The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science

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ABSTRACT

Using as bases the amount of clothing needed to achieve thermal comfort and the reduction in the skin's resistance needed to obtain thermal equilibrium, the relative sultriness of warm-humid and hot-arid summer climates is assessed. Conditions of equal sultriness are referred to a vapor pressure of 1.6 kPa in order to prepare a table of apparent temperature corresponding to summer temperatures and humidities.

1. Introduction

a. Background, definitions and review

The extent to which humidity aggravates physiological effects of high temperature has been the subject of numerous publications. These will be discussed only briefly here, as they have been thoroughly reviewed elsewhere. Although comparisons of hot-arid with warm-humid climates are often the subject of a spirited exchange of opinions, little attention has been paid in the literature to providing an objective basis for such assessments.

These comparisons require a single measure of the combined effects of high temperature and humidity. This will be referred to as "sultriness," just as a combination of wind and low temperature is referred to as "windchill." Corresponding to the windchill equivalent temperature, the "apparent" temperature (Table 1) is the temperature which a given combination of dry-bulb temperature and vapor pressure "feels like" to the typical human. More precisely, it is the ambient temperature adjusted for variations in vapor pressure above or below some base value. The procedure for quantitative determination of apparent temperature will be summarized in Section 4d. The results are shown in Table 2.

Several types of single indices have been proposed for related purposes. Macpherson's (1962) review concluded that "indices based on the calculation of heat exchange ... provide the most satisfactory approach to the problem of the multiple-factor index yet devised, and future advances may well be made in this direction." A useful tabular review has been provided by Sargent and Tromp (1964, p. 16). Landsberg (1972) has reviewed the subject from the viewpoint of human biometeorology.

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b. Sultriness

The concept of absolute sultriness is intuitively clear and no qualitative definition is attempted here. In relative terms, a set of meteorological conditions A is more "sultry" than set B if the typical human copes with A by offering less thermal resistance between his core and the surroundings in A than in B. In general, this resistance includes the resistance of skin and clothing to heat and moisture transfer. Fig. 1 illustrates the resistances to heat and moisture flow from the clothed person to the surroundings. For unclothed parts, the central resistance is omitted. The analysis combines physiological variables on the left and clothing science in the middle with the various meteorological factors that comprise the air resistances on the right side. See the Appendix for an explanation of the symbols.

This higher sultriness may be due to higher ambient temperature, higher humidity, stronger solar radiation, different wind speed, different atmospheric pressure or any combination of these. The present study confines itself to the effects of temperature and humidity. The other factors will be included in a subsequent paper (Steadman, 1979).

Many approaches to sultriness can be taken, but the argument presented here is that it is best assessed in terms of its physiological effect on humans. Although arbitrary realistic assumptions are necessarily made about the person's activity and clothing, the resulting indices provide an objective and versatile basis for assessing hot and humid weather.

c. Criteria for a sultriness index

1) Sultriness should be capable of expression as an equivalent or apparent temperature.

TABLE 1. Correspondence between apparent temperature and clothing-physiological variables.

Mild conditions

Primary variable: Clothing thickness d_f (mm)	Apparent temperature $\mathcal{T}$ (°C)	Secondary variables: Skin thermal resistance R_s (m^2 K W^{-1})	Secondary variables: Skin moisture resistance Z_s (m^2 kPa W^{-1})
7.64	16	0.0387	0.0521
6.72	17	0.0387	0.0521
5.84	18	0.0387	0.0521
4.97	19	0.0387	0.0521
4.13	20	0.0387	0.0521
3.30	21	0.0387	0.0521
2.50	22	0.0387	0.0521
1.72	23	0.0387	0.0521
0.95	24	0.0387	0.0521
0.20	25	0.0387	0.0521

Severe conditions

Primary variable: Skin thermal resistance R_s (m^2 K W^{-1})	Apparent temperature $\mathcal{T}$ (°C)	Secondary variables: Skin moisture resistance Z_s (m^2 kPa W^{-1})	Secondary variables: Clothing thickness d_f
0.0377	26	0.0446	0
0.0364	27	0.0375	0
0.0353	28	0.0320	0
0.0343	29	0.0277	0
0.0334	30	0.0242	0
0.0325	31	0.0214	0
0.0318	32	0.0190	0
0.0311	33	0.0170	0
0.0304	34	0.0153	0
0.0298	35	0.0138	0
0.0292	36	0.0125	0
0.0287	37	0.0113	0
0.0281	38	0.0103	0
0.0276	39	0.0095	0
0.0272	40	0.0087	0
0.0267	41	0.0079	0
0.0262	42	0.0073	0
0.0258	43	0.0067	0
0.0254	44	0.0062	0
0.0250	45	0.0057	0
0.0245	46	0.0052	0
0.0241	47	0.0048	0
0.0237	48	0.0044	0
0.0233	49	0.0041	0
0.0229	50	0.0037	0

2) As in windchill, this apparent temperature should have a one-to-one correspondence with the thickness of clothing needed to maintain thermal equilibrium in "mild" sultriness.

3) If, however, sultriness is such that no clothing is called for, the apparent temperature should correspond to the thermal resistance of the sweating skin.

4) If humidity is higher (lower) than "average," the apparent temperature should be higher (lower) than the dry-bulb temperature.

5) The index should be amenable to allowing for the effects of changing wind speed, air pressure and extra radiation, particularly sunshine.

6) The index should cover the range of sultriness conditions likely to be encountered on the earth's surface.

TABLE 2. Temperature-humidity scale: Apparent temperature (°C) corresponding to each combination of dry-bulb temperature and relative humidity. Values in parentheses correspond to skin humidities above 90% and are approximate.

Dry bulb temperature (°C)	Relative humidity (%): 0	10	20	30	40	50	60	70	80	90	100
20	16	17	17	18	19	19	20	20	21	21	21
21	18	18	19	19	20	20	21	21	22	22	23
22	19	19	20	20	21	21	22	22	23	23	24
23	20	20	21	22	22	23	23	24	24	24	25
24	21	22	22	23	23	24	24	25	25	26	26
25	22	23	24	24	24	25	25	26	27	27	28
26	24	24	25	25	26	26	27	27	28	29	30
27	25	25	26	26	27	27	28	29	30	31	33
28	26	26	27	27	28	29	29	31	32	34	(36)
29	26	27	27	28	29	30	31	33	35	37	(40)
30	27	28	28	29	30	31	33	35	37	(40)	(45)
31	28	29	29	30	31	33	35	37	40	(45)	
32	29	29	30	31	33	35	37	40	44	(51)	
33	29	30	31	33	34	36	39	43	(49)		
34	30	31	32	34	36	38	42	(47)			
35	31	32	33	35	37	40	(45)	(51)			
36	32	33	35	37	39	43	(49)				
37	32	34	36	38	41	46					
38	33	35	37	40	44	(49)					
39	34	36	38	41	46						
40	35	37	40	43	49						
41	35	38	41	45							
42	36	39	42	47							
43	37	40	44	49							
44	38	41	45	52							
45	38	42	47								
46	39	43	49								
47	40	44	51								
48	41	45	53								
49	42	47									
50	42	48									

d. Quantifying the criteria

The scope of the analysis includes summer conditions which, from inspection of the *ASHRAE Handbook of Fundamentals* (1972, pp. 680–688), are exceeded on less than 1% of the earth's surface and for less than 1% of the time:

1) Dry-bulb temperatures from 20–50°C.

2) Vapor pressures[1] from 0–4.6 kPa (i.e., mixing ratios up to 0.030 or dew points up to 31°C). As a further limitation, the saturation vapor pressure can be described by a cubic equation, accurate to ±0.03 kPa in the range 20–50°C,

$$P_{sat}=0.646+0.0555T+7.1\times10^{-5}T^3. \quad (1)$$

3) Apparent temperatures, when all the above factors are taken into account, range from 16–50°C (61–122°F).

