characteristics and attributes of the comprehensive list of the 165 human thermal bioclimatic indices are given in Table 1 along with name and sources in columns (a) and (b) and performance indicators in columns from (c) to (k). Table 2 gives the scoring in each of the six evaluation criteria as well as the total evaluation score for each index. The maximum score for any index is 30.

It is apparent from Table 2 that indices based on single-variables score the lowest (highest score of 14/30). These are followed by simulation devices for integrated measurement (highest score of 18/30), and next indices based on statistical models (highest score of 23/30) and then proxy indices (highest score of 25/30). Indices based on body-environment energy balance score the highest (highest score of 28/30). Special purpose indices generally score reasonably well, as would be expected.

The Thermo-Integrator (score 18) and Resultant thermometer (score 17) stand out as the two best in the category of “simulation devices for integrated measurement” (A Class in Table 2). Air temperature (score 14) is the best “single variable index” (B Class in Table 2), and net effective temperature (score 23) is the best “algebraic or statistical model” index (C Class in Table 2). Among the proxy indices, in both the strain (D Class in Table 2) and stress (E Class) categories, several score in the mid-20s. The top performers in the “proxy thermal strain index” category (D Class in Table 2) are the cold strain index (score 23), index of physiological effect (score 24), integral index of cooling conditions (score 23), and predicted four-hour sweat rate (score 24). The top performers in the proxy thermal stress index category (Class E in Table 2) are classification of weather in moments (score 25), effective temperature (score 25), index of pathogenicity of meteorological environment (score 24), modified effective temperature (score 24), and spatial synoptic classification (score 24).

The best performing indices in the “energy balance strain index” class (F Class in Table 2) score as well as the best performing indices in the “energy balance stress index” class (G Class in Table 2). The difference is that there are 10 thermal stress indices that score higher than 27 while there are only four in the strain category. This is likely a result of the fact that, over time, more attention has been given to developing indices of environmental stress.

Indices that score 27 or better in the category energy balance strain index (Class F in Table 2) are the body-atmosphere energy exchange index (score 28), physiological strain (score 27), respiratory heat loss (score 28), skin temperature energy balance index (score 28), and subjective temperature index (score 28). Indices that score 27 or better in the category energy balance stress index (Class G in Table 2) are clothing insulation (score 27), heat budget index (score 28), outdoor apparent temperature (score 27), perceived temperature (score 27), standard effective temperature for outdoors (score 28), thermal balance (score 27), thermal insulation of clothing (TIC_A) (score 28), thermal insulation of clothing (TIC_B) (score 27), thermal sensation (TSGIV) (score 28), and (universal thermal climate index) (score 27).

The detailed information in Table 2 provides insights into the scoring. In some cases, the performance of several indices in a particular class may be close, so much so that the relative difference is difficult to call. For instance, UTCI is a comprehensive, thermophysiolgically based energy balance index that scores highly in all sets of criteria. Because the index is derived from a multi-node model, it is very difficult to calculate, so the usability score is not the highest possible. Parsons (2014, p. 510) has

Table 2 The list of 165 human thermal bioclimatic indices in eight classes giving total performance score for each index. Questions that guide the scoring in each of the six evaluation criteria (comprehensiveness, scope, sophistication, transparency, usability, and validity) are given in the text. The maximum score for each criterion is 5; thus, the maximum score for any index is 30

(a) Index	(b) Comprehensiveness	(c) Scope	(d) Sophistication	(e) Transparency	(f) Usability	(g) Validity	(h) Total
A. Simulation device for integrated measurement							
Black sphere actinograph	1	3	2	2	3	0	11
Cylinder (C) (modification of Tg as given in Brown and Gillespie 1986)	1	5	2	2	3	0	13
Ellipsoid index	2	1	2	3	3	0	11
Eupathescope (Eupatheostat)	3	3	2	2	3	0	13
Frigorimeter	1	3	2	2	3	0	11
Globe Thermometer Temperature (Tg)	1	5	2	1	3	0	12
Kata thermometer	4	3	2	1	3	0	13
Metal man (thermal manikin)	1	3	2	3	3	0	12
Resultant thermometer	5	3	2	2	3	0	17
Thermo−Integrator	3	3	2	2	3	5	18
Wet Globe Temperature (WGT) or Botsball	3	3	2	2	3	0	13
B. Single−sensor (single−parameter) index							
Air temperature (T_a)	1	5	2	1	5	0	14
Dewpoint temperature	1	3	2	1	5	0	12
Physical saturation deficit	1	3	2	1	3	0	10
Saturation deficit	1	3	2	3	3	0	12
Sultriness value	1	3	2	1	3	0	10
Wet Bulb Temperature (Twb)	2	3	2	2	5	0	14
C. Algebraic or statistical model							
Air Enthalpy (AirE) or (i)	3	3	3	2	5	0	16
Apparent Temperature (AT)	2	3	3	2	5	0	15
Belgian Effective Temperature (BET or TEL)	1	3	3	2	3	5	17
Biometeorological Comfort Index (BCI)	3	3	3	2	5	0	16
Bodman’s Weather Severity Index (BWSI) or (S)	2	3	3	2	5	3	18
Comfort Vote (CmV) or (S)	5	2	3	3	3	5	21
Cumulative Discomfort Index (CumDI)	2	3	3	2	5	0	15
Discomfort Index (DI_T) or Temperature Humidity Index (THI)	2	3	3	2	3	5	18
Discomfort Index (DI_K)	2	3	3	2	3	0	13
Effective Temperature (ET_M)	2	5	3	2	5	5	22
Environmental Stress Index (ESI)	3	3	3	3	5	5	22
Equatorial Comfort Index (ECI) or Singapore Index	3	3	3	3	5	5	22
Equivalent Effective Temperature (EET)	4	5	3	3	5	0	20
Equivalent Warmth (EqW)	4	1	3	3	5	5	21
Humidex (HD)	2	3	3	2	5	0	15
Humisery	4	3	3	2	5	0	17
Humiture	2	3	3	2	5	0	15
Increment Temperature Equivalent to Radiation Load (ITER)	5	1	3	3	1	5	18
Index of thermal sensation (ITSN)	4	1	3	2	1	5	16
Insulation Predicted index (Iclp)	3	3	3	2	5	0	16
Modified Discomfort Index (MDI)	2	1	3	2	5	5	18
Oxford Index (OxI) or Wet−Dry Index (WD)	2	1	3	2	3	5	16
Perceived Temperature (PT_L) Gefühlte Temperature	3	1	3	2	3	0	12

Table 2 (continued)

