Microclimate and Heat Stress of Runners in Mass Participation Events

C. R. DE FREITAS

Department of Geography, University of Auckland, Auckland, New Zealand

N. J. DAWSON AND A. A. YOUNG

Department of Physiology, University of Auckland, Auckland, New Zealand

W. J. MACKEY

P.O. Box 21-149, Auckland, New Zealand

(Manuscript received 24 April 1984, in final form 20 October 1984)

ABSTRACT

The largest mass participation fun run in the world took place in Auckland, New Zealand, where an estimated 80 000 participants ran 10.4 km "Round the Bays" in the early fall of 1982. Even in the relatively mild climate of Auckland, heat stroke and other types of heat illness occur during this annual event. Techniques for thermal assessment of human bioclimate have not been applied to an exercising crowd although it is widely accepted that crowding will reduce the heat loss of individuals. To quantify the possible heat load brought about by running in a large crowd, those components of the microenvironment that affect radiant, evaporative and convective heat exchange were measured, both within the mass of runners and separately from it. These data were used as input for two detailed body–environment heat exchange models which show the effect of the runners themselves on the thermal environment. Since it is assumed that changes in longwave radiation exchange and convective losses from the body are likely to be the major causes of differences between solo and group running, these avenues of heat exchange are carefully assessed. The results show that longwave radiative losses can be reduced substantially by running in a large group compared to solo running, but the absolute size of the increase in net heat load on the individual is small. However, heat loss by convection for group runners is less than half that for solo runners. This may be the result of entrainment of air within an atmospheric envelope below head level in which wind speed and direction are the same as the runner's speed and direction. For the weather conditions prevailing at the time of the experiment, jogging in the main bunch of runners is estimated to cause, on occasions, more than three times the heat stress on the body compared to that experienced when running solo along the same route at the same time of day during identical weather conditions.

1. Introduction

In North America alone, 30 million people participate annually in mass fun runs (Sutton, 1979; Sutton and Bar-Or, 1980). The largest fun run in the world took place in Auckland, New Zealand, where an estimated 80 000 participants ran 10.4 km "Round the Bays" in early fall 1982. Even in the relatively mild climate of Auckland, an incidence of 0.08% for heat stroke and 1% for other types of heat illness has been claimed for this annual event (Nicholson and Somerville, 1978). These cases have occurred under temperature conditions where the risk was considered to be low. According to Sutton (1979), serious heat injury can affect the "fun runner" or jogger even when the prevailing weather conditions seem safe. Sutton warned that with the increasing number of participants in fun runs, the potential for serious heat problems in catastrophic numbers is possible.

Just as animals resort to crowding to keep themselves warm (Mount, 1968), it is widely accepted based on personal experience that crowding of people will reduce the heat loss of individuals within the group. However, techniques for thermal assessment of human bioclimate have not been applied to conditions representing large groups of people or an exercising crowd. Participation in mass fun runs has clearly been shown to lead to medically significant physiological changes (Sutton *et al.*, 1972; Richards *et al.*, 1979a,b,c) including heat exhaustion (Nicholson and Somerville, 1978; Hughson and Sutton, 1978; Richards and Richards, 1980), but the degree to which heat stress is a result of the thermal effect of the microclimate created by the mass of runners has not been determined.

With the above considerations in mind, our purpose here is to quantify and evaluate the additional heat stress caused by running in a large group. Those components of the microenvironment that affect radiant, evaporative and convective heat exchange are measured, both within the mass of runners and separately from it. These data are used as input for two body–atmosphere heat exchange models using established procedures. Since it is assumed that changes to longwave exchanges, and possibly convective loss, are likely to be the main processes affecting the individual in a large group of runners, the modeling procedure relating to these is treated in some detail.

2. Procedure

The Auckland "Round the Bays" run involved an estimated 80 000 participants running a 10.4 km route (Fig. 1) beginning at 0930 LST 27 March 1982 (Pennington and Kay, 1984). Observations were made at two points along the route of the run, one early and the other late in the course (sites 1 and 2, respectively). The instrument stations were in the middle of the road in the center of the mass of runners. The following measurements were taken at 5 min intervals: wet and dry-bulb temperature (ventilated psychrometer); mean radiant temperatures of the sky, ground and other surroundings (Barnes infrared radiometer); and wind speed and direction (hot-wire anemometer). Global solar radiation (Kipp and Zonen pyranometer) together with wet and dry bulb temperatures and wind speed and direction were measured at a control site a short distance away from the route near site 2 (Fig. 1) Runner density and speed were measured from aerial photographs taken at 5 s intervals by elevated cameras mounted at each of the monitoring sites. Descriptions of symbols used for all measurements and formulas, as well as corresponding units are given in Table 1.

