The Assessment of Sultriness. Part II: Effects of Wind, Extra Radiation and Barometric Pressure on Apparent Temperature

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ABSTRACT

A scale is derived in which any likely combination of summer temperature, humidity, wind and extra radiation can be expressed as apparent temperature. The effect of extra radiation (direct and indirect insolation; terrestrial and sky radiation) is considerable. The effect of wind is relatively slight in summer. The total direct effect of altitude (barometric pressure) is negligible. These results are compared with the use of globe thermometers and linear formulas. Maps show wind and extra-radiation effects which combine with ambient temperature and humidity to give the distribution of summer-noon apparent temperature in Anglo-America.

1. Introduction

Part I (Steadman, 1979) has described sultriness in terms of the effects of temperature and humidity on the active human at sea level. In many indoor applications these two variables can be entered in a table or chart which provides an adequate measure of "sultriness," as previously defined. Outdoors a person is generally exposed to wind and extra radiation, which can raise or lower the apparent temperature appreciably and which, along with altitude, must be taken into account in comparing climates at different times or places.

When a person is exposed to "extra" radiation, that is, radiation not described by the assumption that surrounding objects are at the same temperature as the ambient air, a new term appears in the model's heat-transfer equation.

If extra radiation is absorbed at the bare skin at a rate Q_g, the rate of heat loss becomes[1]

$$Q_u=[(T_s-T_\infty)/R_a]+[(P_b-P_\infty)/(Z_s+Z_a)]-Q_g.$$

Also

$$Q_u=(T_b-T_s)/R_s.$$

Therefore

$$Q_u=\frac{T_b-T_\infty}{R_s+R_a}+\left(\frac{P_b-P_\infty}{Z_s+Z_a}\right)\left(\frac{R_a}{R_s+R_a}\right)-Q_g\left(\frac{R_a}{R_s+R_a}\right).$$

[1] See Appendix for a complete list of symbols.

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For the clothed parts, similar analysis gives

$$Q_j=\frac{T_b-T_\infty}{R_s+R_f+R_a}+\left(\frac{P_b-P_\infty}{Z_s+rR_f+Z_a}\right)\left(\frac{R_f+R_a}{R_s+R_f+R_a}\right)-Q_g\left(\frac{R_a}{R_s+R_f+R_a}\right),$$

where $R_s=0.0387$ m^2 K W^{-1} and $Z_s=0.0521$ m^2 kPa W^{-1} under "mild" conditions.

Heat loss from the lungs at sea level is

$$Q_v=25.7-0.202T_\infty-3.05P_\infty, \tag{1}$$

independent of wind speed and extra radiation.

Under severe conditions thermal equilibrium of the unclothed body is given by

$$Q=180=Q_v+\{T_b-T_\infty+R_a[(P_b-P_\infty)/(Z_s+Z_a)]-Q_gR_a\}/(R_s+R_a). \tag{2}$$

Under mild conditions, thermal equilibrium and comfort of the clothed body are given by

$$Q=180=Q_v+(1-\phi_2)Q_u+\phi_2Q_j, \tag{3}$$

where a fraction ϕ_2 of the body is covered.

2. The effects of wind

a. *Convection coefficient*

For the person walking at 1.4 m s^{-1} in a meteorological wind speed (measured by an anemometer) of v_{10}, Part I showed a convective heat transfer coefficient of

$$h_c=c(a^{0.3}-0.0525a^{-1.7}b^2-0.0151a^{-3.7}b^4-\cdots),$$

where $a=(0.53v_{10})^2+1.4^2$; $b=2.8\times0.53v_{10}$; and c is a "constant," not used in the present analysis, which was done as follows.

By determining, as in Part I, the Reynolds number for each combination of wind speed, significant diameter and atmospheric conditions, then using Hilpert's (1933) data to obtain the Nusselt number, the convective heat-transfer coefficients shown in Fig. 1 were obtained for the whole body and for the components of the clothed body. The following linear approximations, valid in the range $2.5\leqslant v_{10}\leqslant 15$ m s^{-1}, are shown as dashed lines:

$$h_c=\begin{cases} 7.6+1.85v_{10} \text{ (entire body)} \\ 7.0+1.76v_{10} \text{ (clothed parts)} \\ 11.0+\ 2.6v_{10} \text{ (bare parts).} \end{cases} \quad (4)$$

Combined with the corresponding radiative heat-transfer coefficient, this gives the surface resistance as

$$R_a=1/(h_c+h_r).$$

b. Evaporative heat-transfer coefficient

As before, the coefficient $g=1/Z_a$ is obtained directly from wind speed. Within a tolerance interval of $\pm2\%$ over the range of climatic variables, it also depends only on v_{10} and is obtained as in Part 1 by multiplying the values of h_c by a factor 16.5 K kPa^{-1}, as illustrated in Fig. 1.

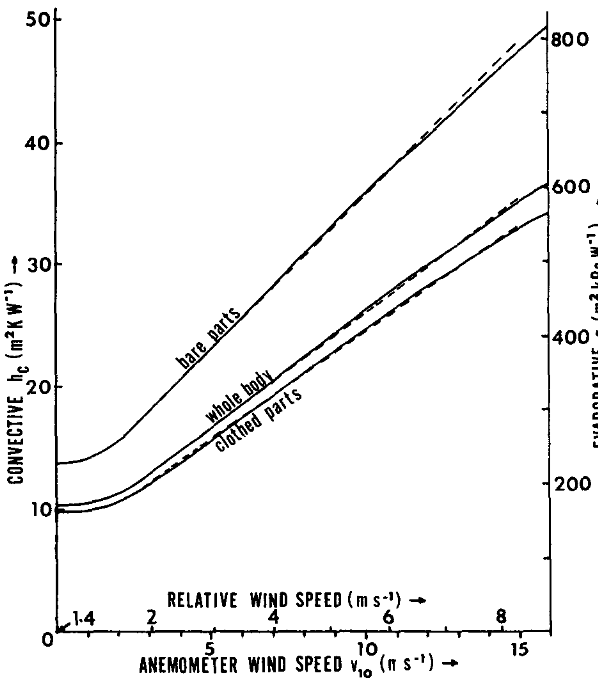

FIG. 1. Convective and evaporative heat-transfer coefficients as a function of meteorological wind speed (v_{10}) and relative wind speed (v) of a walking person.

TABLE 1. Heating or cooling effect (K) of a wind of 15 m s^{-1} without extra radiation.