(a) Index	(b) Comprehensiveness	(c) Scope	(d) Sophistication	(e) Transparency	(f) Usability	(g) Validity	(h) Total
Relative Humidity Dry Temperature (RHDT)	3	1	3	2	3	5	16
Resultant Temperature (RT) or Net Effective Temp. (NET)	4	5	3	3	5	3	23
Severity Rating (S)	4	3	3	3	5	3	21
Subjective Temperature (ST)	5	1	3	2	5	0	16
Summer Simmer Index (SumSI)	2	3	3	2	5	0	15
Temperature Humidity Index (THI_S)	2	3	3	2	5	0	15
Temperature−Wind Speed−Humidity Index (TWH)	3	5	3	3	3	0	17
Thermal−insulation Characteristics of Clothing (TICC)	3	5	3	3	5	0	19
Tropical summer index (Tsi)	3	3	3	2	3	5	19
Wet Bulb Globe Temperature (WBGT)	3	3	3	3	3	5	20
Wet−bulb dry temperature (WBDT)	2	3	3	2	3	5	18
Wet Kata Cooling Power by Hill (WKCP) (H_w)	3	5	3	3	5	0	19
Wind Chill Equivalent Temperature (WCTwc) (Twc)	3	5	3	3	3	0	17
Wind Chill Index (WCI)	2	3	3	3	5	0	16
D. Proxy thermal strain index							
Cold Strain Index (CSI)	2	3	4	4	5	5	23
Cumulative Heat Strain Index (CHSI)	2	1	4	4	1	5	17
Index of Physiological Effect (IPhysE) or (Ep)	5	3	4	4	3	5	24
Index of Thermal Stress (ITS_K) (N)	4	5	4	4	5	0	22
Integral Index of Cooling Conditions (IICC)	4	3	4	4	5	3	23
Mean Equivalence Lines (MEL)	3	3	4	4	3	5	22
Perceptual Hyperthermia Index (PHI)	3	1	4	4	1	5	18
Perceptual strain index (PeSI)	4	1	4	4	1	5	19
Physiological Heat Exposure Limit (PHEL) Chart	5	1	4	4	3	5	22
Physiological Index of Strain (Is)	3	3	4	4	3	5	20
Physiological Strain Index (PSI)	2	3	4	4	3	5	19
Predicted Four−hour Sweat Rate (P4SR)	5	3	4	4	3	5	24
Skin Temperature (SkT) or (tsk)	5	3	4	4	1	5	22
Skin wettedness (SkW)	2	3	4	4	3	5	21
E. Proxy thermal stress index							
Bioclimatic Index of the Severity of Climatic Regime (BISCR)	5	5	4	4	3	0	21
Classification of Weather in Moments (CWM)	4	5	4	4	5	3	25
Comfort Index (CI)	2	5	4	4	5	0	20
Corrected Effective Temperature (CET)	4	3	4	4			
Daily Weather Types (DWT)	5	3	4	4	3	3	22
Effective Temperature (ET)	4	3	4	4	5	5	25
Index of Pathogenicity of Meteorological Environment (IPME)	5	5	4	4	3	3	24
Index of Sultriness Intensity (ISI)	2	3	4	4	5	0	18
Evans Scale (ES)	4	3	4	3	5	0	19
Mahoney Scale (MS)	2	3	4	3	5	0	17
Meteorological Health Index (MHI)	5	5	4	4	5	0	23
Modified Effective Temperature (MET)	5	3	4	4	3	5	24
Spatial Synoptic Classification (SSC)	5	5	4	4	3	3	24
Summer Severity Index (SSI) or (I_o)	5	3	4	3	3	0	18
Thermal Sensation Index (TSNI) (S)	5	1	4	4	3	5	22
Wind Effect Index (WEI)	3	5	4	3	5	0	20

Table 2 (continued)

(a) Index	(b) Comprehensiveness	(c) Scope	(d) Sophistication	(e) Transparency	(f) Usability	(g) Validity	(h) Total
F. Energy balance strain index							
Body−atmosphere Energy Exchange Index (BIODEX)	5	5	5	5	3	5	28
Body Temperature Index (BTI)	5	1	5	5	3	5	24
Effective Heat Strain Index (EHSI)	5	1	5	5	3	2	21
Equilibrium Rectal Temperature (ERT) or(T_{rec})	5	1	5	5	5	5	26
Exposed Skin Temperature (EST)	4	3	5	5	5	2	22
Heart Rate Index (HRI_G)	5	1	5	5	3	5	24
Heart Rate Index (HRI_D)	5	1	5	5	3	5	24
Heat Strain Decision Aid Model (HSDA)	5	1	5	5	3	5	24
Heat Stress Index − Belding and Hatch (HSI_{BH})	5	1	5	5	5	5	26
Heat Stress Prediction Model (HSPM) or Heat Strain Model	5	1	5	5	5	5	26
Index of Thermal Stress (ITS)	5	1	5	5	3	5	24
Heat Tolerance Limits (HTL)	5	3	4	4	3	5	24
Maximum Exposure Time (MET)	5	3	5	5	5	2	25
Maximum Recommended Duration of Exercises (MRDE)	4	3	5	5	3	2	22
Physiological Strain(PhS)	5	5	5	5	3	4	27
Physiological Subjective Temperature (PST)	5	5	5	5	3	2	23
Predicted Heat Strain (PHS)	5	1	5	5	5	5	26
Reference Index (RI)	5	1	5	5	3	5	24
Relative Heat Strain (RHS)	5	3	5	5	5	2	25
Required Sweat Rate (Req SR)	5	3	5	5	3	5	26
Respiratory Heat Loss (RHL) (Qr)	5	5	5	5	3	3	26
Skin Temperature Energy Balance Index (STEBIDEX)	5	5	5	5	3	5	28
Subjective Temperature Index (STI)	5	5	5	5	5	3	28
Survival Time Outdoors in Extreme Cold (STOEC)	4	3	5	5	5	2	24
Thermal Acceptance Ratio (TAR)	4	1	5	5	1	5	21
Thermal Discomfort (DISC)	5	1	5	5	1	2	19
Thermal Strain Index (TSI)	5	3	5	5	3	2	20
Thermal Work Limit (TWL)	5	1	5	5	3	5	24
G. Energy balance stress index							
Air Cooling Power (ACP)	5	1	5	5	3	2	21
Apparent Temperature (AT) or Heat Index (HI)	5	3	5	5	3	2	23
Climate Index (CLIM)	3	5	5	5	3	2	23
Clothing Insulation (Ic)	5	5	5	5	5	2	27
Clothing Thickness (Clo)	3	3	5	5	5	2	23
Comfort Chart (CmCh)	4	3	3	3	3	0	16
Heat Budget Index (HEBIDEX)	5	5	5	5	3	5	28
Heat Stress Index (HSI_{WK})	5	3	5	5	5	3	26
Humid Operative Temperature (HToh)	5	3	5	5	3	3	24
Index of Clothing Required for Comfort (CLODEX)	5	4	5	5	5	2	26
Modified (Reduced) Temperature (MTTR) or ($T_{пр}$)	3	3	5	5	5	2	23
Natural Wet Bulb Temperature (NWBT) or (Tn)	4	5	5	5	5	2	26
New Effective Temperature (ET*)	5	3	5	5	5	3	26
New Wind Chill Temperature Index (NWCI or WCET)	2	4	5	5	5	5	26
Operative Temperature (OpT) or (To)	3	3	5	5	5	5	26
Outdoor Apparent Temperature (OAT)	5	5	5	5	5	2	27
Outdoor Thermal Environment Index (OTEI) or (ETVO)	5	5	5	5	3	2	25