3. Microclimate data

Rather than to simply amass general microclimatic information, the object of the measurements taken was to provide a data base that would enable comparison of the thermal stress likely to be experienced by a solitary runner with that experienced by the same runner in the midst of a large group along the same route during identical weather conditions. To approximate this, two points in time during the run were selected for each monitoring site: one that described conditions a few seconds before the arrival of the first runners and another during which the density of runners was highest. Conditions prevailing at these times, along with the corresponding average speeds and densities of runners, are given in Table 2. Time differences between the observations are small. However, to compensate for possible thermal differences that might be due to the time lapse between each pair of observations rather than thermal effects caused by the presence of large groups of runners, a "controlled" data set was generated (conditions A and B, Table 2). All thermal changes likely to be the result of normal, thermal progression of conditions approaching solar noon, namely, longwave radiation from ground and sky, or T_{gr} and T_{sky}, respectively, were held constant. Based on readings at the nearby monitoring site off the run route, changes in T_a outside the influence of the runners were negligible. As the variation in solar radiation intensity between the times selected was small, a mean value of 558 W m^2, which corresponds to the 0950 reading, was used throughout. The control data (condition 4) were selected as representative of conditions "late" in the run when the combined effect of body heat on the ambient air is likely to be greatest.

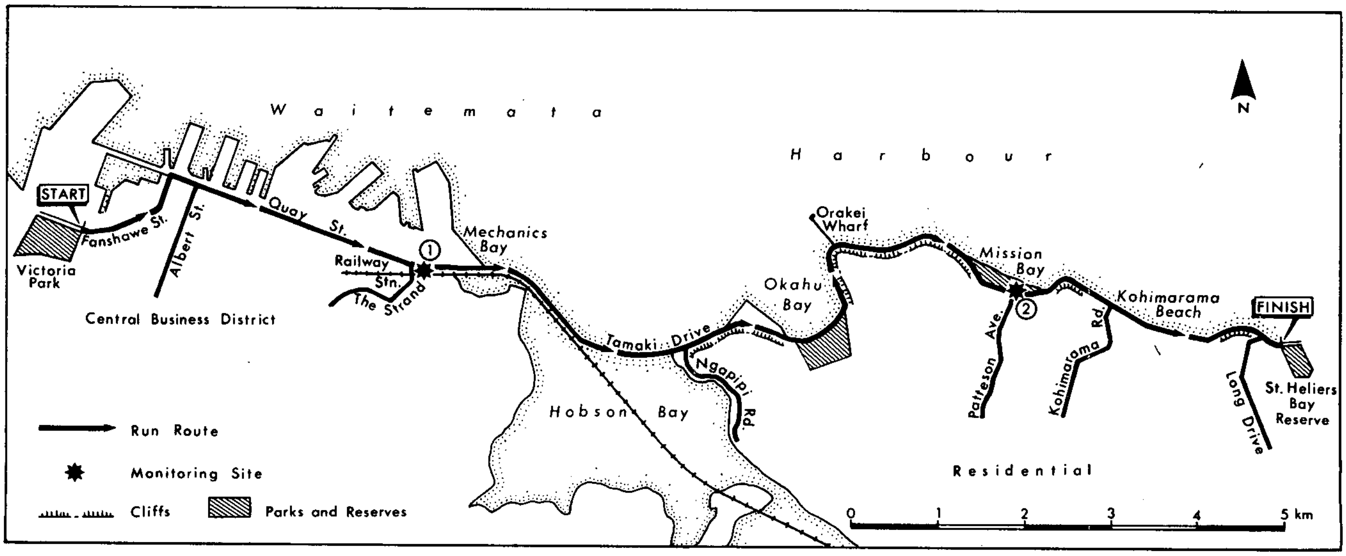

FIG. 1. Route map of the Auckland "fun run" showing monitoring sites and geographical features of potential microclimatological significance.

TABLE 1. List of symbols.