Many values in the tables and figures lie just outside these ranges or, like zero humidity, are only approached in practice, but are included to facilitate interpolation.

[1] Vapor pressure above 4.0 kPa are seldom encountered outdoors, but pressures in the range 4–5 kPa sometimes exist in mines and factories. Under all such conditions, the apparent temperature will exceed 50°C or the skin's relative humidity will exceed 90%. 1 Pa is a pressure of 1 N m^{-2}. 1 atm = 101.3 kPa.

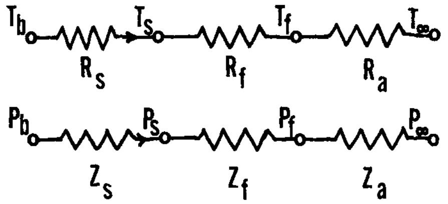

FIG. 1. Diagram illustrating potentials and resistances to dry (upper) and evaporative (lower) heat transfer.

Limitation of the scope of all conclusions to these ranges is implicit in the remainder of this paper.

e. Alternative criteria

The use of skin resistance (R_s) under severe conditions or clothing thickness (d_f) under mild conditions as a measure of sultriness is unusual but is justified by deficiencies in other approaches.

The perspiration rate, a proven index of severe sultriness at appreciable rates of exertion, is less applicable to typical summer conditions. Moreover, under mild conditions, when only exhaled moisture and insensible perspiration are secreted, the perspiration rate is highest when the humidity is lowest.

Another widely used criterion of sultriness, which was considered and rejected, is some measure of skin wetness. Even if it could be measured accurately, a conceptual defect is that skin humidity falls, in both absolute and relative terms, as wind speed increases, the reverse of perceived discomfort in dry winds hotter than 35°C.

Conditions under which thermal equilibrium cannot be achieved at normal body temperature correspond to apparent temperatures above 60°C and are beyond the scope of this study. Short-term exposures to such conditions are more important in industry than in meteorology; other references, such as Haines and Hatch (1952), should be consulted.

f. Base levels for determining apparent temperature

Normal levels of the meteorological variables are 1) vapor pressure = 1.6 kPa, 2) wind speed = 2.5 m s^{-1} (5.6 mph), 3) barometric pressure = 101.3 kPa (in practice, sea level elevation), 4) extra radiation = 0. The base vapor pressure corresponds to a sea level dew point of 14.0°C or a mixing ratio of 10 g water vapor per kilogram of dry air; this is the standard vapor pressure at which testing laboratories are held in the "temperate" zone. Thus, for instance, an apparent temperature of 24°C refers to the same level of sultriness, and the same clothing requirements, as a dry-bulb temperature of 24°C with a vapor pressure of 1.6 kPa.

Some indices of sultriness refer to a base vapor pressure, since the evaporative heat loss is proportional to the pressure difference between the body core and the surrounding air, just as "dry" heat transfer varies with the corresponding temperature difference. One common index (ASHRAE, 1972, p. 136), however, is based on a *relative* humidity of 50% and a measure of skin wetness. The base vapor pressure with which higher humidities can be compared varies greatly with temperature and rises as high as 4.2 kPa, while air-conditioning design data in the same publication (p. 684) show that no weather station on the earth's surface is likely to have a vapor pressure above 4.0 kPa. Relative humidity provides an uncertain base since, for example, a relative humidity of 50% at 20°C would be perceived as dry, while the same relative humidity at 40°C feels, and is, very humid.

g. Limitations

This work has been written from the viewpoint of human biometeorology, with the objective of deriving a definitive scale of apparent temperature which takes account of the effects of temperature and humidity on the reaction of the normal human. The results are not intended to be applicable to plants, which are more sensitive to humidity; to quadrupeds, which are more sensitive to overhead solar radiation; to birds, which are more sensitive to temperature; or to buildings, which are generally less sensitive to wind.

2. The human model

This section describes the physiological, clothing and heat-transfer basis on which sultriness is expressed as apparent temperature. It produces intermediate data which, it is hoped, will be of use to other researchers, but which may be omitted by readers concerned only with the assessment of sultriness.

The typical human taken as the model is, with some refinements, similar to that described previously in evaluating windchill (Steadman, 1971). Some of the refinements are based on the work of Fanger (1970), whose measurements on 256 adults provided the means of deriving physiological data describing the average human's heat and moisture transfer.

As before, this makes it possible to apply accurate and versatile physical data to analyze heat and moisture transfer from the model rather than resort to elaborate and inevitably limited assessments of comfort. The wide range of conditions covered by the apparent-temperature scale can be more feasibly compared by applying existing information than by performing a necessarily large number of human experiments. Details of the model and its environment follow.

a. Basic dimensions

The typical adult human of either sex, with a height of 1.7 m and a weight of 67 kg, is considered. Standard physiological data (e.g., Newburgh, 1949, p. 50) show that such a person has a surface area $S = 1.78$ m^2.

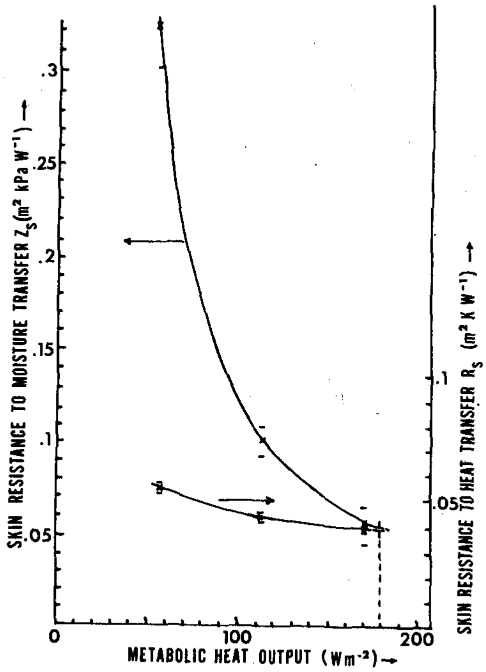

FIG. 2. Resistance of human skin to heat transfer and moisture transfer as a function of activity.

b. Effective radiation area ($\phi_1 S$)

The area of the skin surface which exchanges radiant heat with the surroundings is less than the total surface area. Under mild conditions, the average ratio ϕ_1 is taken as 0.79 for the clothed parts and 0.85 for the bare parts of the body.

Under severe conditions, without clothing, $\phi_1=0.80$.

c. Significant diameter (D)

The approach to determining this parameter for convective heat transfer is to apply standard engineering practice, using the body's volume V, to yield $D=4V/S$. Since the model is a typical adult with a density of 0.98 g cm^{-3}, this gives, for the entire body,

$$D=(4\times67\times10^3)/(0.98\times1.78\times10^4)=15.3 \text{ cm}.$$

Because the unclothed parts have a lower total resistance and a smaller diameter than the trunk and legs, their diameter is considered separately. Using standard anthropometric data gives a significant diameter for the head and arms of 7.8 cm and, for the clothed parts of the body, 17.1 cm. If the clothed body were considered as a unit, as is conventional, with $D=15.3$ cm, the error in estimating the apparent temperature would be in the range of 0.0–0.4 K.

d. Clothing cover

The basis of the proposed temperature-humidity scale is to assume that at least part of the skin is exposed and to determine the thickness of clothing on the remainder of the body to maintain thermal equilibrium and comfort. Use of long trousers and a short-sleeved shirt or blouse is assumed, with the clothed fraction of the body's surface $\phi_2=0.84$. Just as there are individual variations in skin insulation, so these estimates take no account of personal differences in apparel or hair length, but represent average values which provide a reasonable basis for comparing different climatic environments.