Table 2 (continued)

(a) Index	(b) Comprehensiveness	(c) Scope	(d) Sophistication	(e) Transparency	(f) Usability	(g) Validity	(h) Total
Perceived Temperature (PT_J)	5	5	5	5	5	2	27
Physiological Equivalent Temperature (PET)	5	5	5	5	3	3	26
Predicted Mean Vote – indoors (PMV)	5	1	5	5	3	5	24
Predicted Mean Vote – outdoors (PMV*)	5	3	5	5	3	2	23
Predicted Mean Vote – Fuzzy (PMV_F)	5	4	5	5	3	2	24
Predicted Mean Vote – outdoors (PMVo)	5	5	5	5	3	2	25
Predicted Percentage Dissatisfied (PPD) Index	5	1	5	5	3	5	24
Qs Index	5	3	5	5	3	4	22
Quotient of Heat Stress ($Q_{dif,H}$)	5	3	3	3	1	5	20
Radiation Equivalent Effective Temperature (REET)	4	3	5	5	5	2	24
Required Clothing Insulation (I_{req})	5	4	5	5	3	4	26
Standard Effective Temperature (SET*)	5	3	5	5	3	5	26
Standard Effective Temperature for Outdoors (OUT_SET*)	5	5	5	5	3	5	28
Standard Operative Temperature (To´)	4	3	5	5	3	5	25
Still Shade Temperature (SST)	4	3	5	5	5	2	24
Thermal Balance (ThBal) (Q_s)	5	5	5	5	5	2	27
Thermal Insulation of Clothing (TIC_A)	5	4	5	5	5	4	28
Thermal Insulation of Clothing (TIC_B)	4	4	5	5	5	4	27
Thermal Insulation of Clothing (TIC_R)	5	4	5	5	5	2	26
Thermal Insulation of Protective Clothing (TIPC)	3	3	5	5	5	5	26
Thermal Resistance of Clothing (TRC)	3	4	5	5	3	4	24
Thermal Sensation (TSGIV)	5	3	5	5	5	5	28
Total Thermal Stress (TTS)	5	5	5	5	3	2	25
Universal Thermal Climate Index (UTCI)	5	5	5	5	3	4	27
Wind Chill Equivalent Temperature (WCET)	2	3	5	5	5	2	22
H. Special purpose index							
Adaptation Strain Index (ASI)	5	5	5	4	3	2	24
Acclimatization Thermal Strain Index (ATSI)	5	5	5	4	5	2	26
Bioclimatic Contrast Index (BCI)	5	5	5	4	3	2	24
Bioclimatic Distance Index (BDI)	5	5	5	4	5	2	26
Draught Risk Index (DRI) or (PD)	2	1	3	5	1	5	17
Grade of Heat Strain (GHSI) (HRI_H)	5	2	5	5	1	5	23
Heat Tolerance Index (HTI)	4	1	3	3	3	5	19
Integral Load Index (ILI)	5	5	3	5	3	3	24
Predicted effects of heat acclimatization (PEHA)	5	1	4	5	3	3	21
Weather Stress Index (WSI)	5	5	5	4	3	0	22
Weather–Climate Contrasts (WCC)	5	5	3	3	5	3	24

also commented on this. However, it is reasonable to argue that once user-friendly routines are made available (on a website, say) to run the calculations and the appropriate models are on hand to produce the necessary input data based on available meteorological data and routines, the usability would achieve a top score. Similarly, since the index has been compared with others, it might be claimed it meets acceptable standards of validation. Bröde et al. (2012) compare the UTCI with ISO standards methods and note limitations of UTCI owing to a fixed metabolic rate and limited clothing. Clearly, the importance of these considerations is debatable and users of that index and others should be free to decide.

Discussion

The 165 index schemes identified here differ according to the kind of modeling or rationale employed, number of atmospheric and physiological variables taken into account, and the particular design for application. They also vary considerably the method used to express output. Given that there are 165 indices from which to choose, the one selected for any particular application will depend on the context in which it is being used and data availability. In some cases, ease of interpretation might be of primary concern; in others, simplicity in calculation might be the overriding consideration. In this sense, there is no "best" index. It is clear the best performing indices are those of the body-atmosphere energy balance variety. The downside is that all of them involved more complicated calculation routines and more detailed input data. Although body-atmosphere energy balance indices are more sophisticated in every respect as well as more "rational" as they approximate reality, they are often based on numerical models that have not been validated. This is the biggest problem. The same applies to many of the indices in proxy thermal stress and thermal strain classes; however, these indices, although less reliable, are often easier to calculate. Another consideration is that, within the energy balance-based index category, the evaluation process does not distinguish between the more traditional procedure of energy budget modelling the human body using two nodes (body core and shell) and the more sophisticated multi-node method. However, both approaches share the limitations mentioned above.

The work reported here is the final part of a study of the 165 human thermal climatic indices found in literature. Others have considered the topic (for example, Givoni 1969, Fanger 1970, Landsberg 1972, Driscoll 1992), but this study is the first detailed, genuinely comprehensive, and systematic comparison that makes it simpler to decide which index might be most appropriate for a particular application or investigation.

A key determinant of a worthwhile evaluation of a full range of indices is that they should be compared with an identical class or type of index. Based on earlier work, we suggest six evaluation criteria. The exercise is essentially a hypothesis regarding how one might go about the ranking process. Clearly, the list of criteria may be condensed, expanded, or altered, but we consider these six criteria provide a reasonable framework for a full evaluation without excessive complication. A danger in this kind of approach is that a user of the work might simply pick the index with the highest overall score and assume that it is always superior to other indices in that classification category. In some instances, indices in the same class might be measuring different bioclimatic factors. For example, in Class B, air temperature has a higher score than saturation deficit (Table 2), but there are situations where saturation deficit would be superior to temperature, such as in comparing two separate ambient atmospheric conditions that are "hot" but differ in terms of the moisture content of the air.

The choice between indices of thermal stress or indices of thermal strain is important; the significance of which is often not fully grasped. In terms of performance, the top indices in the category of energy balance strain index score as well as those in the top energy balance stress index category, but the information they provide is quite different. The latter provides a measure of thermal environmental stress imposed on the human body, whereas the former afford a measure of physiological strain on the body as consequence of thermal environmental stress. Given that there are indices within both classification categories that perform well, the one selected for any particular application will depend on whether an evaluation of the environment is required, or whether the consequences of this on the human body is the focus.