a_{cl}	albedo of clothing (0.3)
a_s	albedo of skin (0.35)
a_g	albedo of ground (0.15)
A_D	DuBois area (m^2)
C	body–atmosphere convective heat flux (W)
C_r	convective heat flux from respiration (W)
C_{cs}	convective heat flux from clothing–skin surface (W)
e	vapor pressure of air (mm Hg)
E	evaporative heat flux (W)
E_r	evaporative heat flux due to respiration (W)
E_{req}	equilibrium requirement for sweat evaporation at skin temperature of 35°C (W)
E_{rsw}	total heat load on body before sensible sweating (W)
E_{max}	evaporative capacity of the air (W)
f	cooling efficiency of sweating
f_{eff}	total effective radiation-area factor (0.82)
f_{pz}	ratio of effective radiation area of body facing zenith to DuBois area (0.11)
f_{pg}	ratio of effective radiation area of body facing ground to DuBois area (0.11)
f_{ph}	ratio of effective radiation area of body facing horizon to Dubois area (0.6)
f_{acl}	ratio of clothed area to DuBois area (0.29)
f_{aun}	ratio of unclothed area to DuBois area (0.71)
f_s	shadow-area factor for direct radiation
G_{rest}	metabolic rate at rest (W m^{-2})
G_{total}	total metabolic rate (W m^{-2})
h_c	convective heat transfer coefficient (W m^{-2} °C^{-1})
H	body height (cm)
L	heat loss or gain by longwave radiation (W)
L_{cs}	longwave radiation from clothing–skin (body) surface (W m^{-2})
L_e	longwave radiation from environment (W)
L_{gr}	longwave radiation from ground (W m^{-2})
L_{sky}	longwave radiation from sky (W m^{-2})
L_{su}	longwave radiation from surroundings other than the sky (W m^{-2})
M	heat gain of body from metabolism (W)
P_{sk}	saturation vapor pressure for skin (mm Hg)
q	diffuse solar radiation (W m^{-2})
q_{gm}	diffuse solar radiation reflected by ground onto body (W m^{-2})
q_h	diffuse solar radiation on horizontal surface (W m^{-2})
q_{vm}	diffuse solar radiation falling on vertical body (W m^{-2})
Q	direct solar radiation (W m^{-2})
Q_m	direct solar radiation falling on body (W m^{-2})
r	speed of runner (m s^{-1})
R	heat gain of body from solar radiation (W m^{-2})
R_{cl}	solar heat load on clothing (W m^{-2})
R_{un}	solar heat load on skin (W m^{-2})
R_t	total solar irradiance on body (W)
S	heat load on body (W m^{-2})
S_I	index of thermal stress
T_a	air temperature (°C)
T_{cs}	mean temperature of clothing and skin (K)
T_{gr}	mean radiant temperature of ground (K)
T_s	temperature of skin (°C)
T_{sky}	mean radiant temperature of sky (K)
T_{su}	mean radiant temperature of surroundings other than the sky and ground (K)
V	wind speed (m s^{-1})
V_{tr}	treadmill speed (m s^{-1})
V_r	relative wind speed (m s^{-1})
W	body weight (kg)
β	altitude angle (deg)
ϵ_{gr}	mean emissivity of ground (0.95)
ϵ_{sky}	mean emissivity of sky (0.95)
ϵ_{cs}	mean emissivity of clothing–skin surface (0.95)
ϵ_{su}	mean emissivity of surroundings other than sky and ground (0.95)
κ	Lewis relation coefficient
θ	azimuth angle (deg)
σ	Stefan–Boltzmann coefficient (5.674 × 10^{-8} W m^{-2} K^{-4})
α	solar angle (deg)

Observed increases in temperature due to the presence of a large number of hot bodies in close proximity are not as large as might be expected (Table 2). Increases in T_a for the group conditions are in the order of 2°C, while increases in T_{su} are apparently small. In the zone between the ground and the average height of the runners, the direction and speed of air movement is that of the runner when densities are greater than approximately 2 (100 m^2)$^{-1}$, regardless of the prevailing regional wind speed and direction. The group runner appears to be moving along in the atmospheric envelope resulting from entrainment of air by the crowd. Because of this, effective wind speed appears to be more like that for a runner on a treadmill, where turbulence results solely from the effect of body movement. In the case of the solo runner, on the other hand, the minimum wind speed will be equal to the effective wind speed due to body movement plus running speed, even under conditions of zero regional wind.

4. Physioclimate

Thermal exchanges between the runner and surroundings can be expressed by the energy balance equation

$$M + R + L + C + E = S, \tag{1}$$

where M is metabolic rate, R the solar heat load on the body, and L, C and E are longwave radiative, convective and evaporative exchanges, respectively. The output parameter S represents the net heat load on the body. Each term in (1) represents a rate of heat exchange per unit area of body surface. The surface area of the body, A_D, can be estimated from the formula of DuBois and DuBois (1915):

$$A_D = 0.00718W^{0.425}H^{0.725}. \tag{2}$$

A surface area of 1.8 m^2 is taken to be representative of the average man (Durnin and Passmore, 1967; Givoni, 1969; Fanger, 1973).

Allowing for energy converted to mechanical work, the net gain of heat from metabolism, M, is given by Givoni and Sohar (1968) as

$$M = (0.8G_{\mathrm{total}} + 0.2G_{\mathrm{rest}})A_D. \tag{3}$$

The metabolic rate at rest, G_{rest}, is taken as 58 W m^{-2}. Values for G_{total} depend on the runner's speed.

TABLE 2. Microclimatic conditions representative of solo and group runners at two sites along the route, one early and the other late in the course. The "control" reference condition is described in the text.