Ambient temperature (°C)	Ambient relative humidity (%) 0	10	20	40	60	80	100
20	−4.3	−4.3	−4.3	−4.2	−4.0	−3.9	−4.1
25	−4.5	−4.2	−3.8	−3.3	−3.3	−3.8	−4.3
30	−1.3	−1.5	−1.8	−2.2	−3.1	−4.5	(−7)
35	+1.3	+1.2	+1.0	+0.4	−1.6		
40	+3.2	+3.0	+2.5	0.0			
45	+4.1	+3.5	+2.4				
50	+4.6	+3.4	(0.0)				

Thus the human's coefficients for evaporative heat transfer in the range $2.5\leqslant v_{10}\leqslant 15$ m s^{-1} are given by

$$g=\begin{cases} 126+30.4v_{10} \text{ (entire body)} \\ 115+29.0v_{10} \text{ (clothed parts)} \\ 182+40.5v_{10} \text{ (bare parts).} \end{cases} \quad (5)$$

c. Heating and cooling effects of wind

With the body's total heat loss, when walking at 1.4 m s^{-1}, set at 180 W m^{-2}, the resistance of skin (R_s) needed to maintain thermal equilibrium under severe conditions, or the thickness of clothing (d_f) needed to maintain equilibrium and comfort under mild conditions, was determined for various combinations of wind speed, temperature and vapor pressure.

Whether the wind makes a person feel warmer or colder and the extent of this heating or cooling depends considerably on ambient conditions. Table 1 shows the difference in apparent temperature between a 15 m s^{-1} wind and the base wind of 2.5 m s^{-1}, in the absence of extra radiation. Very slight irregularities appear in the upper rows because some values are derived from comparisons of the clothed with the unclothed model. As before, comparisons based on apparent temperatures >50°C or skin humidities >90% are enclosed in parentheses.

The cooling of a wind at low temperatures is more obvious than the effects on the person of summer winds. Winds less than the base speed of 2.5 m s^{-1} are scarcely detectable by the average moving person and any arbitrary base up to 2.5 m s^{-1} would produce similar results.

Because of the body's high heat capacity—under the worst possible conditions its time constant is 2 h—peak gusts are meaningless in determining the body's thermal equilibrium. In determining apparent temperature, wind speeds are averaged for at least a minute, preferably for 1 h.

At low humidities, when the apparent temperature is below ambient and the skin is relatively dry, appreciable heat is transferred into the body when air temper-

TABLE 2. Apparent temperature scale. Values in parentheses correspond to skin humidities above 90% and are approximate.

Dry-bulb temperature	Relative humidity (%) 0	10	20	30	40	50	60	70	80	90	100	Increment for wind (m s^{-1}) when $P_\infty \approx 1.6$ kPa 0–3	4	8	12	16
20	16	17	17	18	19	19	20	20	21	21	21	0	−1	−3	−4	−4
21	18	18	19	19	20	20	21	21	22	22	23	0	−1	−3	−4	−4
22	19	19	20	20	21	21	22	22	23	23	24	0	−1	−2	−3	−4
23	20	20	21	22	22	23	23	24	24	24	25	0	−1	−2	−3	−4
24	21	22	22	23	23	24	24	25	25	26	26	0	−1	−2	−3	−4
25	22	23	24	24	24	25	25	26	27	27	28	0	−1	−2	−3	−4
26	24	24	25	25	26	26	27	27	28	29	30	0	−1	−2	−3	−3
27	25	25	26	26	27	27	28	29	30	31	33	0	−1	−2	−3	−3
28	26	26	27	27	28	29	29	31	32	34	(36)	0	−1	−2	−3	−3
29	26	27	27	28	29	30	31	33	35	37	(40)	0	0	−1	−2	−3
30	27	28	28	29	30	31	33	35	37	(40)	(45)	0	0	−1	−2	−2
31	28	29	29	30	31	33	35	37	40	(45)		0	0	−1	−2	−2
32	29	29	30	31	33	35	37	40	44	(51)		0	0	−1	−1	−1
33	29	29	30	31	33	36	39	43	(49)			0	0	0	−1	−1
34	30	31	32	34	36	38	42	(47)				0	0	0	0	0
35	31	32	33	35	37	40	(45)	(51)				0	0	0	0	+1
36	32	33	35	37	39	43	(49)					0	0	0	+1	+1
37	32	34	36	38	41	46						0	0	0	+1	+2
38	33	35	37	40	44	(49)						0	0	0	+1	+2
39	34	36	38	41	46							0	0	+1	+2	+2
40	35	37	40	43	49							0	0	+1	+2	+3
41	35	38	41	45								0	0	+1	+2	+3
42	36	39	42	47								0	0	+1	+2	+3
43	37	40	44	49								0	0	+1	+2	+3
44	38	41	45	52								0	0	+1	+2	+3
45	38	42	47									0	0	+1	+2	+3
46	39	43	49									0	0	+1	+2	+3
47	40	44	51									0	0	+1	+2	+3
48	41	45	53									0	0	+1	+2	+3
49	42	47										0	0	0	+2	+3
50	42	48										0	0	0	+1	+2

Extra radiation (Q_g) under cloudless sky at sea level when $P_\infty \approx 1.6$ kPa.*

Time before or after solar noon (h)	0	1	2	3	4	5	6	7	8–12
Latitude 34°N, summer	92	101	114	124	127	119	67	−24	−26
Latitude 34°S, summer	107	117	132	141	146	135	79	−24	−26
Latitude 34°N, or °S, Equinox	125	128	134	138	132	83	−25	−26	−26
Equator, June–July	113	120	130	138	134	91	−25	−26	−26
Equator, December–January	133	138	149	158	154	106	−25	−26	−26
Equator, Equinox	98	113	132	146	147	107	−24	−26	−26

* Increment for extra radiation: (a) if $v_{10} \leqslant 3$ m s^{-1}, add $0.056\, Q_g$; (b) if $v_{10} \geqslant 3$ m s^{-1}, add $0.61\, Q_g/(8+v_{10})$.

ature exceeds skin temperature. Because wind increases this heat flow, a hot dry wind raises the apparent temperature. As the humidity increases at the same ambient temperature, the person depends more on active perspiration to maintain equilibrium. Although the previous "dry" effect still operates, evaporative heat transfer predominates. Since the body's vapor pressure, unlike its temperature, always exceeds that of the surroundings, the sweating person derives an evaporative cooling effect as wind speed increases at high humidities.

Table 1 includes uncommon extreme values of humidity. In compiling Table 2, to be described later, the "base" vapor pressure of 1.6 kPa is used in determining the wind increments on the right-hand side.