Conclusion

Human health, well-being, and comfort are a result of the complex influence of many factors, one of which is the thermal state of climatic environment. The latter involves the interplay of a great variety of atmospheric variables such as air temperature, humidity, wind and solar radiation as well as physiological and behavioral variables such as activity levels, clothing, posture, and the like. In reality, all these variables come together in a complex way. The very large number of human thermal climate indices that have been proposed over the past 100 years or so is an indication of the perceived importance within the scientific community of the thermal environment and a desire to quantify it. The indices differ in approach taken to approximate the significance of the human thermal environment. They also vary considerably in type and quality, as well as in many other aspects, but the extent to which they provide a precise quantification of the thermal environment has not been undertaken. To date, there has been no comprehensive documentation, classification, and evaluation of them. A three-part project set out to do this. This is a report on the third and final part that aims to determine the best performing thermal indices.

Based on a thorough search of the research literature, a comprehensive list of 165 thermal indices was assembled earlier by de Freitas and Grigorieva (2015). In the work, the indices were classified into a series of eight mutually exclusive categories. In the current work, the 165 indices are evaluated according to six evaluation criteria, namely validity, usability, transparency, sophistication, comprehensiveness, and scope. According to the method used, each grouping was assessed separately, the indices within each classification category being compared. An exhaustive classification and evaluation of all the existing thermal indices has never before been attempted.

Six evaluation criteria are used to assign a score for each index that varies between 1 and 5, 5 being the highest and the results reported in Table 2. The process is informed by performance indicators shown in Table 1. The indices with the best performance of the eight primary classification categories are those within the body-atmosphere energy balance (stress and strain) classes. Although these indices are more sophisticated in every respect, they are often based on models that have not been validated. The same applies to many of the indices in proxy thermal stress and thermal strain classes; however, these indices, although less reliable, are often easier to calculate and use. There is the added consideration that, since the characteristics of the human body vary from person to person, the use of a standardized human body could introduce errors. The significance of this would depend on the intended use of the index and thus its evaluation.

The work reported here is the final stage of a three-part study of the all human thermal climatic indices that could be found in literature. Others have considered the topic, but this study is the first detailed, genuinely comprehensive and systematic comparison. The results make it simpler to locate and compare indices. It is now easier for users to reflect on the merits of all available thermal indices and decide which is most suitable for a particular application or investigation.

References

Adamenko VN, Khairullin KS (1972) Evaluation of conditions under which unprotected parts of the human body may freeze in urban air during winter. Bound.-Layer Meteor 2:510–518

Afanasieva R (1977) Hygienic theory of cold protection clothes projection. Legkaya Industriya, Moscow (in Russian)

Afanasieva R, Bobrov A, Sokolov S (2009) Cold assessment criteria and prediction of cooling risk in humans: the Russian perspective. Ind Health 47(3):235–241

Aizenshtat BA (1964) Methods for assessment of some bioclimate indices. Meteorol Hydrol 12:9–16 (in Russian)

Aizenshtat LB, Aizenshtat BA (1974) Equation for equivalent-effective temperature. Questions of biometeorology. Leningrad, Hydrometeoizdat, pp. 81–83 (in Russian)

Akimovich NN, Balalla OA (1971) Sultry weathers at the south of Primorye and their influence on human body. Izvestia ASc USSR, Geography 4:94–100 (in Russian)

Arnoldy IA (1962) Acclimatization of the man in north and south. Medgiz, Moscow (in Russian)

Auliciems A, Kalma JD (1981) Human thermal climates of Australia. Australian Geographical Studies 19(1):3–24

Auliciems A, Szokolay SV(2007) Thermal comfort. Brisbane, Qld. PLEA in association with Dept. of Architecture, University of Queensland, 1997

Becker S (2000) Bioclimatological rating of cities and resorts in South Africa according to the Climate Index. Int J Climatol 20:1403–1414

Bedford T (1936) Warmth factor in comfort at work, Med Res Council, Industrial Health Research Board, Report No.:76

Bedford T (1961) Researches on thermal comfort. The society's lecture given at Bristol, 17 April. Ergonomics 4(4):289–310

Bedford T (1964) Basic principles of ventilation and heating, 2nd edn. H. K. Lewis and Co., London

Bedford T, Warner CD (1934) The Globe Thermometer in Studies of Heating and Ventilation. J Hyg (Lond) 34(4):458–473

Belding HS, Hatch TF (1955) Index for evaluating heat stress in terms of resulting physiological strain. Heat Pip Air Condit 27:129–136

Belkin VS (1992) Biomedical aspects of the development of mountain regions: case-study for the Gorno-Badakhshan autonomic region. Tajikistan. J. Mount. Res. and Dev. 12:63–70

Beshir MY, Ramsey JD (1988) Heat stress indices: a review paper. Int J Indust Ergon 3:89–102

Bidlot R, Ledent P (1947) Travail dans les milieux a haute temperature. Que savons-nous des limites de temperature humainement supportables? Hasselt: Institute d'Hygiene des Mines

Blazejczyk K (2005) New indices to assess thermal risks outdoors. In: Holmér I, Kuklane K, Gao C (eds) Environmental Ergonomics XI. Proc. Of the 11th International Conference, 22–26 May, 2005, Ystat, Sweden, pp. 222–225

Blazejczyk K (2011) Assessment of regional bioclimatic contrasts in Poland. Miscellanea Geographica 15(1):79–91

Blazejczyk K, Matzarakis A (2007) Assessment of bioclimatic differentiation of Poland based on the human heat balance. Geogr Pol 80: 63–82

Błażejczyk K, Vinogradowa V (2014) Adaptation Strain Index for tourists traveling from central and northern Europe to the Mediterranean. Finisterra XLIX 98:139–152

Blazejczyk K, Holmer I, Nilsson H (1998) Absorption of solar radiation by an ellipsoid sensor simulated the human body. Appl Human Sci 17(6):267–273

Bodman G (1908) Das Klima als eine Funktion von Temperatur und Windgeschwindigkeit in ihrer Verbindung. Lithogr. Institut des Generalstabs, Stockholm

Bogatkin OG (2006) Meteorological index of Health and economic possibilities of its application. Proceedings of the International conference "Weather and Biosystems", St.-Petersburg

Botsford JH (1971) A wet globe thermometer for environmental heat measurement. Am Indust Hyg Association J 32:1–10

Brake D, Bates G (2002) Limiting Metabolic Rate (Thermal Work Limit) as an index of Thermal Stress. Appl Occup Environ Hyg 17(3):176–186

Brauner N, Shacham M (1995) Meaningful wind chill indicators derived from heat transfer principles. Int J Biometeorol 39:46–52

Bröde P, Fiala D, Blazejczyk K, Holmér I, Jendritzky G, Kampmann B, Tinz B, Havenith G (2012) Deriving the operational procedure for the universal thermal climate index (UTCI). Int J Biometeor 56(3): 481–494