		Runner								
Site	Time (LST)	Speed ($\mathrm{m\ s^{-1}}$)	Density ($(100\ \mathrm{m}^2)^{-1}$)	T_a (°C)	e (mm Hg)	V ($\mathrm{m\ s^{-1}}$)	T_{gr} (K)	T_{sky} (K)	T_{su} (K)	Condition reference
1 (Solo)	0915	3.0	1	19.7	14.0	3.0	306	268	283	I
1 (Group)	0950	2.2	42	22.0	13.5	1.7	305	264	293	II
2 (Solo)	0940	3.7	1	20.5	13.5	3.7	301	268	295	III
2 (Group)	1020	3.8	21	22.0	14.3	1.7	306	265	304	IV
Control:										
A (Solo)	—	3.7	1	20.5	13.5	3.7	306	265	295	A
B (Group)	—	—	21	22.0	14.3	1.7	306	265	304	B

The net longwave radiative heat transfer L between the runner and the surroundings is

$$L = L_e - L_{cs}. \tag{4}$$

Longwave radiation from the environment, L_e, is comprised of radiation from the sky, L_{sky}, from the ground, L_{gr}, and from the surroundings other than the sky and ground, L_{su}. Longwave radiant fluxes from each of these sources can be calculated using a combination of the Kirchoff and Stefan–Boltzman relations, where

$$L_{sky} = \epsilon_{sky}\sigma T^4_{sky}, \tag{5}$$

$$L_{gr} = \epsilon_{gr}\sigma T^4_{gr}, \tag{6}$$

$$L_{su} = \epsilon_{su}\sigma T^4_{su}. \tag{7}$$

Here, T_{sky}, T_{gr} and T_{su} are the mean radiant temperatures (K) of the sky, ground and rest of the surroundings, respectively. Emissivities of the sky, ϵ_{sky}, ground, ϵ_{gr}, and surroundings, ϵ_{su}, were taken as 0.95 (Sellers, 1965).

The areas of the body involved in radiant energy exchange are a function of the geometry of the body and the directional properties of the radiation. The various methods available for estimating these areas are complex and depend on body posture and nature of the surroundings. The procedure used here is based on the geometry of angular variation of radiation components described by Pugh and Chrenko (1966), Breckenridge and Goldman (1972) and Fanger (1973). Radiation-area factors calculated from empirical formulas taken from the above experiments were averaged for an erect body posture. Using a method presented by Fanger (1973), the effective radiation-area factor for the proportion of the body area facing the zenith, f_{pz}, and ground, f_{pg}, were taken as the mean of that for an altitude angle β of 90° with azimuth angle θ of 0° ($f_p = 0.081$), and $\beta = 67.5°$ with $\theta = 45°$ ($f_p = 0.150$), respectively, giving a value of 0.11 for each of f_{pz} and f_{pg}. The side view factor f_{ph} for each half of the runner's body is the ratio of the effective radiation area of the body facing the horizon to the DuBois area. A value for f_{ph} of 0.3 was calculated from the mean area factors of side-view angles of $\beta = 22.5°$ with $\theta = 45°$ ($f_p = 0.286$), and $\beta = 0$ with $\theta = 45$ ($f_p = 0.306$).

Based on the above, longwave radiation from the surroundings onto the runner, L_e, is given by

$$L_e = (0.11L_{sky} + 0.11L_{gr} + 0.6L_{su})A_D. \tag{8}$$

The sum of the partial area factors gives a total effective radiation area f_{eff} for the body of 0.82. This value represents the maximum possible area available for heat exchange by radiation. Thus, longwave radiation from the runner, L_{cs}, is given by

$$L_{cs} = \sigma\epsilon_{cs}T^4_{cs}f_{eff}A_D, \tag{9}$$

where ϵ_{cs} is the mean emissivity of the clothing–skin surface of the runner, here taken as 0.95 (Hardy, 1949; Fourt and Harris, 1949).

The net solar heat load on the runner, R, was calculated using a procedure based in part on the work of Terjung and Louie (1971) and on the directional radiation factors described above. The formulas are

$$R = R_{un} = R_{cl}, \tag{10}$$

$$R_{un} = [R_t(1 - a_{cl})]f_{acl}, \tag{11}$$

$$R_{cl} = [R_t(1 - a_s)]f_{aun}, \tag{12}$$

$$R_t = (Q_m + q_{vm} + q_{gm})A_D 697.7, \tag{13}$$

$$Q_m = [(Q + q)_h - q_h]f_s, \tag{14}$$

$$q_{vm} = (Q + q)_h 0.5 a_g f_{ph}, \quad (15)$$

$$q_{gm} = (Q + q)_h 0.5 a_g f_{ph}. \quad (16)$$

Diffuse radiation q_h was calculated from $0.18Q$ (Roller and Goldman, 1967). Values for the clothed and unclothed body-area factors f_{acl} and f_{aun} were completed from formulas presented by Myrup and Morgan (1972). Clothing ensembles typical of participants in the run, namely, light T-shirt and shorts (0.2 *clo* units), give f_{acl} and f_{aun} values of 0.29 and 0.71, respectively. Albedo values for clothing, a_{cl}, were taken as 0.30 (Lee and Vaughan, 1964), for skin, a_s, as 0.35 (Sellers, 1965), and for the ground, a_g (dark road asphalt), as 0.15 (Sellers, 1965). The shadow-area factor f_s for direct radiation was calculated from (Taylor, 1956)