In full sunshine, the effect of a wind is nearly always to lower the apparent temperature. In the present analysis, including Table 2 but excluding Section 2d, wind in the absence of extra radiation is evaluated first, then the effect of extra radiation in the presence of that wind. The effect of extra radiation will be described in the next section, but has been taken into account in the climate comparisons of the following paragraph.

d. *Wind effects in assessing climate*

Just as Part I described the effects of humidity on apparent temperature in Anglo-America, the effect of wind on the sensation of temperature shows geographic variation. For the purpose of comparing summer climates, July means of wind speed (ESSA, 1968; DOT Canada, 1967) were increased by 10% to give an estimate of midsummer noon winds, reflecting

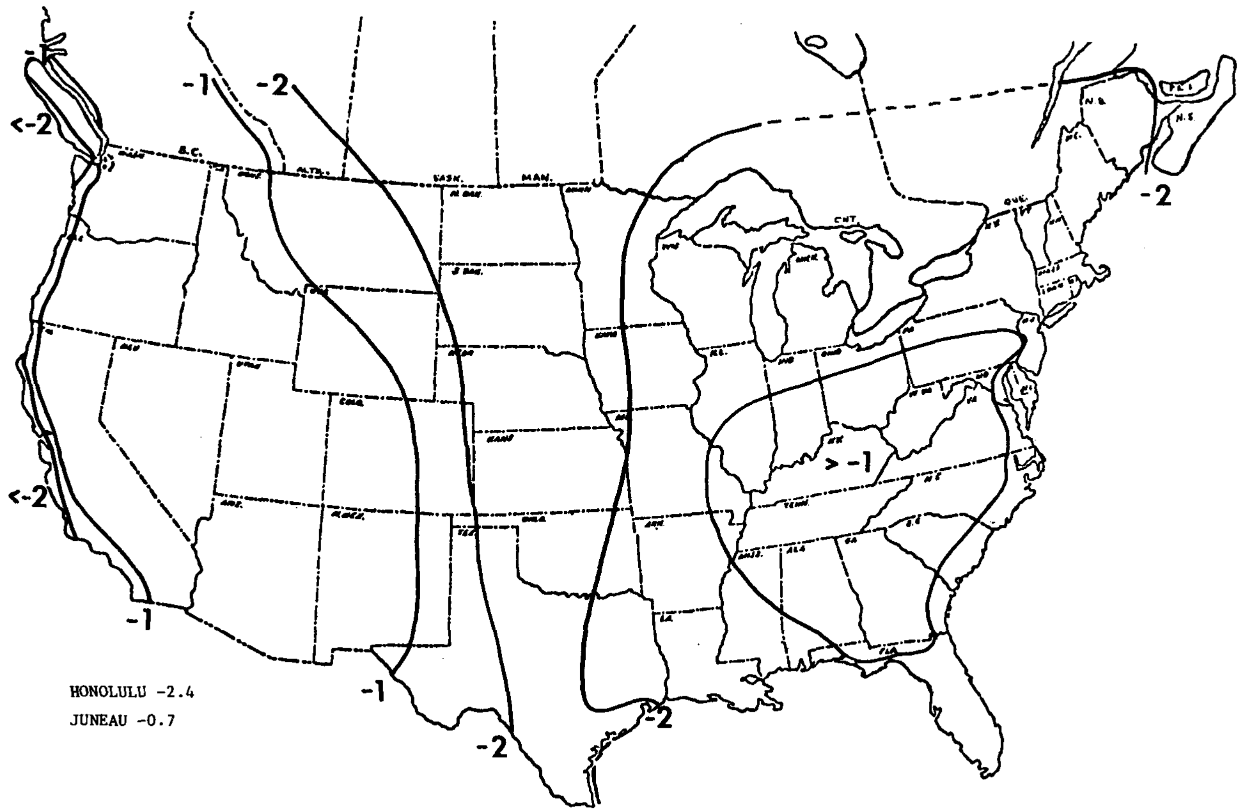

Fig. 2. Geographic variation in the effect of wind on apparent temperature (K) in Anglo-America, normal solar noon, midsummer conditions.

the heat-transfer coefficients of Eqs. (4) and (5). Using the methods of Section 3, extra radiation was also taken into account and all variables were entered into Eqs. (1) and (2) or (3) to determine apparent temperature. By changing v_{10} to its base value of 2.5 m s^{-1} with all other variables held constant, a "base" apparent temperature was determined, with the result that the effect of wind is shown as the difference between the two results.

Performing this procedure for the 59 cities[2] referred to in Part I leads to Fig. 2, showing the cooling effect of wind in midsummer noon conditions.

e. Cooling effect of perspiration

Using the analysis under the more general conditions of Part I shows that the efficiency with which perspiration cools the body, $\eta_e = R_a/(R_s+R_a)$, is as low as 38% when $v_{10}=16$ m s^{-1} and $T_\infty=28$°C. This contrasts with the value of 100% implicit in most of the literature.

3. The effect of extra radiation

Outdoors, the model is generally exposed to four types of extra radiation. Since the effects on the person of direct sunlight, diffuse sunlight, terrestrial and sky radiation differ in many ways they must be analyzed separately in the light of the body's means of exchanging extra radiation with its environment.

a. Projected-area factor

The body's surface area on which direct insolation impinges is much less than the du Bois area. Although the intensity varies across the surface, the incident direct radiation is given by $\phi_1\phi_3 Q_d$ averaged over the effective radiative or du Bois area. The ratio ϕ_3 is the quotient of the body's projected area normal to the sun's rays divided by the du Bois area.

This projected area factor depends on the sun's altitude and azimuth relative to the model. The most versatile data relating these variables seem to be those of Fanger (1970, p. 64) for standing humans. More limited data of Roller and Goldman (1968) show that the projected-area factor of walking humans consistently exceeds that of standing subjects by 2%. Fanger's data for altitudes of 0°, 15°, 30°, 45°, 60°, 75° and 90° were each averaged for all values of azimuth, the adjustment of 0.02 was added and the results plotted as Fig. 3. A useful approximation describing the walking human and accurate in the

[2] Since the completion of Part 1, which used 58 cities, Spokane has been added because eastern Washington was found to have the highest normal extra radiation ($Q_g=112$ W m^{-2}) at midsummer noon.

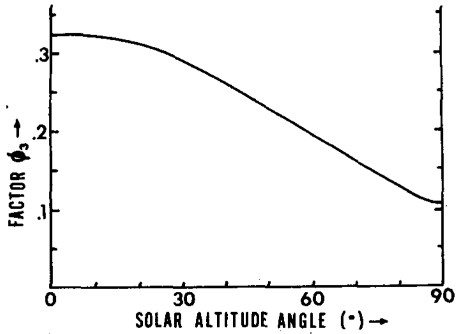

FIG. 3. The body's projected-area factor to direct insolation at different solar altitudes.

range $25° \lesssim A \lesssim 85°$ is

$$\phi_3 = 0.386 - 0.0032A.$$

The solar altitude seldom exceeds 85° in Anglo-America and, when $A < 25°$, direct sunshine is not intense. The factor, i.e., the effect of sunshine on apparent temperature, would be slightly greater for a person facing toward or away from the sun, and correspondingly less for a person in profile. For a prone person, as in sunbathing, the solar heat load is usually much greater.