Under severe conditions, no clothing is called for, i.e., $R_f=\phi_2=0$. Although a little clothing may nevertheless be worn for the sake of modesty, its slight thermal insulation is neglected in comparisons of sultriness. Assumption of a minimum clothing thickness up to ~5 mm produces results differing little from those presented here.

e. Internal or core temperature (T_b)

Because the body's perspiration rate can vary greatly (Fig. 2), the temperature of the skin is less constant than that of the body's core. Because of evaporation, skin temperature may be coolest when the person feels hottest, as during exertion, and cannot be used as an index of sultriness. Although athletes may achieve thermal equilibrium but not comfort at core temperatures as high as 41°C (Hill, 1970), a person feels comfortable only at a core temperature close to 37°C, which is therefore taken as a criterion of comfort and equilibrium under all conditions in the present paper.

f. Internal or core vapor pressure (P_b)

There is consensus in the medical literature (e.g., Buettner, 1959) that the body's core vapor pressure corresponds to a saline solution with an effective relative humidity of ~90%. Since saturation vapor pressure of water at 37°C is 6.28 kPa, vapor pressure of the body is taken as $0.90\times6.28=5.65$ kPa.

g. Surface temperatures and vapor pressures of skin (T_s,P_s) *and clothing* (T_f,P_f)

The determination of apparent temperature, reduced to the independent variables of core (T_b,P_b) and ambient (T_∞,P_∞) conditions, requires knowledge of surface conditions only to the extent that they slightly affect heat-transfer coefficients and serve as a check (see Section 5b) on the assumptions used in the analysis.

Although the core temperature has been taken as the independent variable, surface temperature determines the radiative heat-transfer coefficient between the model and the surroundings as well as the mean film temperature on which the convective and radiative coefficients depend.

The surface temperatures were obtained by iteration using the following relationships.

For mild sultriness, the temperature of the exposed skin surface is given by

$$T_s = T_b - Q_u R_s \quad (2)$$

and the clothing surface temperature by

$$T_f = T_b - Q_j(R_f + R_s) + (P_b - P_\infty)R_f/(Z_s + rR_f + Z_a). \quad (3)$$

For severe sultriness, without clothing,

$$T_s = T_b - (Q - Q_v)R_s. \quad (4)$$

For both mild and severe sultriness,

$$P_s = P_b - (P_b - P_\infty)Z_s/(Z_s + rR_f + Z_a), \quad (5)$$

$$P_f = P_\infty + (P_b - P_\infty)Z_a/(Z_s + rR_f + Z_a). \quad (6)$$

The iterative procedure was as follows:

(i) Assume trial values of surface termperatures T_s and T_f, beginning with $T_s = T_f = (37 + T_\infty)/2$.

(ii) Determine the mean film temperatures as the average of the surface and ambient temperatures.

(iii) Repeat the above for vapor pressures, beginning with $P_f = P_s = (5.65 + P_\infty)/2$.

(iv) Look up and interpolate the physical properties (k, μ and $\mathfrak{D}$) of moist air at this film temperature and vapor pressure, hence determine the heat-transfer coefficients for convection (h_c), radiation (h_r) and evaporation (g), by applying Sections 2*h*-2*r*.

(v) Using the analysis of Section 4, calculate the required clothing resistance (R_f) or skin resistance (R_s).

(vi) Determine the corrected surface temperatures (T_s,T_f) and vapor pressures (P_s,P_f) from Eqs. (2)–(6).

(vii) Repeat the above steps until consistent results are obtained, typically with three or four iterations.

For the special case of $P_\infty = 1.6$ kPa, the results of this procedure are shown in Fig. 3. Once determined, these results make it unnecessary to repeat the above procedure in assessing sultriness.

h. Activity

Since perception of sultriness depends on the body's rate of heat production, this variable must be specified. The assumption of thermal equilibrium implies that the body regulates its heat loss (Q) to equal its metabolic output. The normal level chosen for this study is that of a person walking outdoors at 1.4 m s^{-1}. Newburgh (1949) quotes the corresponding heat output as equivalent to 180 W m^{-2} of skin surface. Thus, the value $Q = 180$ is a constant in the present analysis. Higher levels of activity would increase the sensitivity to humidity, because of heavier reliance on sensible perspiration. Few people, however, sustain activity above the level considered here for long enough to reach a steady state.

The present study is more concerned with the average person's perception of sultriness and with climate comparison. For assessing the effects of environment on

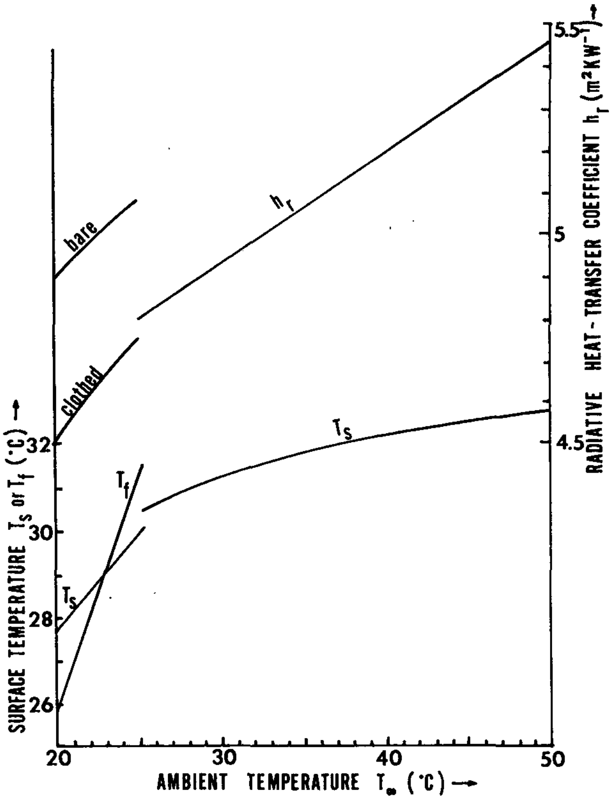

FIG. 3. Surface temperature (lower) and radiative heat-transfer coefficient as a function of ambient temperature when $P_\infty = 1.6$ kPa.

persons at higher levels of exertion, such works McArdle *et al.* (1947) should be consulted.

i. Effective wind speed (v)

The combined effect of the model's movement and the base wind speed must be determined in order to calculate convective and evaporative heat-transfer coefficients. At the level of the average person, the wind is less than that measured by a meteorological anemometer. Buckler's (1969) data indicate that, in summer, the wind speed varies with the 0.24 power of the distance above ground level. If the anemometer is at a standard height of 10 m,

$$v = v_{10}(y/10)^{0.24}.$$

The average wind speed encountered by a stationary observer, 1.7 m in height, is therefore

$$\bar{v} = \int_0^{1.7} v dy \Big/ \int_0^{1.7} dy,$$

$$= 0.527 v_{10},$$

$$= 1.32 \text{ m s}^{-1} \text{ in the base wind of } 2.5 \text{ m s}^{-1}.$$

When the observer walks at 1.4 m s^{-1} at an angle θ to such a wind, he encounters a relative air movement of

$$v=[(0.53v_{10})^2+1.4^2-(2\times0.53v_{10}\times1.4\sin\theta)]^{\frac{1}{2}}. \quad (7)$$

This will be developed further in Section 2*p*.

j. Ventilation rate (Q_v)

Because exhaled air is almost at the same temperature and vapor pressure as the body, its enthalpy is usually much higher than, but slightly dependent on, that of the air which is breathed in. Heat loss from the lungs is taken as proportional to the metabolic output. Combining the expressions for the sensible and the latent heat loss given by McCutchan and Taylor (1951) gives the fraction of the total heat loss accounted for by the lungs as

$$0.143-0.00112T_\infty-0.0168P_\infty, \quad (8)$$

equal to 8% under common summer conditions.

This component of the heat loss, although only 2–12% of the total at sea level, is thus quite sensitive to humidity. As would be expected, when the proportion is plotted on a psychrometric chart, the slope of the isopleths is identical with that of the wet-bulb lines.