Broughton V (2001) Faceted classification as a basis for knowledge organization in a digital environment; the Bliss Bibliographic Classification as a model for vocabulary management and the creation of multidimensional knowledge structures. New Review of Hypermedia and Multimedia 7(1):67–102

Brown RD, Gillespie TJ (1986) Estimating outdoor thermal comfort using a cylindrical radiation thermometer and an energy budget model. Int J Biometeor 30:43–52

Bruce JL (1916) Vortrag. Roy Soc NSW (public health section) 14(11): 1916

Brüner H (1959) Arbeitsmöglichkeiten unter Tage bei erschwerten Klimatischen Bedingungen. Int Z angew Physiol einschl Arbeitsphysiol 18:31–61

Budyko M, Cicenko V (1960) Climatic factors of human thermal sensation. Izv AS USSR Ser Geogr 3:3–11 (in Russian)

Bureau of Indian Standards (1987) Handbook of functional requirements of buildings (other than industrial buildings). New Delhi, SP:41

Burton A, Edholm O (1955) Man in cold environment: physiological and pathological effects of exposure to low temperatures. Edward Arnold, London

Cadarette BS, Montain SJ, Kolka MA, Stroschein L, Matthew W, Sawka MN (1999) Cross validation of USARIEM heat strain prediction models. U.S. ARMY Research Institute of Environmental Medicine. Aviat Space Environ Med 70(10):996–1006

Dasler AR (1977) Heat stress, work function and physiological heat exposure limits in man. Thermal Analysis-Human Comfort-Indoor Environments, National Bureau of Standards, Washington, D.C. https://play.google.com/books/reader?id=49fL2qrLF8gC&printsec=frontcover&output=reader&authuser=0&hl=en&pg=GBS.PP2

Dayal D (1974) An index for assessing heat stress in terms of physiological strain. PhD thesis, Texas Tech University

De Freitas CR (1985) Assessment of human bioclimate based on thermal response. Int J Biometeorol 29:97–119

De Freitas CR (1986) Human thermal climates of New Zealand. New Zealand Meteorological Service, Misk Publ, 190, Wellington

De Freitas CR (1987) Bioclimates of heat and cold stress in New Zealand. Weather and Clim 7:55–60

De Freitas CR, Grigorieva E (2009) The Acclimatization Thermal Strain Index (ATSI): a preliminary study of the methodology applied to climatic conditions of the Russian Far East. Int J Biometeorol 53: 307–315

De Freitas CR, Grigorieva EA (2015) A comprehensive catalogue and classification of human thermal climate indices. Int J Biometeorol 59(1):109–120

De Freitas CR, Ryken MG (1989) Climate and physiological heat strain during exercise. Int J Biometeorol 33:157–164

De Freitas CR, Symon L (1987) A bioclimatic index of human survival time in the Antarctic. Polar Record 23:651–659

De Paula Xavier AA, Lamberts R (2000) Indices of thermal comfort developed from field survey in Brazil. ASHRAE Trans 106:45–58

Dorno C (1928) Die Abkühlungsgrösse in verschiedenen Klimaten nach Dauerregistrierungen mittels des Davoser Frigorimeters. Meteorol Zeitschr 45:401–421

Driscoll DM (1992) Thermal comfort indexes: current uses and abuses. Natl Weather Dig 17:33–38

Dufton AF (1929) The eupatheostat. J Scientific Instruments 6:249–251

Eissing G (1995) Climate assessment indices. Ergonomics 38(1):47–57

Evans M (1980) Housing. Climate and comfort. London: Architectural Press. J. Wiley, New York 186 p

Falconer R (1968) Windchill, a useful wintertime weather variable. Weatherwise 21:227–229

Fanger PO (1970) Thermal comfort: analysis and applications in environmental engineering. Danish Technical Press, Copenhagen

Fanger PO, Melikov AK, Hanzawa H, Ring J (1988) Air turbulence and sensation of draught. Energ Bldg 12(1):21–39

Flügge C (1912) Akten des Kgl. Oberbergamtes zu Halle/Sa. XXVa, 36-1, 13248/05; 18583/05

Frank A, Moran D, Epstein Y, Belokopytov M, Shapiro Y (1996) The estimation of heat tolerance by a new cumulative heat strain index. In: Shapiro Y, Moran D, Epstein Y (eds) Environmental Ergonomics: Recent Progress and New Frontiers. Freund Publishing House, Tel Aviv-London, pp. 194–197

Gagge AP (1941) Standard operative temperature, a single measure of the combined effect of radiant temperature, of ambient temperature and of air movement on the human body. In: Temperature, Its Measurement and Control in Science and Industry. Reinhold, New York, pp. 544–552

Gagge AP, Fobelts AP, Berglund LG (1986) A standard predictive index of human response to the thermal environment. ASHRAE Trans 92: 709–731

Gagge AP, Stolwijk JAJ, Nishi Y (1971) An effective temperature scale based on a simple model of human physiological temperature response. ASHRAE Trans 72:247–262

Gallagher M Jr, Robertson RJ, Goss FL, Nagle-Stilley EF, Schafer MA, Suyama J, Hostler D (2012) Development of a perceptual hyperthermia index to evaluate heat strain during treadmill exercise. Europ J Appl Physiol 112(6):2025–2034

Givoni B (1969) Man, Climate and Architecture. Elseveir Publishing Company Limited, Amsterdam

Givoni B, Goldman RF (1972) Predicting rectal temperature response to work, environment and clothing. J Appl Physiol 32:812–822

Givoni B, Goldman RF (1973a) Predicting effects of heat acclimatization on heart rate and rectal temperature. J Appl Physiol 35:875–879

Givoni B, Goldman RF (1973b) Predicting heart rate response to work, environment, and clothing. J Appl Physiol 34:201–204

Givoni B, Noguchi M, Saaroni H, Pochter O, Yaacov Y, Feller N, Becker S (2003) Outdoor comfort research issues. Energy and Buildings 35: 77–86

Gonzalez RR, Bergulnd LG, Gagge AP (1978) Indices of thermoregulatory strain for moderate exercise in the heat. J Appl Physiol 44:889–899

Gonzalez RR, Nishi Y, Gagge AP (1974) Experimental evaluation of standard effective temperature a new biometeorological index of man's thermal discomfort. Int J Biometeorol 18(1):1–15

Graveling RA, Morris LA, Graves RJ (1988) Working in hot conditions in mining: a literature review. Historical research report. Research Report TM/88/13. Institute of Occupational Medicine, Edinburgh Scotland

Gregorczuk M (1968) Bioclimates of the world related to air enthalpy. Int J Biometeorol 12:33–39

Gregorczuk M, Cena K (1967) distribution of effective temperature over the surface of the Earth. Int J Biometeorol 2:145–149