The solar altitude angle for any time of day and year is found and entered in Fig. 3 to determine the projected-area factor. For any latitude λ it is given by

$$\sin A = \sin\lambda \sin\delta + \cos\lambda \cos\delta \cos 15H,$$

where H is the time in hours before or after solar noon and the solar declination angle $\delta = 23.45 \sin 0.986n$ (deg), where n is the number of days after 21 March.

b. The radiative environment

Extra-radiative exchanges can appreciably modify the perceived sultriness, as described so far. Form factors for all parts of the model with respect to the surroundings are taken as 0.50 to the ground; 0.10 to other objects, which are taken as being at air temperature; and 0.40 to the sky. These are further multiplied by the factor ϕ_1, which is 0.80 for the whole body, 0.85 for the bare parts and 0.79 for the clothed parts.

Both skin and clothing are assumed to have absorptivities to solar radiation of 0.70 and emissivities of 0.97, typical of "white" skin and summer garments. Variations about these values are generally slight and, as Renbourn (1962) has pointed out, choice of clothing color can have little effect on the total heat load.

c. Exchanges of extra radiation

1) DIRECT INSOLATION

That part of the solar radiation which can be regarded as having a point source varies both in intensity and in its effect on humans. Because of the human's upright stance, direct summer insolation on the person reaches peaks in mid-morning and mid-afternoon and is greater at higher latitudes than in the tropics.

The proportion of insolation which is direct (ϕ_5) is derived from ASHRAE (1972, p. 387) as 0.88 in midsummer and 0.925 at the equinoxes under a clear sky. Following Budyko (1956), this proportion is expressed more generally as $\phi_5(1-\phi_4^2)$. The average fraction ϕ_4 for the daylight hours is given by ESSA (1968, p. 71). Since Landsberg's (1965, p. 134) data show that noon sky cover is normally 85% of this average, the ESSA values were multiplied by 0.85 to determine ϕ_4 for the present analysis, hence the amounts of direct insolation at the 59 cities. From the climatic data of total daily sunshine on a horizontal actinometer, updated by Baldwin (1973), and the ASHRAE data on the diurnal variation of both normally and horizontally incident insolation, a simple conversion gives, for each latitude, the average insolation on a surface perpendicular to the sun's rays (Q_d), the average indirect insolation (Q_i), and the total insolation incident on a horizontal surface (Q_h). When $35° \leqslant \lambda \leqslant 48°$, for instance, total normal daily summer insolation in langleys per day on a horizontal surface is converted to noon insolation in watts per square meter ($Q_i + Q_d$) perpendicular to the sun's rays by multiplying by 1.44. At other latitudes in Anglo-America, the conversion factor is in the range 1.45 to 1.49.

Other examples are based on the populated latitude $\lambda = 34°$ N (e.g., Los Angeles). Since the earth is 7% closer to the sun in the southern summer than in the northern summer, analyses based on northern data, such as ASHRAE (1972), must take this into account in determining summer sultriness in the Southern Hemisphere. If $\lambda = 34°$ S (e.g., Sydney), corresponding values of direct, indirect and terrestrial radiation are therefore increased by 14% in summer and reduced by 12% in winter.

The direct solar radiation absorbed by the person's skin or clothing surface is given by

$$Q_1 = \alpha\phi_1\phi_3 Q_d,$$
$$= 0.56\phi_3 Q_d \text{ for the unclothed model.} \quad (6)$$

At sea level it may vary from 0 at night to ~150 W m^{-2} in January at latitudes near 40°N.

2) INDIRECT INSOLATION

Incoming radiation is assumed to be uniformly distributed over the 40% of the surroundings occupied by the sky. From the discussion of direct radiation, it follows that the proportion of insolation which is indirect is $(1-\phi_5)(1-\phi_4^2)$. Using, as before, ASHRAE conversions to change horizontally incident daily totals to normally incident noon intensities gives the corresponding values of Q_i.

The intensity absorbed at the human surface is

$$Q_2=0.40\propto\phi_1 Q_i$$
$$=0.224\ Q_i \text{ for the unclothed model, independent of solar altitude.} \quad (7)$$

At sea level it may vary from 0 at night to $\sim$100 W m^{-2} in summer on cloudy days; even under clear skies it reaches $\sim$30 W m^{-2}.

3) Terrestrial radiation

Sunlight reflected from terrestrial objects depends appreciably on the earth's albedo, which is here taken as 0.10, Landsberg's (1965, p. 122) value for urban surroundings. This component is determined from the total incident insolation on a horizontal surface as

$$Q_3=0.10\times0.50\propto\phi_1 Q_h$$
$$=0.028\ Q_h \text{ for the unclothed model.} \quad (8)$$

It varies from 0 at night to $\sim$35 W m^{-2} in the Northern Hemisphere and $\sim$40 W m^{-2} in the Southern at midsummer noon. Under conditions beyond the intent of this paper, particularly on snow, terrestrial radiation absorbed by the human can be as high as 200 W m^{-2}.

4) Sky radiation

Much of the study of insolation has been concerned with its penetration of glass objects, particularly in buildings, solar heaters and actinometers. These do not measure longwave outgoing radiation, which affects human comfort appreciably but is seldom noticeable during the day because of the effects of the above three types of extra radiation. Of the available data, the best seem to be Budyko's (1956) equation which has been modified by the writer to refer to the human model, giving the radiation from the surface to the sky as

$$Q_4=0.40\epsilon\sigma\phi_1[1-\phi_4{}^2(0.50-0.0043\lambda)]$$
$$\times[1-0.62e^{-0.108E}-0.16\sqrt{P_\infty}]T_{Ks}^4. \quad (9)$$

For the special, but common, case of a nearly cloudless sky at sea level, using the fact that $T_{Ks}\approx304$ K or $T_s\sim31$°C when $\mathcal{T}>26$°C, this becomes

$$Q_4=150(0.38-0.16\sqrt{P_\infty})\ [\text{W m}^{-2}].$$

At sea level, it varies from $\sim$15 under an overcast sky to $\sim$40 W m^{-2} on a hot dry cloudless day. Kondryatev (1969, p. 572) has pointed out that Budyko's equation represents an average about which great variation has been recorded.