The fraction lost by ventilation is multiplied by the total heat loss ($Q=180$) to give Q_v, the rate of heat loss from the lungs, per unit of body surface.

k. Skin resistance to heat transfer (R_s)

Reliable data on the thermal resistance of the skin and its variation with activity have only recently been obtained (Fanger, 1970). These data were not quoted explicity but have been derived by analysis of Fanger's results and are shown in Fig. 2. The points represent averages of four sets of results obtained on 256 human subjects wearing four different clothing ensembles, varying in insulation from 0 to 0.225 m^2 K W^{-1}. The associated dashes represent 95% confidence intervals for the mean resistance. The narrowness of these intervals indicates the predominant effect of activity; the effects of ambient conditions and clothing have a lower order of magnitude. The analysis was based on the assumptions made or implied by Fanger, including uniform coverage of the body by clothing. The estimate of skin resistance used for the present work was obtained by slight extrapolation, since Fanger's highest activity rate was 174 W m^{-2}. This resistance is 0.0387 m^2 K W^{-1} for the present model under mild conditions.

l. Skin resistance to moisture transfer (Z_s)

These values were likewise obtained by analysis of Fanger's data. They confirm that some sweating is compatible with comfort, the rate of sensible perspiration increasing with activity. The transition from purely insensible diffusion through the skin to sensible perspiration is commonly referred to in the literature, but is rather indefinite. With the information shown in Fig. 2, it is neither desirable nor necessary to distinguish between insensible and sensible perspiration for the purpose of climate comparison; nor is it necessary to invent such concepts as "wetted area" of skin or "wetness factor" of clothing, quantities which at present do not lend themselves to accurate independent measurement.

The resistance of unit area is defined as the quotient of the vapor-pressure difference across the skin divided by the moisture flow rate per unit area, i.e., as

$$(P_b-P_s)\ m^{-1} \text{ in units of m}^2 \text{ s kPa g}^{-1}.$$

Since the thermal resistance is in m^2 K W^{-1}, the mass flow is converted to a heat flow by multiplying it by the latent heat of vaporization of water at the skin temperature. Small changes in sensible heat between the body's core and the skin are subtracted from quoted values of the latent heat to give the effective values of L used in the present analysis. The difference is close to 1%. Thus the "evaporative" resistance of unit area of the skin is defined as

$$Z_s=(P_b-P_s)/mL \quad \text{in units of m}^2 \text{ kPa W}^{-1}.$$

Under mild conditions, the skin's resistance is 0.0521 m^2 kPa W^{-1}.

All evaporation is assumed to occur at the skin surface, on both clothed and bare parts of the skin. The factor mL refers to heat loss *from the skin.* It will be shown later that this is greater than the amount of the body's heat loss accounted for by evaporation.

m. Clothing resistance to heat transfer (R_f)

Since this forms the basis for comparing mild conditions, some standard must be adopted. Typical summer fabrics containing, by volume, 20% fiber and 80% air are considered here. The entrapped air which provides most of a fabric's insulation loses some of its insulating value when the wearer moves; this is even more true of the air gaps between layers. Although the conductivity of the clothing is not critical in climate comparison, it is required for determining the thickness of clothing to be worn. A conductivity of 4.2 W cm m^{-2} K^{-1} is typical of summer clothing with a small air gap, as measured. The data of Belding *et al.* (1947) indicate the proportionally higher values which take body movement into account. Calculation shows a resistivity per unit thickness of 0.167 m^2 K W^{-1} cm^{-1}.

n. Clothing resistance to moisture transfer (Z_f)

Although much of the heat transfer is through the fibers themselves, almost all the moisture transfer is by vapor diffusion across the fabric pores. The relatively slight transfer of liquid through the fibers is often in the reverse direction since, when perspiration is slight, body heat tends to reduce the fibers' moisture content near the skin. Since most of the fabric's volume is air, only vapor diffusion is considered here.

For diffusion of water vapor through air, Weiner's (1970) data were used, with an adjustment for changes in the mean film vapor pressure. In an environment with total atmospheric pressure $\mathcal{P}$, the diffusion constant is multiplied by a factor $\mathcal{P}/(\mathcal{P}-\bar{P})$. Thus

$$\mathfrak{D}=\mathcal{P}(0.220+0.00147\bar{T})/(\mathcal{P}-\bar{P}). \quad (9)$$

In order to use consistent units of resistance, this must be expressed as resistance to vapor transfer. The resistance of unit area to mass flow, per unit thickness of air gap, is given by

$$\mathcal{R}T_K/\mathfrak{D} \quad \text{in units of m}^2\text{ s kPa g}^{-1}\text{ cm}^{-1},$$

where $\mathcal{R}$ has the value 467 kPa cm^3 K^{-1} g^{-1} for water vapor.

This is converted, as in Section 2*l*, from grams per second to watts, giving the evaporative resistance of a dry air layer of thickness d at 30°C as

$$Z=d/j=0.0220\ d \text{ in units of kPa m}^2\text{ W}^{-1},$$

almost independently of temperature.

In a fabric, the vapor must follow a tortuous path in passing around fibers. According to many sources (e.g., Behmann, 1960) the average path length is close to twice the thickness of summer clothing. In Woodcock's (1962) notation, the fabric has a permeability index of 2. There is an approximately equal amount of air gap between the skin and clothing, giving an average path factor of 1.5. Thus the typical summer clothing ensemble, measured under stationary conditions, offers a resistance to moisture transfer, per unit thickness of fabric, of

$$Z_f/d\approx 0.033 \text{ kPa m}^2\text{ W}^{-1}\text{ cm}^{-1}.$$

Body movement causes an increase in the clothing's vapor conduction. In a previous work (Steadman, 1965) this increase was shown to be $\sim$5% for each 3% increase in heat conduction. Using this information together with that of Section 2*m* gives a resistance to moisture transfer of 0.021 kPa m^2 W^{-1} cm^{-1} for summer clothing on the walking human. The ratio of moisture: heat resistance for the clothing ensemble is 0.124 kPa K^{-1}. This ratio is the only clothing parameter which influences the assessment of sultriness.

o. *Surface radiation* (h_r)

Emissivities of both skin and clothing are assumed to be 0.97 and the mean temperature of surrounding objects is taken as equal to the air temperature. In general, radiative heat exchange between two surfaces at absolute temperatures T_{K1} and T_{K2} is given by

$$\begin{aligned} Q_r &= \epsilon\sigma(T_{K1}{}^4-T_{K2}{}^4) \\ &= \epsilon\sigma(T_{K1}{}^2+T_{K2}{}^2)(T_{K1}+T_{K2})(T_{K1}-T_{K2}) \\ &= \epsilon\sigma'(T_1-T_2). \end{aligned}$$

TABLE 3. Basic heat-transfer coefficients of human in thermal equilibrium.

	Exposed parts	Clothed parts	Entire body, $\mathcal{T}\geqslant 26°$C
Radiative h_r	$4.18+0.036\ T_\infty$	$3.35+0.049\ T_\infty$	$4.10+0.028\ T_\infty$
Convective h_c	17.4	11.6	12.3
Evaporative g	$283+1.9\ P_\infty$	$188+1.6\ P_\infty$	$199+1.6\ P_\infty$

In particular, T_{K1} refers to the surface temperature of skin or clothing and T_{K2} to the ambient temperature ($T_\infty+273.2$). Because of sweating, T_s for a person in thermal equilibrium varies only slightly with the ambient temperature (Fig. 3). Both temperatures were used, along with the effective radiation area, in determining the radiative heat-transfer coefficient as

$$h_r=0.97\phi_1\sigma'.$$

p. *Surface convection* (h_c)

Derivation of the convective heat-transfer coefficient depends on knowledge of the physical properties of air, namely, kinematic viscosity μ/ρ and conductivity at the mean film temperature and vapor pressure. These and most other properties of air and water vapor were obtained by linear interpolation from the *Handbook of Chemistry and Physics* (Weast, 1972–73). Since water vapor is an appreciable and variable component of the air in sultry conditions, all physical properties of air have been adjusted according to the molar concentrations or partial pressures of each component.