Haldane JBS (1905) The influence of high air temperatures. J Hygiene 5: 494–513

Hall JF, Polte JW (1960) Physiological index of strain and body heat storage in hyperthermia. J Appl Physiol 15:1027–1030

Hamdi M, Lachiver G, Michaud F (1999) A new predictive thermal sensation index of human response. Energy and Building 29:167–178

Hevener OF (1959) All about humiture. Weatherwise 12:83–85

Hill L, Hargood-Ash D (1919) On the cooling and evaporative powers of the atmosphere, as determined by the kata-thermometer. Proc R Soc Lond B Biol Sci 90:438–447

Hill L, Griffith OW, Flack M (1916) The measurement of the rate of heat loss at body temperature by convection, radiation and evaporation. Physiological Trans of the Royal Society B 207:183–220

Holmer I (1984) Required clothing insulation (IREQ) as an analytical index of cold stress. ASHRAE Trans 90:1116–1128

Holmer I (1988) Assessing of cold stress in terms of required clothing insulation IREQ. Int J Indust Ergon 3:159–166

Holmer I (1993) Work in the cold. Review of methods for assessment of cold exposure. Int Archives of Occupational and Environmental Health 65(3):147–155

Hori S (1978) Index for the assessment of heat tolerance. J Human Ergol (Tokyo) 7:135–144

Houghten FC, Yagloglou CP (1923) Determining lines of equal comfort. J Am Soc Heat Vent Eng 29:165–176

Hubac M, Strelka F, Borsky I, Hubacova L (1989) Application of the relative summary climatic indices during work in heat for ergonomic purposes. Ergonomics 32(7):733–750

Ionides M, Plummer J, Siple PA (1945) The thermal acceptance ratio. Report from climatology and environmental protection section. United States: Office of the US Quartermaster General (Interim report no 17)

Jendritzky G, Nübler W (1981) A model analysing the urban thermal environment in physiologically significant terms. Arch Met Geoph Biokl Ser B 29:313–326

Jendritzky G, de Dear R, Havenith G (2012) UTCI—why another thermal index? Int J Biometeorol 56(3):421–428

Jendritzky G, Havenith G, Weihs P, Batchvarova E (2009) Towards a Universal Thermal Climate Index UTCI for assessing the thermal environment of the human being. Final Report COST Action 730, Freiburg

Jendritzky G, Staiger H, Bucher K, Graetz A, Laschewski G. (2000) The perceived temperature—the method of the Deutscher Wetterdienst for the assessment of cold stress and heat load for the human body. In: Internet Workshop on Windchill, hosted by Environment Canada, April 3-7, 2000; available at http://windchill-conference.ec.gc.ca/workshop/papers/pdf/session_1_paper_4_e.pdf

Jokl MV (1982) Standard layers—a new criterion of the thermal insulating properties of clothing. Int J Biometeorol 26:37–48

Kalkstein LS, Valimont KM (1986) An evaluation of summer discomfort in the United States using a relative climatological index. Bull Am Meteorol Soc 67:842–848

Kalkstein LS, Valimont KM (1987) An evaluation of winter weather severity in the United States using the weather stress index. Bull Am Meteorol Soc 68:1535–1540

Kalkstein LS, Nichols MC, Barthel CD, Greene JS (1996) A New Spatial Synoptic Classification: application to air mass analysis. Int J Climatol 16(8):983–1004

Kamon E, Ryan C (1981) Effective heat strain index using pocket computer. Am Indust Hyg Assoc J 42:611–615

Kawamura W (1965) Distribution of discomfort index in Japan in summer season. J Met Research 17(7):460–466

Keller AA, Kuvakin VI (1998) Medical ecology. St-Petersburg: "The Petrograd and Co". 256 p. (in Russian)

Kerslake DM (1972) The stress of hot environment. Cambridge University Press, Cambridge

Keyantash J, Dracup JA (2002) The Quantification of Drought: An Evaluation of Drought Indices. Bull Amer Meteorol Soc 83:1167–1180

Kondratyev GM (1957) Approximate thermal assessment of clothing insulation. Trans V(C)NIISP, 6 (in Russian)

Lally VE, Watson BF (1960) Humiture revisited. Weatherwise 13:254–256

Landsberg HE (1972) The assessment of Human Bioclimate. A limited review of physical parameters. W.M.O. Tech. Note No. 123

Latyshev GT, Boksha VG (1965) Concerning medical estimation of weather (weather index and patients response). Questions of kurortol 4:345–351 (in Russian)

Lecha L (1998) Biometeorological classification of daily weather types for the humid tropics. Int J Biometeorol 42:77–83

Lee DHK (1958) Proprioclimates of man and domestic animals. Climatology: reviews of research. UNESCO Conf. Paris, 1956. Arid Zone Research Ser 10:102–125

Lee DHK, Henschel A (1966) Effects of physiological and clinical factors on response to heat. Ann NY Acad Sci 134:743–749

Lee DHK, Vaughan IA (1964) Temperature equivalent of solar radiation on man. Int J Biometeorol 8(1):61–69

Lind AR, Hellon RF (1957) Assessment of physiologic severity of hot climate. J Appl Physiol 11:35–40

Linke F (1926) Die Übertemperatur einer frei aufgestellten schwarzen Kugel. Meteorol Zeitschr 43:11

Liopo TN, Cicenko GV (1971) Climatic conditions and human thermal state. Leningrad Hydrometeorological Publishing House (in Russian)

Macpherson RK (1962) The assessment of the thermal environment. A review. British J Indust Medicine 19:151–164

Mahoney C (1967) (1967) The determination of standards for thermal comfort. The Architectural Association, London

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. Ann Occup Hyg 45(2):123–135

Maloney SK, Forbes CF (2011) What effect will a few degrees of climate change have on human heat balance? Implications for human activity. Int J Biometeorol 55:147–160

Masterson J, Richardson FA (1979) Humidex, a method of quantifying human discomfort due to excessive heat and humidity. Environment Canada, Downsview, Ontario http://ptaff.ca/humidex/?lang=en_CA

Mateeva Z, Filipov A (2003) Bioclimatic distance index in the Rila and Rhodopy area of Bulgaria. Błażejczyk K, Krawczyk B, Kuchcik M (eds.), Postępy w badaniach klimatycznych i bioklimatycznych. Prace Geografi czne IGiPZ PAN 188:295–302

Matyukhin VA, Kushnirenko EY (1987) Complex quality assessment of environmental influence on the human body. Proceedings of the WMO; WHO, UNEP-Symposium on Climate and Human Health in Leningrad 1986, WMO-WCP , Geneva 2:41–45

Mayer H, Höppe P (1987) Thermal comfort of man in different urban environments. Theor Appl Climatol 38:43–49

McArdle B, Dunham W, Holling HE, Ladell WSS, Scott JW, Thomson ML, Weiner JS (1947) The prediction of the Physiological Effects of Warm and Hot Environments. Med. Res. Coun. RNP Rep. 47/391 HMSO, London