5) Total extra radiation

The rate at which extra insolation is absorbed at the skin is given by

$$Q_g=Q_1+Q_2+Q_3-Q_4. \quad (10)$$

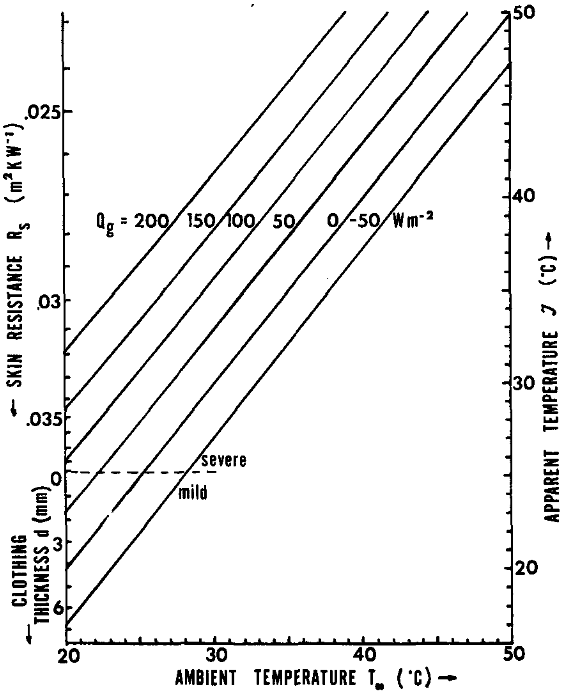

FIG. 4. The effect of extra radiation when $v_{10}=2.5$ m s^{-1} and $P_\infty=1.6$ kPa.

Since the maximum values of these four types do not coincide, the likely range for Q_g for the model at sea level is from ~-30 to $\sim$180 W m^{-2}. All four types of extra radiation are generally appreciable. For example, the first value of Q_g in Table 2 (92 W m^{-2}) consists of 65 direct, 26 indirect, 27 terrestrial and -26 sky radiation.

6) Heat load due to extra radiation

Inspection of the introductory equations shows that not all of the radiation absorbed at the skin surface adds to the body's heat load. The efficiency of this absorption is $\eta_g=R_a/(R_s+R_a)$ for the bare skin and $\eta_g=R_a/(R_s+R_f+R_a)$ for the clothed parts. Under the wide range of conditions considered here, η_g can be as low as 18%, when $v_{10}=16$ m s^{-1}, $T_\infty=20$°C and $P_\infty\to0$ and as high as 72% when $v_{10}\lesssim2.5$ m s^{-1} and $\mathcal{T}=50$°C. It applies to all positive and negative values of Q_g. Thus, from the above paragraph, the heat load imposed by extra radiation under the conditions described here varies in the range -20 to 130 W m^{-2}.

7) The effect of extra radiation on apparent temperature

When other variables are held constant, the effect of changing from a sheltered to a fully exposed position is to raise the apparent temperature by as much as 7.5 K. This is comparable with Roller and Goldman's (1968) empirical finding that full sunshine is equivalent to a temperature increase of 13°F. This increment is almost directly proportional to Q_g, only slightly dependent on T_∞ and increases with P_∞. It falls appreciably in high winds, which reduce R_a, hence the efficiency with which extra radiation reaches the body core. Fig. 4 shows apparent temperatures at various levels of extra radiation when vapor pressure and wind are at their base levels of 1.6 kPa and 2.5 m s^{-1}.

The increment is determined by solving Eqs. (1) and (2) or (3) for apparent temperature, with Q_g equal to the value from Eq. (10); and with $Q_g=0$. This has been done for the conditions of midsummer noon at the 59 cities and the results plotted as Fig. 5. Canadian data, being in mean daily hours of sunshine, were first converted into mean solar intensity by equating figures for four southern cities, Vancouver, Winnipeg, London and Montreal, with the nearest U. S. city and obtaining an average conversion factor. At lower latitudes, the increments are relatively low at that time of day and year, since the noon sun, being almost overhead, casts less radiation on the walking person. Because of low humidity and high radiation to the sky, the effect of sunshine on apparent temperature is sometimes less in deserts than in less sunny but humid places of similar latitude.

If Table 2 is used for climate comparison, the extra-radiation increment for clear sky is multiplied by the proportion of time in which the sun normally shines for that time of day and year to give an approximate estimate which is seldom more than 1 K below that obtained by using Eq. (10) and the more rigorous analysis above.

4. The effect of barometric pressure

Since the largest influence on atmospheric pressure is altitude (E), this analysis will examine the model in terms of altitude effects. High altitude reduces apparent temperature indirectly because of the temperature lapse. Inspection of world climatic data shows that for all places, at least 99% of the time,

$$T_\infty < 50 - 7E. \tag{11}$$

Other indirect effects are enhanced extra radiation and the generally lower vapor pressure. The present analysis takes into account the *direct* effects, those due to a change in altitude when temperature, vapor pressure, wind and extra radiation are held constant.

The direct effects are due to the lower density of air, which is related to the sea-level density by