The Reynolds number for the model is given by $\mathrm{Re}=\rho Dv/\mu$. For a significant diameter of 15.3 cm, Re = 16 800, corresponding to turbulent flow.

Hilpert's (1933) data for flow across cylinders indicate a corresponding Nusselt number of 71.7, varying with an exponent of the wind speed of $\sim$0.60.

The convection coefficient is given by $h_c=\mathrm{Nu}\ k/D$. In general, the relationship is conventionally expressed as $h_c=cv^n$, where neither c nor n is constant.

In order to generalize the approach for a range of wind speeds, the effects of wind and body movement are combined as follows:

Substituting Eq. (7) gives a binomial of the form

$$h_c=c(a-b\sin\theta)^{0.5n},$$

where $a=(0.53v_{10})^2+1.4^2$ and $b=2.8\times 0.53v_{10}$. Substitution of $n=0.60$ and expansion gives

$$h_c=c(a^{0.3}+0.3a^{-0.7}b\sin\theta-0.105a^{-1.7}b^2\sin^2\theta+\cdots).$$

Since θ is equally likely to have any value, the average value of h_c is obtained from

$$\begin{aligned} h_c &= \int_0^{2\pi} h_c d\theta \Big/ \int_0^{2\pi} d\theta \\ &= c(a^{0.3}-0.0525a^{-1.7}b^2-0.0151a^{-3.7}b^4\ldots). \end{aligned}$$

Since v_{10} is taken as 2.5 m s^{-1}, a slowly converging series gives the values shown in Table 3. These values of h_c are almost independent of temperature and vapor pressure.

q. Surface resistance to heat transfer (R_a)

The surface heat-transfer resistance is determined for each ambient temperature as

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

r. Surface resistance to moisture transfer (Z_a)

The transfer of moisture vapor is analogous to the convective transfer of heat and can likewise be discussed in terms of a boundary layer. But, as shown below, the effective thickness of this boundary layer is ~7% above that for heat convection.

Convection is described by

$$\mathrm{Nu} = 0.33\ \mathrm{Re}^{0.6}\ \mathrm{Pr}^{\frac{1}{3}}$$

and moisture transfer, using Reynolds' analogy, by

$$\mathrm{Sh} = 0.33\ \mathrm{Re}^{0.6}\ \mathrm{Sc}^{\frac{1}{3}}.$$

The ratio of the boundary-layer thicknesses at a mean film vapor pressure of 3.0 kPa and temperature of 30°C is given by

$$\frac{\mathrm{Sh}}{\mathrm{Nu}} = \left(\frac{\mathrm{Sc}}{\mathrm{Pr}}\right)^{\frac{1}{3}} = \left(\frac{k}{\mathfrak{D}\rho s}\right)^{\frac{1}{3}}$$

$$= \left(\frac{0.0262\ (101.3-3.0)}{0.264\times10^{-4}\times1158\times1.01\times101.3}\right)^{\frac{1}{3}} = 0.937.$$

The moisture-transfer coefficient is given by

$$g = \mathrm{Sh}j/D = 0.937\ \mathrm{Nu}j/D = 0.937h_cj/k = 16.5h_c.$$

This confirms theoretically the value of the Lewis or Bowen number at 30°C. The present approach allows for examination of the effect of varying the meteorological variables. Further calculations over the full range of temperatures and vapor pressures show this ratio to be always in the range 16.5–16.7 at sea level.

Consequently, the resistance to evaporative heat transfer is

$$Z_a = 1/g = 0.0606/h_c.$$

s. The relationship between skin resistances (Z_s *and* R_s)

Under severe conditions, the action of the sweat glands greatly reduces the skin's resistance to moisture. Simultaneously, the skin's resistance to heat transfer is reduced by vasodilation. Fig. 2 shows the great variation in the skin's resistance to moisture flow, even in the comfort range; the percentage change in the resistance to heat conduction is less by a factor of about 5. In order to incorporate high levels of sultriness, the relationship indicated by Fig. 2 has been extrapolated as far as $Z_s = 0.0034$ m^2 kPa W^{-1} or $R_s = 0.0229$ m^2 K W^{-1}, corresponding to an apparent temperature of 50°C. The equation describing this relationship is

$$Z_s = 6.0\times10^5 R_s^{\,5}.$$

This fifth-power relationship is not intended to be physiologically definitive, but provides a means by which the assessment of sultriness can be extended to severe conditions with reasonable accuracy.

t. Other assumptions

Steady-state equilibrium conditions are assumed—the effect of wind gustiness is negligible because of the body's high heat capacity. The model is assumed capable of sweating at the rates needed to achieve equilibrium, up to 640 g h^{-1} at an apparent temperature of 50°C. It is assumed that all evaporation occurs at the skin surface. The slight increase of surface area when clothing is worn is ignored. Likewise, the effect of curvature (Fourt and Hollies, 1970, p. 60) has no bearing on relative assessments of sultriness and is not considered here.

3. The model under more general conditions

For precise analysis, account must be taken of the effect of different conditions, not only on the model, but on the heat-transfer coefficients. In general,

$$h_c,\ h_r,\ g = f(T,P).$$

Not all of the six possible combinations are significant. The extent of these relationships was assessed by making step changes covering most of the range, in each of the variables singly. Relative to the "normal" conditions of $T_\infty = 30$°C and $P_\infty = 1.6$ kPa, these changes were to $T_\infty = 20$ and 50°C, and $P_\infty = 0$ and 4.0 kPa. Since other publications have implied nonlinearity in the effect of temperature on the radiative heat-transfer coefficient, h_r was evaluated in steps of 5 K from 20 to 50°C.

The iterative procedure of Section 2*g* was used to assess each effect. Whenever the effect on the heat-transfer coefficient proved to be less than 1.0% over the range, it was ignored. For brevity, the results, but not the intermediate steps, are quoted. Only the following are found to be significant:

$$\left.\begin{aligned} h_r &= f(T) \\ g &= f(P) \end{aligned}\right\}. \tag{11}$$

Equations describing the heat-transfer coefficients of humans are summarized in Table 3. These equations are lines of best fit having a maximum deviation of ±1.0%, valid only for the conditions which they describe: mild sultriness for the exposed and clothed parts (20°C$<T_\infty\lesssim$25°C) and severe sultriness for the whole body (26°C$\lesssim T_\infty<$50°C). Significantly, linear equations meet this requirement; it is clearly unnecessary to resort to fourth-power relationships in describing the human's radiative heat exchange. However, the coefficient changes abruptly from mild to severe conditions, reflecting the much slower increase of T_s with T_∞ when sensible perspiration predominates (Fig. 3).

Since vapor pressure and temperature are known precisely only for the body's core and the environment, heat-transfer coefficients are converted to resistances—which are additive (Fig. 1)—and equations of heat transfer are rearranged to express it in terms of those parameters.