McIntyre DA (1973) A guide to thermal comfort. Appl Ergonomics 4(2):66–72

McLaughlin JT, Shulman M (1977) An anthropocentric summer severity index. Int J Biometeorol 21:16–28

McPherson MJ (1992) The generalization of air cooling power. In: Proceedings of the 5th International Mine Ventilation Congress. Johannesburg: Mine Ventilation Society of South Africa http://www.scribd.com/emiliofar/d/78400695/19-Air-Cooling-Power

Mehnert P, Malchaire J, Kampmann B, Piette A, Griefahn B, Gebhardt HJ (2000) Prediction of the average skin temperature in warm and hot environments. Europ J Appl Physiol 82:52–60

Missenard A (1933) Étude physiologique et technique de la ventilation. Léon Eyrolles, Paris

Missenard A (1935) Théorie simplifié du Thermomètre Résultant. Chauf Vent 12:347–352

Missenard A (1948) Équivalence thermique des ambiances: équivalences de passage, équivalences de séjours. Chaleur et Industrie 276:159–172 277:189–198

Mitchell D, Whillier A (1971) Cooling power of underground environments. J S Afr Inst Min and Metallurg 72:93–99

Mochida T (1979) Comfort chart: an index for evaluating thermal sensation. Memoirs of the Faculty of Engineering, Hokkaido University 15(2):175–185

Moran DS (2000) Stress evaluation by the physiological strain index (PSI). J Basic & Clinical Physiol and Pharmacol 11(4):403–423

Moran DS, Shapiro Y, Epstein Y, Matthew W, Pandolf KB (1998a) A modified discomfort index (MDI) as an alternative to the wet bulb globe temperature (WBGT). In: Hodgdon JA, Heaney JH, Buono MJ (eds) Environmental Ergonomics VIII. Int Conf Environ Ergo, San Diego, pp. 77–80

Moran DS, Shitzer A, Pandolf KB (1998b) A physiological strain index to evaluate heat stress. Am J Physiol Regul Integr Comp Physiol 275:R129–R134

Moran DS, Castellani JW, O'Brien C, Young AJ, Pandolf KB (1999) Evaluating physiological strain during cold exposure using a new cold strain index. Am J Physiol 277(46):R556–R564

Moran DS, Pandolf KB, Laor A, Heled Y, Matthew WT, Gonzalez RR (2003) Evaluation and refinement of the environmental stress index (ESI) for different climatic conditions. J Basic Clin Physiol Pharmacol 14(1):1–15

Moran DS, Pandolf KB, Shapiro Y, Heled Y, Shani Y, Mathew WT, Gonzalez RR (2001) An environmental stress index (ESI) as a substitute for the wet bulb globe temperature (WBGT). J Therm Biol 26:427–431

Mount LE, Brown D (1982) The use of the meteorological records in estimating the effects of weather on sensible heat loss from sheep. Agric Meteorol 27:241–255

Mount LE, Brown D (1985) The calculation from weather records of the requirement for clothing insulation. Int J Biometeorol 29:311–321