$$\rho = \rho_0 e^{-0.108E}.$$

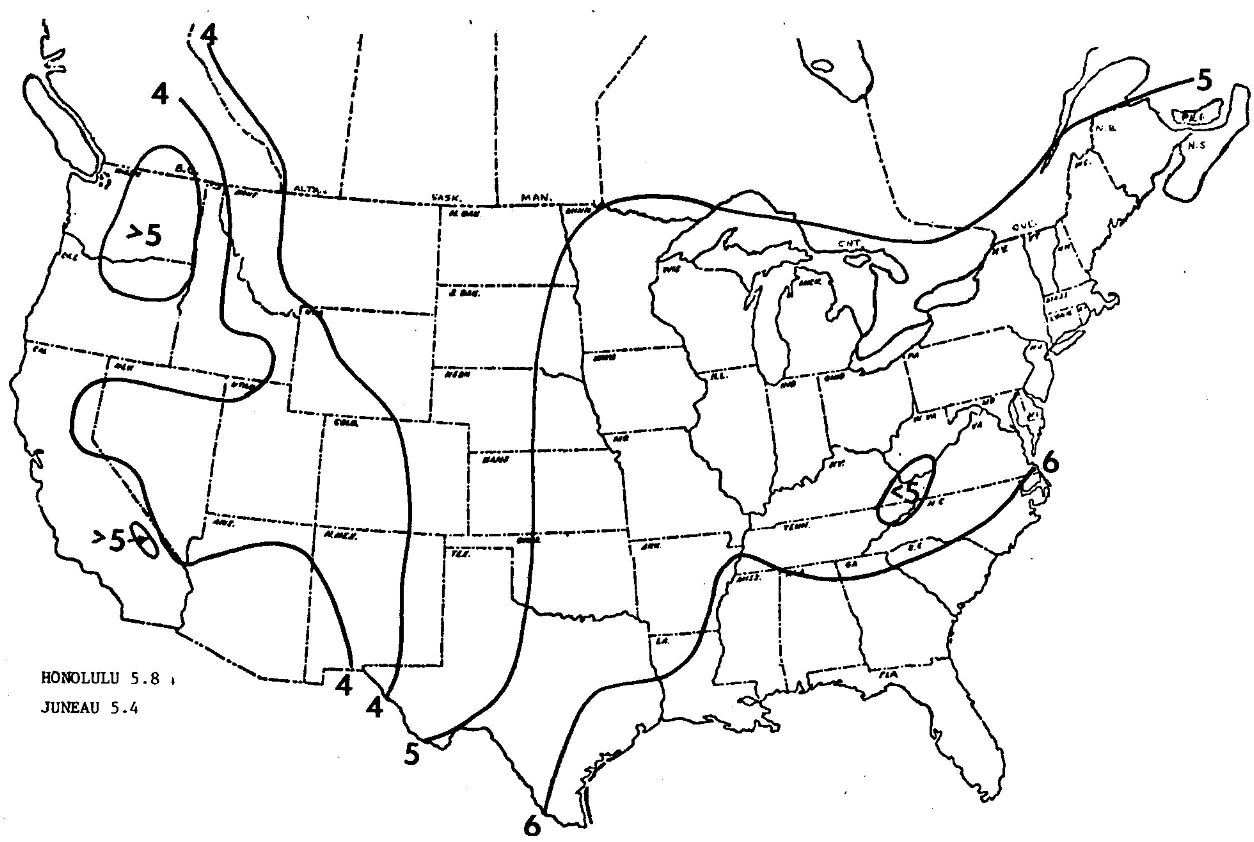

FIG. 5. Geographical variation in the effect of extra radiation on apparent temperature (K) in Anglo-America, normal solar noon, midsummer conditions.

Other physical properties of the air vary only slightly with density.

(i) As a result, convection losses, which vary with $v^{0.6}$, are reduced:

$$h_c = h_{c0}e^{-0.065E}.$$

(ii) Moisture transfer is affected analogously but diffusion through the boundary layer is slightly increased:

$$g = g_0e^{-0.066E}.$$

(iii) Compared with normal sea level atmospheric pressure of $\mathcal{P}_0 = 101.3$ kPa, lower pressures force the lungs to process a greater volume of air to maintain a supply of oxygen. Since the vapor pressure of the exhaled air is increased by an amount almost independent of its density, the evaporative heat loss due to ventilation increases in inverse proportion. Unlike the other two, this effect has not been described in the literature. Eq. (1) is generalized to

$$Q_v = 8.9 + 17.3e^{0.108E} - 0.202T_\infty - \frac{304P_\infty}{\mathcal{P} - P_\infty},$$

where $\mathcal{P} = \mathcal{P}_0e^{-0.108E}$.

At an altitude of 5000 m, evaporative heat loss in breathing accounts for $\sim$13% of the total, almost twice the proportion at sea level. The slight reduction in the proportion of oxygen in high-altitude air reinforces this effect, but is not taken into account here.

When the three effects are combined, the net result is less than 1% of the total heat loss when $T_\infty < 25$°C. Effect (iii) almost exactly offsets the other two. At higher temperatures, when sweating becomes more important, effect (ii) becomes appreciable. When apparent temperatures are determined for a variety of conditions in the range $0 \leqslant E \leqslant 5$ km, with the constraint of (11), the direct effect of altitude is found to be between -0.1 and $+0.4$ K. It is therefore neglected. To effect considerable savings in space, analysis based on this part of the study has been omitted.

5. A generalized index of sultriness

The preceding analysis enables assessment of any set of climatic conditions. Given the ambient temperature, humidity, wind and extra radiation it is possible to solve Eqs. (1) and (2) or (3) to find the required skin or clothing resistance. When this value is substituted in the same equations using the base values of $P_\infty = 1.6$ kPa, $v_{10} = 2.5$ m s^{-1} and $E = Q_g = 0$, the value of T_∞ obtained is the apparent temperature $\mathcal{T}$, This has been done for the range of summer conditions.

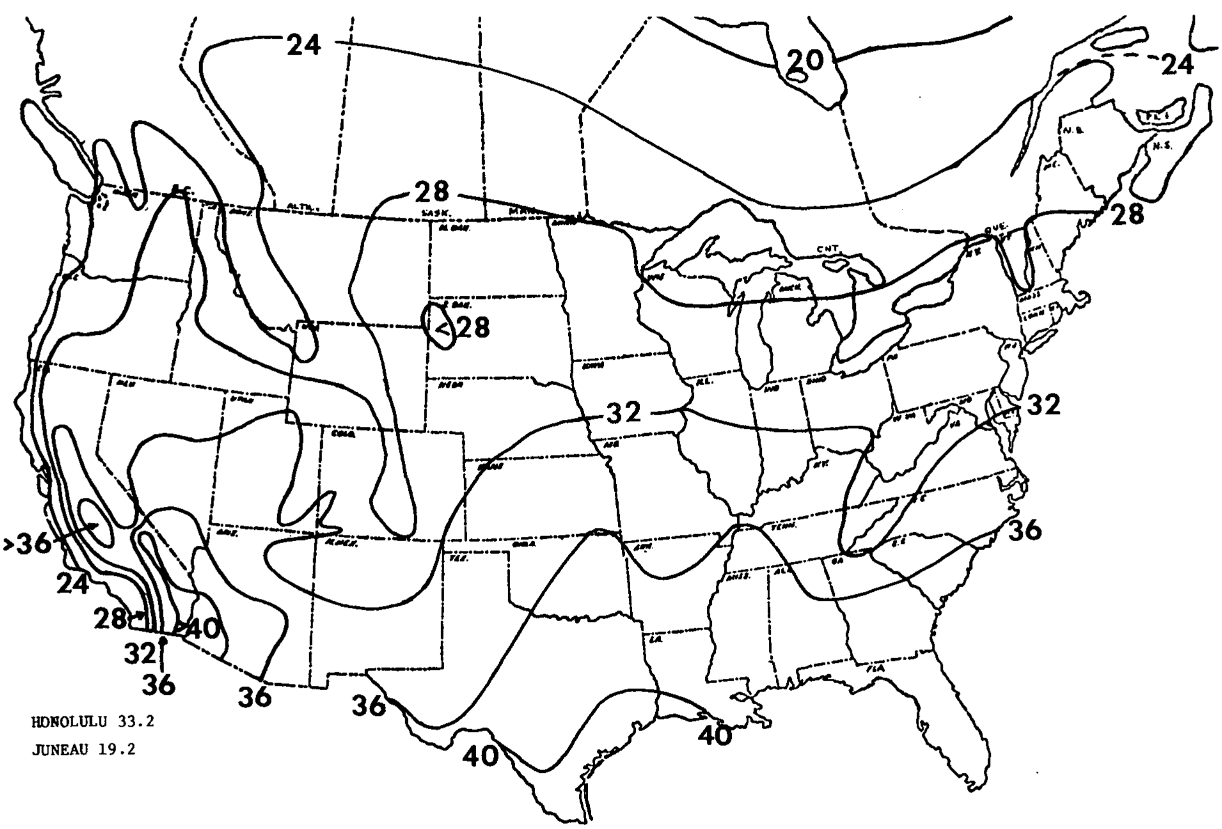

FIG. 6. Geographical variation in apparent temperature (K) in Anglo-America, normal solar noon, midsummer conditions.