$$f_s = 0.29 \cos\alpha + 0.039 \sin\alpha. \quad (17)$$

Dry heat exchange by convection between the runner and surrounding air, C, is given by

$$C = C_r + C_{cs}. \quad (18)$$

Heat exchange through the respiratory passage, C_r, is given by Fanger (1973) as

$$C_r = 1.36 \times 10^{-3} G_{total}(34 - T_a)A_D. \quad (19)$$

Convective exchange from the clothing–skin surface, C_{cs}, is given as

$$C_{cs} = h_c(T_s - T_a)A_D, \quad (20)$$

where the convection coefficient h_c varies as a function of wind speed V:

$$h_c = kV_r^n. \quad (21)$$

The coefficients n and k were given values to represent situations defined according to orientation and posture of the body and wind speeds encountered. Kerslake (1972) has shown that for outdoor conditions and for a wide range of wind speeds and sedentary body positions,

$$h_c = 7.2V^{0.6}\ [\mathrm{W\ m^{-2}}]. \quad (22)$$

When considering the activity of running, air movement resulting from body movement needs to be taken into account. Relative air movement is a function of running speed, body movement and wind speed. According to Steadman (1979), running speed r and wind speed are combined to give a relative wind speed V_r:

$$V_r = [V^2 + r^2 - (2Vr\sin\theta)]^{0.5}, \quad (23)$$

where θ here is the direction in which the runner is moving relative to the wind. Since the route a runner takes is equally likely to be in any direction, a range of θ values from 0 to 360° can be substituted in (23) to obtain a mean V_r.

For a runner, there is also an effect due to the extra velocity of the limbs relative to the trunk resulting from the swinging, pendulum motion. Based on a variety of experiments in "still air" conditions, Nishi and Gagge (1970) defined h_c in terms of treadmill speed V_{tr} as

$$h_c = 6.51 V_{tr}^{0.391}. \quad (24)$$

Effective air movement was interpreted as "linear air velocity." For treadmill running in still air, the equivalent air movement was found to be approximately half the treadmill speed. Using a value of 1.7 m s^{-1}, which is half the mean speed of runners in the Round the Bays run, (24) gives $h_c = 10.5$ W m^{-2} °C^{-1}. On the basis of (22), solving for an effective wind speed of 1.7 m s^{-1} gives $h_c = 10$ W m^{-2} °C^{-1} for a runner in still air. This is very similar to the findings of Clark *et al.* (1974) who obtained an h_c value of 21.8 W m^{-2} °C^{-1} for the thigh of a subject running in still air. If it is assumed that the value for the whole leg is not less than this, that the legs represent 32% of the total body surface, and that the convection for the rest of the body is at least 3 W m^{-2} °C^{-1}, then the mean for the whole body is approximately 10 W m^{-2} °C^{-1}. On the basis of (22), this gives an effective wind speed of 1.7 m s^{-1} due to the pendulum effect of the limbs of the runner and body movement.

Allowance for body movement must also be made for conditions when there is wind. In experiments simulating athletes running outdoors, the convective heat transfer coefficient is increased by as much as a factor of 2 compared to that described by (22) for a subject standing in an airstream (Clark *et al.*, 1974). Clark *et al.* gave h_c as 30 W m^{-2} °C^{-1} for a subject running at 4.5 m s^{-1} with a relative wind speed of 4.5 m s^{-1}. Using the standard form and power function for h_c given by (22), this gives

$$h_c = 12V^{0.6}. \quad (25)$$

For a mean wind speed of 3.4 m s^{-1}, (24) gives h_c as 25 W m^{-2} °C^{-1}. This is only slightly less than twice the value for a standing subject using the standard Kerslake (1972) formula given by (22). The coefficient is also very similar to that found using an alternative expression for h_c which adds the increase due to limb movement to the standard form of (22), giving

$$h_c = 10 + 7.2V^{0.6}. \quad (26)$$

On the basis of the above, (25) was used for the solo runner and (22) for minimum convective losses from the runner in the crowd.

Evaporative heat loss E from the body of the runner is given by

$$E = E_r + E_{rsw}. \quad (27)$$

Part of the evaporative heat loss takes place as respiratory heat loss E_r, given by Fanger (1973) as

$$E_r = G_{total} 2.3 \times 10^{-3}(44 - e)A_D. \quad (28)$$

The remainder of the E term is the rate of evaporative heat exchange by sweating, E_{rsw}, where

$$E_{rsw} = M + R + L + C + E_r. \tag{29}$$

The transfer of E_{rsw} to the air depends on the evaporative capacity of air, $E_{\max}$, which has been shown to be (Gagge *et al.*, 1971; Kerslake, 1972)

$$E_{\max} = \kappa h_c(P_{sk} - e)A_D, \tag{30}$$

where κ is 2.2. The convective coefficient h_c for $E_{\max}$ is given by (22). It need not be modified for the "pendulum" effect as in the case of C_{cs}, because of offsetting effects related to sweat distribution. According to Clark *et al.* (1974), this is because, even when sweat is running off the face and trunk, the lower limbs are not completely wet and the evaporative capacity of the air flowing over the limbs is not fully taken up.