4. Analysis

a. Heat transfer from unclothed parts of the body (Q_u)

For the fraction $(1-\phi_2)$ of the body which is uncovered, moisture flow is determined by the total vapor-pressure difference between the body's core and the environment; and by the sum of the moisture resistance offered by the skin (to liquid flow) and by the surface (to vapor flow), i.e.,

$$mL=(P_b-P_\infty)/(Z_s+Z_a).$$

Heat flow through the skin is given by

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

At the skin, this heat is removed by a mixture of radiation, convection and evaporation:

$$Q_u=(T_s-T_\infty)/R_a+mL.$$

Combining the above three equations gives

$$Q_u=\frac{T_b-T_\infty}{R_s+R_a}+\left(\frac{P_b-P_\infty}{Z_s+Z_a}\right)\left(\frac{R_a}{R_s+R_a}\right). \tag{12}$$

For severe conditions, in which the whole body is unclothed, the model's general equation of heat loss follows:

$$Q=180=Q_v+\frac{T_b-T_\infty}{R_s+R_a}+\left(\frac{P_b-P_\infty}{Z_s+Z_a}\right)\left(\frac{R_a}{R_s+R_a}\right). \tag{13}$$

b. Heat transfer from clothed parts of the body (Q_j)

For the fraction ϕ_2 of the skin which is covered with clothing having a resistance Z_f to moisture transfer, a similar analysis shows

$$mL=(P_b-P_\infty)/(Z_s+Z_f+Z_a).$$

It will be convenient to introduce the ratio $r=Z_f/R_f$, giving

$$mL=(P_b-P_\infty)/(Z_s+rR_f+Z_a).$$

Evaporation at the skin gives a latent as well as a

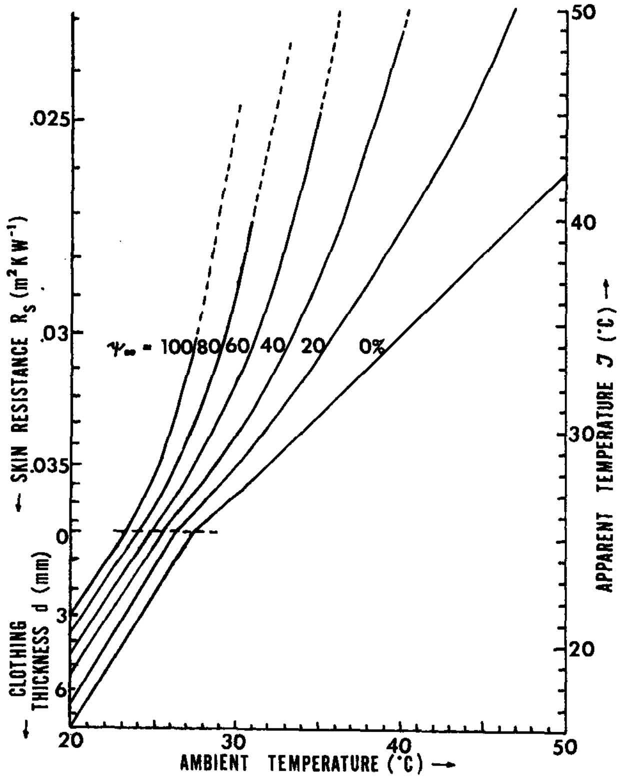

FIG. 4. The effect of ambient humidity (ψ_∞) on apparent temperature.

sensible heat flux, i.e., $Q_j=(T_s-T_f)/R_f+mL$. Hence

$$Q_j=\frac{T_b-T_\infty}{R_s+R_f+R_a}+\left(\frac{P_b-P_\infty}{Z_s+rR_f+Z_a}\right)\left(\frac{R_f+R_a}{R_s+R_f+R_a}\right). \tag{14}$$

As a check of this and similar equations in the literature, setting $R_f=0$ reduces Eq. (14) to Eq. (12).

Not all the latent heat of vaporization contributes to body cooling. With the significant exception of Höschele (1970), most of the literature assumes tacitly that the efficiency of perspiration in cooling the body is unity. In fact, some cooling is lost to the surroundings. The efficiency of evaporation is given by $\eta_e=(R_a+R_f)/(R_s+R_a+R_f)$, for all values of R_f, including zero.

This efficiency varies in the range 59–71% over the conditions described in the present paper. Under more severe conditions than those described here, the dripping of sweat would further reduce efficiency (Givoni and Belding, 1962).

c. Total heat transfer (Q)

In mild sultriness, the total heat loss from covered and uncovered parts of the skin and from the lungs is obtained by combining the latter with Eqs. (12) and (14) and equating with the rate of heat production Q, i.e.,

$$Q=180=Q_v+(1-\phi_2)Q_u+\phi_2Q_j.$$

The only unknown is the required resistance of clothing, which is obtained from a quadratic equation

$$R_f=[-b+(b^2-4ac)^{\frac{1}{2}}]/2a, \tag{15}$$

where

$$a=r(Q-Q_v)-r(1-\phi_2)\times[T_b-T_\infty+R_a(P_b-P_\infty)/(Z_s+Z_a)](R_s+R_a)^{-1},$$

$$2b=(Q-Q_v)(Z_s+Z_a)+(Q-Q_v)r(R_s+R_a)-r(T_b-T_\infty)-\phi_2(P_b-P_\infty)-(1-\phi_2)\times[(Z_s+Z_a)(T_b-T_\infty)+R_a(P_b-P_\infty)]\times(R_s+R_a)^{-1}+R_a(P_b-P_\infty)(Z_s+Z_a)^{-1},$$

$$c=(Q-Q_v)(R_s+R_a)(Z_s+Z_a)-(Z_s+Z_a)(T_b-T_\infty)-R_a(P_b-P_\infty).$$

For each set of conditions, R_f is evaluated by computer and expressed as the clothing thickness (mm) required to maintain thermal comfort, by dividing by the factor 0.0167, i.e., $d_f=60R_f$. If R_f is negative or imaginary, severe sultriness is indicated and the reduction in skin resistance to achieve equilibrium is computed by iteration using Eq. (13). Such values as the skin's resistance to evaporative heat transfer, the sweat rate and the skin's temperature and humidity can be readily derived. Solutions to Eqs. (13) and (15) have been plotted for the indicated conditions in Fig. 4.

d. Determination of apparent temperature

Any set of conditions (T_∞,P_∞) can now be equated with an apparent temperature ($T=\mathcal{T}$, $P=1.6$). The apparent temperature may be determined in any of the following ways:

1) Using the data of Sections 2 and 3 and the summary in Table 3 for any given combination of conditions, Eq. (13) (severe conditions) or (15) (mild conditions) is solved as described above for R_s or d_f. This solution is then substituted in Eq. (13) or (15), to solve for T_∞ when $P_\infty=1.6$; the value of T_∞ is then the apparent temperature $\mathcal{T}$.

2) The value of R_s or d_f found in the first stage above is compared with the values of Table 1; interpolation gives the apparent temperature to 0.1 K.

3) More simply but approximately, Table 2 or Fig. 4 can be consulted.

In order to determine the apparent temperature directly from meteorological observations, the condensed Tables 4 and 5, based on wet-bulb and dew-point temperatures, have been prepared.

5. Results and discussion

a. Sensitivity to humidity

Fig. 4 shows an upper limit of comfort for the walking human at an apparent temperature of 25.3°C. In the comfort zone, a vapor-pressure change of 1 kPa has the same effect as a temperature change of 1.9 K. This correspondence rises to 1 kPa≈6.5 K for any combination of T_∞ and P_∞ giving $\mathcal{T}=50$°C. The effect of an increase in humidity is well below that of an adiabatic humidity change (virtually along lines of equal wet-bulb temperature, where the correspondence is 1 kPa ≈14.8 K). Hence, provided that it can be done without an accumulation of moisture, evaporative cooling will always reduce the apparent temperature, but (from Fig. 4) an active person could achieve absolute comfort only if $T_{wb}<25$°C. Adiabatic cooling offers good possibilities for local climate modification in cities and at outdoor gatherings having high densities of people.

TABLE 4. Apparent temperature from dry- and wet-bulb temperatures.

Dry-bulb temperature T_∞ (°C)	Wet-bulb temperature (°C)										
	10	12	14	16	18	20	22	24	26	28	30
	Enthalpy (J g⁻¹)										
	9.2	10.5	12.0	13.6	15.5	17.5	19.8	22.4	25.2	28.4	31.8
20	18	19	19	20	20	21	—	—	—	—	—
22	20	20	21	22	22	23	24	—	—	—	—
24	22	22	23	24	24	25	26	26	—	—	—
26	24	24	25	26	26	26	27	28	30	—	—
28	26	26	27	27	27	28	29	30	33	(36)	—
30	—	28	28	29	29	30	31	33	35	38	(45)
32	—	29	30	30	31	32	33	35	37	41	47
34	—	—	31	32	32	33	35	37	39	43	50
36	—	—	32	33	34	35	37	39	41	45	—
38	—	—	34	34	35	36	38	40	43	47	—
40	—	—	—	36	37	38	40	42	45	49	—
42	—	—	—	37	38	39	41	43	46	51	—
44	—	—	—	38	39	40	42	45	48	—	—
46	—	—	—	—	41	42	44	46	49	—	—
48	—	—	—	—	42	43	45	47	50	—	—
50	—	—	—	—	43	44	46	49	52	—	—

TABLE 5. Apparent temperature from dry-bulb and dew-point temperatures.