TABLE 3. Comparative reactions of human model and globe thermometer in full sunshine.

A	60°	
Q_d	900 W m^{-2}	
Q_i	120 W m^{-1}	
v_{10}	2.5 m s^{-1}	
P_∞	1.6 kPa	
T_∞	30°C	
	Human model	Globe thermometer
ϕ_1	0.80	1.00
ϕ_3 (direct insolation)	0.194	0.250
ϕ_3 (indirect insolation and sky radiation)	0.40	0.40
ϕ_3 (terrestrial radiation)	0.50	0.50
α	0.70	0.98
h_c	12.30	14.03
h_r	4.94	6.49
g	201	no evaporation
Q_v	18.46	no respiration
Gross incident insolation (direct, indirect and terrestrial)	222	331
Gross absorbed insolation	156	324
Sky radiation	28	40
Q_g	128	284
Net solar heat load	86	284
Increase in apparent or globe temperature (K)	7.1	13.9

resulting in Table 2. A traditional version of Table 2, with v_{10} expressed in miles per hour and temperatures in degrees Fahrenheit, is available from the author. Increments for wind and extra radiation in this table are exact only when $P_\infty = 1.6$ kPa, but in most climates are accurate to ± 2K.

Solution of the heat-transfer equations for the 59 cities produces Fig. 6, mapping the normal apparent temperature at midsummer noon. Exposed to sun and wind, the human typically encounters an apparent temperature between 3 and 6 K above the dry-bulb temperature with extreme discrepancies of 11 K in the most humid parts of the Gulf coast and 1 K in the dryest parts of the southwestern desert.

Although the full analysis was used to determine apparent temperatures in the 59 cities, it is onerous and can be replaced with reasonable accuracy by Table 2 when data on cloudiness are available to modify the values of Q_g. These values were calculated for $\lambda = 34°$ but are accurate (in summer only) within ± 21 W m^{-2} when $0 \leqslant \lambda \leqslant 50°$. Thus they are applicable approximately in most populated parts of North America when $T_\infty > 20°$C. Table 2 (but with previously derived values of Q_g) was applied to the 59 cities and, when $P < 2.4$ kPa ($T_{dp} < 20°$C), it produced, on average, the same result, with a standard deviation of 0.6 K. This is probably within the limits of error of the whole analysis. But at higher humidities, this approach underestimates the synergism between humidity and wind, and between humidity and extra radiation. Errors >1 K occur unless Eqs. (1) and (2) or (3) are solved when $P_\infty > 2.4$ kPa.

6. Alternative measures of sultriness

a. The use of globe thermometers

The globe thermometer has often been used as a measure of radiation effects on humans. Since the globe-thermometer index of Yaglou and Minard (1957) will be compared with the present results, heat transfer to or from the globe will be contrasted with that of the model.

Being a sphere 6 inches in diameter, the globe has a significant diameter, 10.2 cm, less than that of the cylinder which represents the model. If it is mounted stationary 1.2 m above ground level, the relative wind speed when $v_{10} = 2.5$ m s^{-1} is 1.60 m s^{-1}, giving a convective heat-transfer coefficient[3] of 14.0 W m^{-2} K^{-1}. The comparison of other quantities is explained by Table 3, which describes the reactions of the globe thermometer and of the human model in typical sunny conditions of "severe" sultriness.

Unlike the human, the spherical globe is quite insensitive to the sun's altitude, having $\phi_3 = 0.25$ at all times. This is comparable to the human model only when $A = 42°$. Having neither skin nor clothing, the globe thermometer is much more sensitive to wind changes. As Table 3 shows, the globe thermometer exaggerates the effect of insolation on the human by a factor of ~ 2, the factor increasing with increasing solar altitude. The proposal of Gagge *et al.* (1967), to reduce the globe's absorptivity to that of the human skin by painting, would reduce the discrepancy but would not imitate the human's ability to exchange heat by perspiration and breathing; nor would it provide comparable radiation area factors ϕ_1 and ϕ_3.

b. Prediction of apparent temperature directly from basic thermometer readings: A brief review

The literature contains many formulas for equating some single index of sultriness with dry-bulb and wet-bulb—and sometimes globe—temperatures, usually of the form

$$T_x = c_1 T_{db} + c_2 T_{wb} + c_3 T_{gt} + c_4, \qquad (12)$$

where T_x is some temperature index of sultriness or discomfort and c_1, c_2, c_3, c_4 are constants.

A partial review of the literature reveals a wide range of results:

Until fairly recently it was accepted that humidity played a sufficiently great role in indoor comfort for its precise control to be important (e.g., Yagloglou and Miller, 1925). The well-known effective tempera-

[3] Free-convective conditions are sometimes quoted in the literature. It is often impracticable to arrange free convection together with full sunshine. Calculation based on conventional heat-transfer theory shows that under such conditions the total heat-transfer coefficient would typically be $\sim 40\%$ lower and the globe's excess temperature, $T_{gt} - T_\infty$, $\sim 65\%$ higher.

ture (e.g., ASHRAE, 1961) or the temperature-humidity index (Thom, 1956) can be expressed in a form which gives similar weight to wet- and dry-bulb temperatures.

One of three formulas for the latter is $T_x=0.40T_{db}+0.40T_{wb}+15$ [°F]. The index is usually less than the dry-bulb temperature, always so if $T_\infty>75$°F.

Robinson *et al.* (1945) recognized that the influence of humidity had been overestimated because hygroscopic clothing worn by test subjects produced latent heat of sorption as they passed to a relatively humid room—a transient effect unrelated to thermal equilibrium.

Subsequent research, which allowed subjects time to equilibrate before assessing their thermal comfort (e.g., Nevins *et al.*, 1966), showed a much lower humidity effect. The widespread use of synthetic fibers with little moisture uptake has also reduced this "thermostatic effect" in modern clothing. The results of Fanger (1970, p. 66), now adopted for use by engineers (ASHRAE, 1972, pp. 140, 141), imply that the relative weighting given to dry- and wet-bulb temperatures varies over the narrow range 84:16 to 88:12 for comfortable test subjects, in contrast to the earlier 50:50.

The Humidex, used officially in Canada because of dissatisfaction with the temperature-humidity index (Meteorological Branch, 1965), is based on a vapor pressure of 10 mb or 1.0 kPa, with 1°F added arbitrarily to the dry-bulb temperature for each additional millibar above 10. This corresponds to a relative weighting for dry-bulb: wet-bulb of 47:53. With such a weighting for humidity, Humidex values above 50°C are recorded annually in Canada.