5. Model operation and assessment of heat stress

The skin is the interface between the body and the environment for all forms of heat exchange other than C_r and E_r. Skin temperature is the principal property of this interface since it modifies heat exchange gradients which affect body–atmosphere energy transfers. Several heat stress indices take skin temperature to be constant at 35°C, the point at which the skin is normally completely wet, and further increases in skin temperature to be negligible. While this is roughly true for the sedentary subject, sweating occurs at a much lower temperature during exercise (Nielsen, 1969). Nishi and Gagge (1970) have shown that skin temperature averages 27°C for a variety of exercises.

With the above considerations in mind, two modeling procedures were employed. The first, referred to as Model One, uses a skin temperature of 27°C and provides as output a heat stress index calculated as $E_{\rm rsw}/E_{\max}$, expressed as a percentage, along the lines of the heat stress index of Belding and Hatch (1955). When $E_{\rm rsw} = E_{\max}$ the heat index is 100. At larger values the rate of evaporation required for body–atmosphere thermal equilibrium exceeds the maximum evaporative capacity. Under these circumstances body heat storage will increase at a rate $E_{\rm rsw} - E_{\max}$.

The second model, referred to as Model Two, is based on the scheme devised by Givoni (1969) as part of this Index of Thermal Stress (ITS). According to this scheme, skin temperature is taken as 35°C and the index S_l, expressed as the equilibrium heat loss requirement $E_{\rm req}$, is nonlinear and depends on the thermal efficiency of sweating f where

$$E_{\rm req} = M + R + L + C_{\rm cs}, \tag{31}$$

$$1/f = \exp[0.6(E_{\rm req}/E_{\max} - 0.12)], \tag{32}$$

$$S_l = E_{\rm req}/f. \tag{33}$$

According to Kerslake (1972), who examined several heat stress indices, the ITS is an astute blend of theory and empiricism.

The required evaporation rate $E_{\rm req}$ is not under direct physiological control so it cannot be used as an expression of physiological heat strain on the body as a result of environmental heat stress. However, Givoni's sweating efficiency term $1/f$ provides an expression of required sweat rate rather than required rate of evaporation. If the ratio $E_{\rm req}/E_{\max}$ is less than 0.12, then $1/f$ is taken as 1.0; if the ratio is greater than 2.15, $1/f$ is taken as 0.29. According to Kerslake (1972), extension of this relation to values of $E_{\rm req}/E_{\max}$ greater than 1.0 can compensate for the assumption of constant skin temperature in (30).

It is noteworthy that for effective wind speeds of 1.7 and 3.4 m s^{-1} for conditions described earlier, h_c calculated using Givoni's empirical term ($10 \times 1.7^{0.3}$ and $10 + 3.4^{0.3}$, respectively) give very similar results to the value calculated using (22), and (25) and (26), respectively. The same also applies to Givoni's term for $E_{\max}$ where $19.7V^{0.3}$ compares to $15.8V^{0.6}$ from (30) which, for $V = 1.7$, gives 23.1 and 22 W m^{-2} mm Hg^{-1}, respectively.

6. Discussion of model output

For the conditions described in Table 2, the mean running speed was 3.4 m s^{-1}. This corresponds to a net gain of heat from metabolism, M, of 691 W. All other heat exchange terms were calculated from formulas given earlier. Tables 3 and 4 summarize energy budgets and heat stress assessments for both schemes. It is clear from the results that, compared to running solo, a runner in a crowd is subjected to a greatly increased heat load. The individual net energy terms in the heat budget show those aspects of the runner's environment that contribute most to the difference.

Mean radiant temperature of the surroundings, $T_{\rm su}$, for the group runner is approximately 2°C higher. The net effect of this on the radiant heat load of the environment, L_e, is only about 60 W greater than that of the solo runner (Table 3). The difference in skin temperature between the two models results in the net heat flux via longwave radiation from the body, L, being many times greater for Model Two than for Model One. However, in absolute terms L values are surprisingly small relative to other net energy terms. The overall significance of the net increase in the body's heat load caused by reduced longwave loss depends on the ratio $E_{\rm rsw}/E_{\max}$. When $E_{\rm rsw}$ approaches $E_{\max}$, reductions in heat loss due to the proximity of the hot bodies of other runners may make the difference between severe heat stress on the one hand and the beginnings of hyperthermia on the other. This is especially true if the efficiency of sweating term, $1/f$, is used as in Model Two, where,

TABLE 3. Various categories of heat exchange between runner and environment for solo and group runners using Model One for the conditions defined in Table 2. Positive and negative values refer to net heat flow to and from the body, respectively.