Dry-bulb temperature T_∞ (°C)	Dew-point temperature (°C) / Vapor pressure P_∞ (kPa)															
	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
	0.67	0.71	0.81	0.94	1.07	1.23	1.40	1.60	1.82	2.06	2.34	2.64	2.98	3.36	3.78	4.24
20	18	18	18	19	19	19	20	20	21	21	21	—	—	—	—	—
22	20	20	21	21	21	22	22	22	22	23	23	24	—	—	—	—
24	22	23	23	23	23	24	24	24	24	25	25	26	26	—	—	—
26	24	25	25	25	25	25	26	26	26	27	27	28	29	30	—	—
28	26	27	27	27	27	27	28	28	29	29	30	31	32	33	(36)	—
30	28	28	28	29	29	29	30	30	31	31	32	33	35	36	38	(45)
32	30	30	30	31	31	31	31	32	33	33	34	36	37	39	41	(50)
34	32	32	32	33	33	33	33	34	35	36	37	38	40	42	45	—
36	33	33	34	34	34	35	35	36	37	38	39	41	43	45	48	—
38	35	35	35	36	36	37	37	38	39	41	42	44	46	49	52	—
40	36	37	37	38	38	39	39	40	41	43	45	47	49	52	—	—
42	38	38	39	39	40	40	41	42	43	45	47	49	52	—	—	—
44	40	40	41	41	42	42	43	44	45	47	49	52	—	—	—	—
46	42	42	42	43	44	44	45	46	47	49	51	—	—	—	—	—
48	43	44	44	45	45	45	46	48	49	51	—	—	—	—	—	—
50	45	45	46	46	47	47	48	50	52	—	—	—	—	—	—	—

b. Humidity in skin and clothing

When exertion causes appreciable perspiration in an atmosphere of high relative humidity, sweat may either accumulate on the skin in hot surroundings or recondense in the outer layers of clothing, often in cold conditions. In the former instance, there would be an insulating layer of water; in the latter, evolution of latent heat in the clothing. Since neither possibility

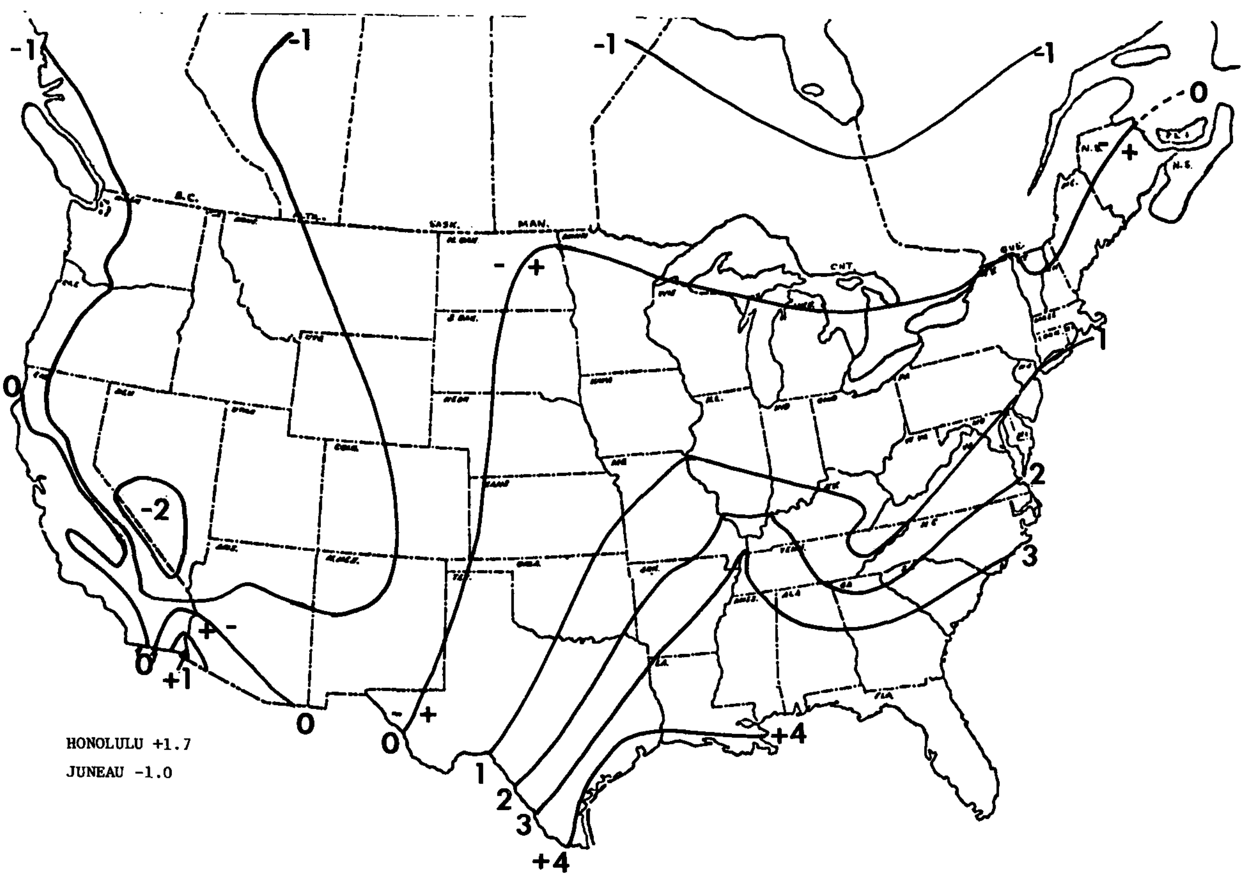

FIG. 5. Geographic variation in the effect of humidity on apparent temperature (K) in Anglo-America, normal solar noon, midsummer conditions.

has been taken into account in the analysis, either would vitiate the results if it occurred.

A check was therefore made, using Eqs. (2)–(6), of the temperatures and vapor pressures at the skin and outer fabric surfaces, the latter being compared with the saturation vapor pressures in order to determine if saturation was approached.

The highest value of ψ_f was found to be only 66%, when $T_\infty = 20°C$ and $\psi_\infty = 100\%$. At high temperatures and humidities, however, ψ_s may exceed 90%. Corresponding results are shown as dashed lines in Fig. 4 and are enclosed by parentheses in Table 2. Under these conditions, which are extreme, comparisons based on the model may be only approximate. Since ψ_b is taken as 90%, there is a possibility that a saline film of perspiration may form on the skin and hinder heat transfer under very sultry conditions. The thickness and effect of this water layer have not been examined. They depend on two opposing factors, the effect of osmosis in the preferential retention of salt by the skin and the accumulation of salt, with a consequent reduction of P_s, as the sweat evaporates. It is of parallel interest that long-distance athletes maintain a high surface vapor pressure, hence evaporation rate, by training in salt conservation and by periodically sponging saline solution from the skin.

6. Geographic variation in the temperature-humidity index

The above analysis has been performed on climatic data in Anglo-America to adjust dry-bulb normals for the effects of humidity. The approach corresponds to that used to determine Buettner's (1962) Desert Equivalent Temperature. Results, plotted in Fig. 5, were derived as follows:

For 40 cities on the U.S. mainland, as well as Honolulu and Juneau, and 16 cities in Canada, July normals were taken from ESSA (1968) and for Canada from Department of Transport (1967), for the dew-point; and for the normal dry-bulb temperature, which was taken as the average of the normal daily mean and the daily maximum. A table of saturation vapor pressure was used to convert dew point to vapor pressure. For each of the 58 cities, the apparent temperature was derived by solving Eqs. (13) or (15) and substituting in Table 1.