Until about 1969 the majority of publications, and some subsequent ones, on the subject included the assumption that the path to thermal equilibrium is simply for the body to produce perspiration at a rate which equals the gap between heat production and dry-plus-respiratory heat loss. It was invariably assumed also that the cooling efficiency of perspiration is 100%. While ***equilibrium*** can be achieved in this way, the same equilibrium under different conditions may correspond to quite differing levels of *comfort*. Since such an approach underestimates the effects of humidity variation, it cannot be meaningfully applied to the comparison of climates.

Outdoors, globe thermometers have often been used as a measure of solar radiation and its effect on personnel. The wet-bulb globe-thermometer index of Yaglou and Minard (1957) is given by

$$T_x=0.1T_{db}+0.7T_{wb}+0.2T_{gt}.$$

In absence of sunshine, the authors prescribe coefficients of 0.15, 0.85 and 0. The wet-bulb globe-thermometer index can also be obtained directly by means of the apparatus of Taylor *et al.* (1969).

The relationship between extra radiation (Fig. 5) and the amount by which T_{gt} exceeds T_{db} can be determined for the special case of $\phi_3=0.25$ ($A=42°$). Interpretation of globe-thermometer readings and the use of formulas such as Eq. (12) must take into account that any change in T_{db} involves an equal change in T_{gt} in the absence of sunshine.

The relative influence of these three variables on skin resistance, hence on apparent temperature, can be determined by partially differentiating R_s in Eq. (2) with respect to dry bulb, wet bulb and globe temperatures.

Since $h_c=f(v_{10})$, $h_r=f(T_\infty)$, $g=f(v_{10}, P_\infty)$, $Z_s=f(R_s)$ and $Q_v=f(T_\infty, P_\infty)$, the three differential coefficients have a common denominator, $Q-Q_v+5(5.65-P_\infty)\times R_aZ_s/[R_s(Z_s+Z_a)^2]$, and weightings for the relative influences of T_{db}, T_{wb} and T_{gt} are $c_1:c_2:c_3$, i.e.,

$$\left\{1+0.210(R_s+R_a)+\frac{0.028(5.65-P_\infty)R_a^2}{Z_s+Z_a}-0.028R_a^2(Q-Q_v)-\frac{R_aQ_g}{R_{a(gt)}Q_{g(gt)}}^{*}\right\}$$
$$:\left\{[0.124+0.00021T_{wb}^2]\left[\frac{R_a}{Z_s+Z_a}+3.14(R_s+R_a)+\frac{1.52(5.65-P_\infty)R_aZ_a^2}{(Z_s+Z_a)^2}\right]\right\}:\frac{R_aQ_g}{R_{a(gt)}Q_{g(gt)}}^{*}.$$

Under mild conditions the ratio becomes complicated and is omitted here. Clearly, the weightings are far from constants; they depend considerably on temperature and appreciably on activity, humidity and wind. The above ratios have been determined for some representative special cases described in Table 4. Values of the ratio $c_1:c_2$ are roughly comparable with those obtained empirically by Lee (1958), who did not take c_3 into account.

The distribution of extra radiation between direct, indirect, terrestrial and outgoing is not critical, but the proportions, where applicable, are identical with those of Table 3. The effect of solar altitude angle on the globe temperature is apparent in Table 4.

Inspection of these results shows the great dependence of the constants on ambient conditions. Understandably, published data show an extraordinary variation, since most were obtained under a fairly narrow range of conditions.

It must be concluded, therefore, that any equation in which some single index is regarded as an additive compound lacks versatility and is an approximation valid only for a specified range of conditions. In compar-

* This term and factor are omitted if the effect of sunshine is not being considered.

TABLE 4. Coefficients in the wet-bulb globe thermometer equation.

								Without insolation		With insolation		
$\mathcal{T}$	T_∞	T_{wb}	T_{gt}	P_∞	v_{10}	Q_g	A	c_1	c_2	c_1	c_3	c_4
20	20	16.3	20	1.6	2.5	0	42	0.78	0.22	0.30	0.48	0.8
30	30	19.7	30	1.6	2.5	0	42	0.67	0.33	0.28	0.39	3.4
40	40	22.7	40	1.6	2.5	0	42	0.48	0.52	0.20	0.28	9.0
50	50	25.4	50	1.6	2.5	0	42	0.36	0.64	0.14	0.22	15.7
42.3	30	29.2	30	4.0	2.5	0	42	0.39	0.61	0.17	0.22	12.8
30.5	30	19.8	30	1.6	0	0	42	0.67	0.33	0.29	0.38	3.9
27.9	30	19.8	30	1.6	15	0	42	0.81	0.19	0.27	0.54	−0.2
36.6	30	19.8	42.3	1.6	2.5	125	42	0.55	0.45	0.10	0.45	5.7
32.8	30	19.8	35.4	1.6	15	125	42	0.73	0.27	0.25	0.48	3.0
30	30	19.8	30	1.6	2.5	→0	→0	0.67	0.33	0.17	0.50	3.4
30	30	19.8	30	1.6	2.5	→0	90	0.67	0.33	0.49	0.18	3.4

ing widely different climates, even of similar sultriness, such formulas are ineffective and a systems approach which assessess the effect of all variables on a typical human is considered preferable.

APPENDIX

List of Symbols

A solar altitude angle (degrees above horizon)
E elevation above sea level (km)
P vapor pressure (kPa)
Q heat-transfer rate per unit of body surface area (W m^{-2})
R resistance of unit area (m^{2}K W^{-1})
T temperature (°C)
Z moisture resistance of unit area (m^2 kPa W^{-1})
c constant
g evaporative heat transfer coefficient (W m^{-2} kPa^{-1})
h heat-transfer coefficient (W m^{-2} K^{-1})
r ratio of moisture transfer resistance: heat transfer resistance for clothing ensemble (kPa K^{-1})
v air velocity relative to observer (m s^{-1})
$\mathcal{P}$ total atmospheric pressure (kPa)
$\mathcal{T}$ apparent temperature (°C)
α absorptivity
ϵ emissivity
η efficiency
λ latitude (degrees)
ϕ_1 ratio of effective radiating area to total surface area
ϕ_2 proportion of body covered by clothing
ϕ_3 projected area factor of body
ϕ_4 proportion of sky covered by cloud
ϕ_5 ratio of direct to total insolation normal to sun's rays
ρ density of air (g cm^{-3})
σ Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
ψ relative humidity (%)

Subscripts

a air; boundary layer of air
b body core
c by convection
d direct insolation per unit area normal to sun's rays
db dry bulb
dp dew point
f clothing; at outer surface of clothing
g net insolation per unit area of body surface
gt globe thermometer
i indirect insolation per unit area normal to sun's rays
j through covered part of body
K absolute (Kelvin) degrees
0 at sea level
r by radiation
s skin; outer surface of skin
u through uncovered part of body
v by ventilation through lungs
wb wet bulb
x general subscript denoting multi-factor temperature indices
10 refers to measurements made by anemometer 10 m above ground
∞ ambient

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