Nagano K, Horikoshi T (2011) Development of outdoor thermal index indicating universal and separate effects on human thermal comfort. Int J Biometeorol 55(2):19–227
NIOSH (1986) Criteria for a recommended standard: occupational exposure to hot environment, National Institute for Occupational Safety and Health. DHHS (NIOSH) Publication No 86–113, Washington DC, pp. 101–110
Nishi Y, Gagge AP (1971) Humid operative temperature: a biophysical index of thermal sensation and discomfort. J de Physiologie 63:365–368
OFCM (2003) Report on Wind Chill Temperature and Extreme Heat Indices: Evaluation and Improvement Projects. US Department of Commerce, Federal Coordinator for Meteorological Services and Supporting Research, FCM-R19-2003, Washington DC (http://www.ofcm.gov/jagti/r19-ti-plan/r19-ti-plan.htm)
Ogunsote OO, Prucnal-Ogunsote B (2003) Choice of a thermal index for architectural design with climate in Nigeria. Habitat International 27:63–81
Ono HP, Kawamura T (1991) Sensible climates in monsoon Asia. Int J Biometeorol 35:39–47
Osczevski R, Bluestein M (2005) The new wind chill equivalent temperature chart. Bull Am Meteorol Soc 86(10):1453–1458
Osokin IM (1968) About severity of winter in northern Asia. Problems of regional researches of winter season. Chita, Zabaikalsk Geographical Society of the USSR 2:28–31 (in Russian)
Ott WR, Thom GA (1976) A critical review of air pollution index system in the. United States and Canada J Air Pollut Contr Assoc 26(5): 460–470
Pandolf KB, Moran DS (2001) New Heat and Cold Strain Predictive Indices. RTO HFM Symposium on "Blowing Hot and Cold: Protecting Against Climatic Extremes", Dresden, Germany
Pandolf KB, Stroschein LA, Drolet LL, et al. (1986) Prediction modelling of physiological responses and human performance in the heat. Comput Biol Med 6:319–329
Parsons K (2014) Human thermal environments: the effects of hot, moderate, and cold environments. CRC Press (Taylor and Francis Group), London 635 pp
Pedersen L (1948) Vaermestraalingsundersogelser. Committee for the study of domestic heating, Contribution Nr. 2, Kopenhagen
Pepi JW (1987) The summer simmer index. Weatherwise 3:143–145
Pepi JW (1999) The new Summer Simmer Index: a comfort index for the new millennium (http://www.summersimmer.com/home.htm)
Pickup J, de Dear R (2000) An Outdoor Thermal Comfort Index (OUT_SET*)—Part I—the model and its assumptions. In: de Dear R, Kalma J, Oke T, Auliciems A (eds): Biometeorology and urban climatology at the turn of the millennium. Selected Papers from the Conference ICB-ICUC'99 (Sydney, 8–12 Nov. 1999). WMO, Geneva, WCASP 50:279–283
Poschmann A (1932) Dissertation. Frankfurt
Pulket C, Henschel A, Burg WR, Saltzman BE (1980) A comparison of heat stress indices in a hot-humid environment. Am Indust Hyg Assoc J 41(6):442–449
Rissanen S, Rintamäki H (2007) Cold and heat strain during cold-weather field training with nuclear, biological, and chemical protective clothing. Military Medicine 172(2):128–132
Robinson S, Turrel ES, Gerking SD (1945) Physiologically equivalent conditions of air temperature and humidity. Am J Physiol 143:21–32
Rodriguez C, Mateos J, Garmendia J (1985) Biometeorological Comfort Index. Int J Biometeorol 29(2):121–129
Rohles FH, Nevin RG (1971) The nature of thermal comfort for sedentary man. ASHRAE Trans 77(1):239–246
Rohles F, Hayter R, Milliken G (1975) Effective temperature (ET*) as a predictor of thermal comfort. ASHRAE Trans 81(2):148–156
Rublack K, Medvedeva EF, Gaebelin H, Noach H, Schulz G (1981) Integrative bewertung der warmebelastung durch arbeit und klima (Integrative evaluation of heat loading due to work and climate). Zeitschrift fur die Gesamte Hygiene und ihre Grenzgebiete 27:12–17
Rusanov VI (1973) Methods of climate research in medical purposes. Tomsk State University, Tomsk (in Russian)
Rusanov VI (1981) Complex meteorological indices and methods of climate assessment in medical purposes. Tomsk, Tomsk State University, Handbook for Students (in Russian)
Rusanov VI (1987) Climate and human health. Proceedings of the WMO; WHO, UNEP-Symposium on Climate and Human Health in Leningrad 1986. WMO-WCP, Geneva 2:101–106
Rusanov VI (1989) Appraisal of meteorological conditions defining human respiration. Bull Russ Acad Med Sci 1:57–60 (in Russian)
Santee WR, Wallace RF (2003) Evaluation of weather service heat indices using the USARIEM heat strain decision aid (HSDA) model. USARIEM technical report
Scharlau K (1943) Die Schwüle als Messbare Grösse. Bioklimat Beibl 10:19–23
Schoen CA (2005) New empirical model of the Temperature–Humidity Index. J Appl Meteorol 44:1413–1420
Sheleihovskyi GV (1948) Microclimate of southern cities. Moscow, Academy of Medicine Sciences of the USSR (in Russian)
Sheridan SC (2002) The redevelopment of a weather type classification scheme for North America. Int J Climatol 22:51–68
Siple PA, Passel CF (1945) Measurements of dry atmospheric cooling in sub-freezing temperatures. Proc Am Philos Soc 89:177–199
Smith FE (1952) Effective temperature as an index of physiological stress. Royal Navy Personnel Research Committee Report No RNP 53/728. London, Medical Research Council
Smithson PA, Baldwin H (1979) The cooling power of wind and its influence on human comfort in upland areas of Britain. Arch Meteorol Geoph Biokl, Ser B 27:361–380
Sohar E, Tennenbaum J, Yaski D (1962) Estimation of daily water intake (to replace water loss) from the cumulative discomfort index. In: Tromp SW (ed) Biometeorology. Pergamon Press, Oxford, pp. 401–403
Staiger H, Laschewski G, Grätz A (2012) The perceived temperature—a versatile index for the assessment of the human thermal environment. Part A: scientific basics. Int J Biometeorol 56:165–176
Steadman RG (1971) Indices of windchill of clothed persons. J Appl Meteorol 10:674–683
Steadman RG (1979) The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. J Appl Meteorol 18:861–873
Steadman RG (1984) A universal scale of apparent temperature. J Clim Appl Meteorol 23:1674–1687
Steadman RG (1994) Norms of apparent temperature in Australia. Aust Met Mag 43:1–16
Tennenbaum J, Sohar E, Adar R, Gilat T, Yaski D (1961) The physiological significance of the cumulative discomfort index (Cum DI). Harefuah 60:315–319
Terjung WH (1966) Physiologic climates of the conterminous US: a bioclimatological classification based on man. Ann Am Ass Geogr 56:141–179
Terjung WH (1968) World patterns of distribution of the monthly comfort index. Int J Biometeorol 12:119–151
Thilenius R, Dorno C (1925) Das Davoser Frigorimeter (ein Instrument zur Dauerregistrierung der physiologischen Abkühlungsgrösse). Meteorol Zeitschr 42:57–60
Thom EC (1957) A new concept of cooling degree days. Air Condit Heat and Ventil 54(6):73–80
Thom EC, Bosen JF (1959) The discomfort index. Weatherwise 12:57–60
Thornthwaite CW (1948) An approach toward a rational classification of climate. Geographical review 84(1):55–94
Thornthwaite CW, Mather JR, Carter DB (1957) Instructions and tables for computing potential evapotrancpiration and the water balance.

Centerton NJ, Laboratory of Climatology, Publications in Climatology 10(3):1–104

Tikhomirov II (1968) Bioclimatology of Central Antarctica and human acclimatization. Nauka, Moscow (in Russian)

Tikuisis P, Mclellan TM, Selkirk G (2002) Perceptual versus physiological heat strain during exercise-heat stress. Med Sci Sports Exerc 34(9):1454–1461

Tromp SW (1966) A physiological method for determining the degree of meteorological cooling. Nature 210:486–487

Vernon HM (1932) The measurement of radiant heat in relation to human comfort. J Indust Hyg 14:95–111

Vernon HM, Warner CG (1932) The influence of the humidity of the air on capacity for work at high temperatures. J Hyg 32:431–462

Vogt JJ, Candas V, Libert JP (1982) Graphical determination of heat tolerance limits. Ergonomics 25(4):285–294

Vogt JJ, Candas V, Libert JP, Daull F (1981) Required sweat rate as an index of thermal strain in industry. In: Cena K, Clark JA (eds) Bioengineering, thermal physiology and comfort. Elsevier, Amsterdam, pp. 99–110

Wallace RF, Kriebel D, Punnett L, Wegman DH, Wenger CB, Gardner JW, Gonzales RR (2005) The effects of continuous hot weather training on risk of exertional heat illness. Med Sci Sports Exerc 37:84–90

Watts JD, Kalkstein SL (2004) The development of a Warm-Weather Relative Stress Index for environmental applications. J Appl Meteorol 43:503–513

Webb CG (1959) An analysis of some observations of thermal comfort in an equatorial climate. British J Indust Medicine 16:297–310

Weiss M (1982) The humisery and other measures of summer discomfort. Nat Weather Digest 7(2):10–18

Wenzel HG (1978) Heat stress upon undressed man due to different combinations of elevated environmental temperature, air humidity, and metabolic heat production: a critical comparison of heat stress indices. J Human Ergol 7:185–206

Winslow CEA, Herrington LP (1949) Temperature and human life. Princeton University Press, Princeton

Winslow CEA, Gagge AP, Greenburg L, Moriyama IM, Rodee EJ (1935) The calibrating of the thermo-integrator. Am J Hygiene 22:137–156

Winslow CEA, Herrington LP, Gagge AP (1937) Physiological reactions of the human body to varying environmental temperatures. Am J Physiol 120:1–22

Winterling GA (1979) Humiture-revised and adapted for the summer season in Jacksonville, Florida. Bull Am Meteorol Soc 60:329–330

Yaglou CP, Minard D (1957) Control of heat casualties at military training centers. Arch Indust Health 16:302–316

Young KC (1979) The influence of environmental parameters on heat stress during exercise. J Appl Meteorol 18:886–897

Zaninović K (1992) Limits of warm and cold bioclimatic stress in different climatic regions. Theoretic Appl Climatol 45(1):65–70