The amounts by which these values exceed the corresponding dry-bulb temperatures were plotted in Fig. 5. This difference depends on, but is not proportional to, the amount by which the vapor pressure differs from 1.6 kPa.

Fig. 5 may be seen as a chart of corrections to the dry-bulb temperature to allow for the effect of humidity on the walking human who is not exposed to wind or sunshine. At this stage, no map of apparent temperature is presented, since the effects of such factors as wind and sunshine have yet to be considered. A companion paper will include a generalized chart of apparent temperature (Steadman, 1979).

APPENDIX

List of Symbols

- D significant diameter (cm)
- L latent heat of evaporation of water, corrected by subtracting sensible heat change from body core to skin (J g^{-1})
- P vapor pressure (kPa)
- Q heat transfer rate per unit of body surface area (W m^{-2})
- R heat resistance of unit area (m^2 K W^{-1})
- S surface area of part or whole of body (m^2)
- T temperature (°C)
- V volume of part or whole of body (m^3)
- Z moisture resistance of unit area (m^2 kPa W^{-1})
- c constant
- d thickness (mm or cm)
- g evaporative heat transfer coefficient (W m^{-2} kPa^{-1})
- h heat-transfer coefficient (W m^{-2} K^{-1})
- j moisture conductivity (W cm m^{-2} kPa^{-1})
- k conductivity (W cm m^{-2} K^{-1})
- m moisture transfer rate per unit of body surface area (g m^{-2} s^{-1})
- r ratio of moisture-transfer resistance: heat-transfer resistance for clothing ensemble (kPa K^{-1})
- s specific heat of air at constant pressure (J g^{-1} K^{-1})
- v air velocity relative to observer (cm s^{-1} or m s^{-1} or mph
- y height above ground (m)
- $\mathfrak{D}$ diffusivity of very dilute water vapor in air (cm^2 s^{-1})
- $\mathcal{P}$ total atmospheric pressure (kPa)
- $\mathcal{R}$ gas constant for water vapor (kPa cm^3 K^{-1} g^{-1})
- $\mathcal{T}$ apparent temperature (°C)
- θ angle between directions of wind and of model's movement
- μ viscosity of air (g cm^{-1} s^{-1})
- ϕ_1 ratio of effective radiating area to total surface area
- ϕ_2 proportion of body covered by clothing
- ρ density of air (g cm^{-3})
- σ Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
- σ' linear Stefan-Boltzmann constant (W m^{-2} K^{-1})
- ψ relative humidity (%).

Subscripts

- a air; boundary layer of air
- b body core
- c by convection
- e by evaporation
- f clothing; at outer surface of clothing
- j through covered part of body
- K absolute (Kelvin) degrees
- r by radiation
- s skin; outer surface

sat saturation vapor pressure
u through uncovered part of body
v by ventilation through lungs
wb wet-bulb
10 refers to measurements made by anemometer 10 m above ground
∞ ambient.

REFERENCES

American Society of Heating, Refrigerating and Air Conditioning Engineers, 1972: *ASHRAE Handbook of Fundamentals.* New York, 688 pp.

Baldwin, J., 1973: *Climates of the United States.* NOAA, Washington, DC, 113 pp.

Behmann, F. W., 1960: Grundlagen der Bedleidungsphysiologie in elementarer Darstellung. Vertrauensstelle für Lieferungstuchmacher, e. V., Erpel/Rhein, 59 pp. [See also *Wool Sci. Rev.*, No. 22, 44–52].

Belding, H. S., H. D. Russell, R. C. Darling and G. E. Folk, 1947: Analysis of factors concerned in maintaining energy balance for dressed men in extreme cold: Effects of activity on the protective value and comfort of an arctic uniform. *Amer. J. Physiol.*, **149**, 223–239.

Buckler, S. J., 1969: The vertical wind profile of monthly mean winds over the Prairies. Canada Dept. of Transport, Tech. Memo. TEC 718, 16 pp.

Buettner, K. J. K., 1959: Diffusion of liquid water through human skin. *J. Appl. Physiol.*, **12**, 261–268.

——, 1962: Human aspects of bioclimatological classification. *Biometeorology*, S. W. Tromp, Ed., Vol. 1, Macmillan, 91–98.

Department of Transport, Canada (1967): *The Climate of Canada*, 1st ed. Toronto, 74 pp.

Environmental Science Services Administration, 1968: *Climatic Atlas of the United States.* Washington, D.C., 80 pp.

Fanger, P. O., 1970: *Thermal Comfort.* Danish Technical Press, 244 pp.

Fourt, L., and N. R. S. Hollies, 1970: *Clothing: Comfort and Function.* Dekker, 254 pp.

Givoni, B. and H. S. Belding, 1962: The cooling efficiency of sweat evaporation. *Biometeorology*, S. W. Tromp, Ed., Macmillan, 304–314.

Haines, G. F., and T. Hatch, 1952: Industrial heat exposures—Evaluation and control. *Heat. Vent.*, **49**, November, 93–101.

Hill, R., 1970: *Textiles in Sport.* Shirley Link, Manchester, England, Shirley Institute, 22–24 pp.

Hilpert, R., 1933: Wärmeabgabe van geheitzen Drähten and Röhren, Forsch. *Gebiete Ing.*, **4**, p. 220. [Quoted in Kreith, F., 1958: *Principles of Heat Transfer*, Scranton, N. J., International, p. 376.]

Höschele, K., 1970: Ein Modell zur Bestimmung des Einflusses der klimatischen Befinden des Menschen. *Arch. Meteor. Geophys. Bioklim.*, **B18**, 83–99.

Landsberg, H. E., 1972: The assessment of human bioclimate. Geneva, WMO, No. 331, TN123, 36 pp.

Macpherson, R. K., 1962: The assessment of the thermal Environment: A review. *Brit. J. Ind. Med.*, **19**, 151–164.

McArdle, B., W. Dunham, H. E. Holling, W. S. S. Ladell, J. W. Scott, M. L. Thompson and J. S. Weiner, 1947: The prediction of the physiological effects of warm and hot environments, Med. Res. Coun. (London), R.N.P. Rep. No. 47/391. [The information is more accessible in secondary references such O. G. Edholm, 1967: *The Biology of Work*, London, World University Library, p. 76.]

McCutchan, J. W., and C. L. Taylor, 1951: Respiratory heat exchange with varying temperatures and humidity of inspired air. *J. Appl. Physiol.*, **4**, 121–135.

Newburgh, L. H., Ed., 1949: *Physiology of Heat Regulation and the Science of Clothing.* Saunders, 448 pp.

Sargent, F., and S. W. Tromp, 1964: A survey of human biometerology. Geneva, WMO, No. 160. TP. 78, 113 pp.

Steadman, R. G., 1965: Simultaneous heat and moisture transfer through clothing textiles in the presence of wind. Ph.D. thesis, University of New South Wales, 202 pp.

——, 1971: Indices of windchill of clothed persons. *J. Appl. Meteor.*, **10**, 674–683.

——, 1979: The assessment of sultriness. Part II: Effects of wind, extra radiation and barometric pressure on apparent temperature. *J. Appl. Meteor.*, **18**, 874–885.

Weast, R. C., Ed., 1972–73: *Handbook of Chemistry and Physics*, 53rd ed. Chemical Rubber Co. Press.

Weiner, L. I., 1970: The relationship of moisture vapor transmission to the structure of textile fabrics. *Textile Chem. Color.*, **2**, 378–383.

Woodcock, A. H., 1962: Moisture transfer in textile systems, Part 1. *Textile Res. J.*, **32**, 628–633.