Condition reference	M (W)	R (W)	L_{sky} (W)	L_{gr} (W)	L_{su} (W)	L_e (W)	L_{cs} (W)	L (W)	C_r (W)	C (W)	E_r (W)	E_{rsw} (W)	E_{max} (W)	Heat index
I (Solo)	691	203	278	454	346	518	−644	−126	−17	−322	−58	388	717	54
II (Group)	691	203	262	466	397	573	−644	−71	−14	−114	−59	650	535	121
III (Solo)	691	203	278	442	408	584	−644	−60	−16	−324	−59	451	844	53
IV (Group)	691	203	266	473	460	643	−644	−1	−14	−114	−57	722	503	144
A (Solo)	691	203	266	473	409	588	−644	−56	−16	−324	−59	455	844	54
B (Group)	691	203	266	473	460	643	−644	−1	−14	−114	−57	722	503	144

under conditions of severe heat stress, the effect of $1/f$ on the increase in heat load on the runner is logarithmic.

The convection term C accounts for the largest difference between solo and group running, even under the conservative conditions of minimum difference in air movement between group and solo runners defined by the models. Convection losses for the solo runner are approximately three times greater than those for the group runner. This applies regardless of the modeling procedure employed (Tables 3 and 4). With the advantages of hindsight this is not surprising. On the one hand, convection is a major avenue of energy transport away from the body. On the other, the "geometry" effect of the group runner's environment on airflow around a tightly encircled individual within the group is different from that of a solo runner. In the turbulent environment of the solo runner, omnidirectional air movement due to body movement is supplemented by forced convection due to forward movement even under conditions of zero atmospheric wind, and much more when there is wind, leading to high and efficient ventilation of the body.

The net effect of the cumulative difference of all energy terms is reflected in the size of the Heat Index and heat load S_l in Model One and Model Two, respectively. The difference between the solo and group runners in Model Two is quite pronounced. It is particularly noteworthy that this difference exists in both the required heat loss for equilibrium term, E_{req}, and the E_{req}/E_{max} ratio as well as the S_l term of Model Two. According to Kerslake (1972), who has examined Givoni's Index of Thermal Stress (ITS) and tested the results against the empirical findings of other researchers, the ITS gives good quantitative predictions of required sweat rate similar to the Predicted Four Hour Sweat Rate Index of McArdle *et al.* (1974). In this sense, the ITS is a measure of physiological strain on the body as a result of environmental heat stress, whereas the Heat Index is a straightforward index of environmental heat stress. If this is the case, then for the conditions examined the runner is under almost ten times more heat strain in a group than when running solo (Tables 3 and 4). However, precise calibration of the index and the extent to which the above stress–strain proportions apply to the conditions of a mass participation fun run is not known.

It should be emphasized that relatively mild weather

TABLE 4. As in Table 3 but for Model Two.

Condition reference	M (W)	R (W)	L_{sky} (W)	L_{gr} (W)	L_{su} (W)	L_e (W)	L_{cs} (W)	L (W)	C (W)	E_{req} (W)	E_{max} (W)	E_{req}/E_{max}	$1/f$	S_l (W)
I (Solo)	691	203	278	454	346	518	−716	−197	−639	58	1542	0.04	0.95	55
II (Group)	691	203	262	466	397	573	−716	−143	−234	517	1129	0.46	1.22	633
III (Solo)	691	203	278	442	408	584	−716	−132	−686	76	1780	0.04	0.95	72
IV (Group)	691	203	266	473	460	643	−716	−73	−234	587	1097	0.54	1.28	753
A (Solo)	691	203	266	473	409	588	−716	−128	−686	80	1780	0.05	0.96	77
B (Group)	691	203	266	473	460	643	−716	−73	−234	587	1097	0.54	1.28	753

conditions existed on the day of the run. On a warmer day, the heat load on the runner would be many times greater than that identified for Auckland in this study. In a more general context it is worth noting that dense crowding combined with exertion is also characteristic of other mass participation events such as the Hajj in Mecca during which large numbers of cases of heat illness occur (Weiner and Khogali, 1980). The bioclimatological effects demonstrated here no doubt contribute to the heat load experienced by the Mecca pilgrims.

Acknowledgments. Assistance provided by the following is gratefully acknowledged: the Geography, Physiology and Engineering students who took atmospheric measurements; Mr. P. Crossley who gave technical assistance; the New Zealand Ministry of Transport; the Auckland Joggers Club; and the Medical Research Council of New Zealand which provided financial support.

REFERENCES

Belding, H. S., and T. F. Hatch, 1955: Index for evaluating heat stress in terms of the resulting physiological strain. *Heat. Piping Air Cond.*, **27**, 129–136.

Breckenridge, J. R., and R. F. Goldman, 1972: Human solar heat load. *ASHRAE Trans.*, **78**, 110–118.

Clarke, R. P., B. J. Mullan, L. G. C. E. Pugh and N. Toy, 1974: Heat losses from the moving limbs in running: The 'pendulum' effect. *J. Physiol.*, **240**, 8–9.

DuBois, D., and E. F. DuBois, 1915: The measurement of the surface area of man. *Arch. Int. Med.*, **15**, 868–881.

Durnin, J. V., and R. Passmore, 1967: *Energy, Work and Leisure.* Heinemann, 166 pp.

Fanger, P. O., 1973: *Thermal Comfort-Analysis and Applications in Environmental Engineering,* McGraw-Hill, 244 pp.

Fourt, L., and M. Harris, 1949: Physical properties of clothing fabrics. *Physiology of Heat Regulation and the Science of Clothing,* L. H. Newburgh, Ed., Saunders, 291–319.

Gagge, A. P., J. A. J. Stolwijk and Y. Nishi, 1971: An effective temperature scale based on a simple model of human physiological regulatory response. *ASHRAE Trans.*, **77**, 247–260.

Givoni, B., 1969: *Man, Climate and Architecture.* Elsevier, 364 pp.

——, and E. Sohar, 1968: Rectal temperatures in the prediction of permissible work rates in hot environments. *Int. J. Biometeor.*, **12**, 41–50.

Hardy, J. D., 1949: Heat transfer. *Physiology of Heat Regulation and the Science of Clothing,* L. H. Newburgh, Ed., Saunders, 291–319.

Hughson, R. L., and J. R. Sutton, 1978: Heat Stroke in road races. *Brit. Med. J.*, **2**, 1158–1159.

Kerslake, D. McK., 1972: *The Stress of Hot Environments,* Cambridge University Press, 316 pp.

Lee, D. H. K., and J. A. Vaughan, 1964: Temperature equivalent of solar radiation on man. *Int. J. Biometeor.*, **8**, 61–69.

McArdle, B., W. Dunham, H. E. Hollong, W. S. S. Lovell, J. W. Scott, M. L. Thomson and J. S. Weiner, 1947: The prediction of the physiological effects of warm and hot environments. Rep. RNP 47/391, Medical Research Council, London.

Mount, L. E., 1968: *The Climatic Physiology of the Pig.* Edward Arnold, 333 pp.

Myrup, L. O., and D. L. Morgan, 1972: Numerical model of the urban atmosphere, Vol. 1. *Contributions in Atmospheric Science,* No. 4. University of California, Davis.

Nicholson, M. R., and K. W. Somerville, 1978: Heat stroke in a 'run for fun.' *Brit. Med. J.*, **1**, 1525–1526.

Nielsen, B., 1969: Thermoregulation in rest and exercise. *Acta Physiol. Scand.*, Suppl., **323**, 10–74.

Nishi, Y., and A. P. Gagge, 1970: Direct evaluation of convective heat transfer coefficient by naphthalene sublimation. *J. Appl. Physiol.*, **29**, 830–838.

Pennington, G., and C. Kay, 1984: *Round the Bays.* Whitcoulls, Christchurch, New Zealand, 81 pp.

Pugh, L. G. C. E., and F. A. Chrenko, 1966: The effective area of the human body with respect to direct solar radiation. *Ergonomics,* **9**, 63–67.

Richards, D., R. Richards, P. J. Schofield and V. Ross, 1979a: Biochemical and haematological changes in Sydney's *The Sun* city-to-surf fun runners. *Med. J. Aust.*, 2, 449–453.

——, ——, ——, ——, and J. R. Sutton, 1979b: Management of heat exhaustion in Sydney's *The Sun* city-to-surf fun runners. *Med. J. Aust.*, **2**, 457–461.

Richards, R., and D. Richards, 1980: Fatal heat stroke in a 'fun run.' *Med. J. Aust.*, **2**, 225–226.

——, ——, P. J. Schofield and J. R. Sutton, 1979c: Reducing the hazards in Sydney's *The Sun* city-to-surf runs, 1971 to 1979. *Med. J. Aust.*, **2**, 453–457.

Roller, W. L., and R. F. Goldman, 1967: Estimation of solar radiation environment. *Int. J. Biometeor.*, **11**, 329–336.

Sellers, W. D., 1965: *Physical Climatology,* University of Chicago Press, 272 pp.

Steadman, R. G., 1979: The assessment of sultriness. Part I: A temperature-humidity index based on human physiology and clothing science. *J. Appl. Meteor.*, **18**, 861–873.

Sutton, J. R., 1979: 40°C in fun runners. *Med. J. Aust.*, **2**, 463–464.

——, and O. Bar-Or, 1980: Thermal illness in fun running. *Amer. Heart. J.*, **100**, 778–781.

——, M. J. Coleman, A. P. Millar, L. Lazarus and P. Russo, 1972: The medical problems of mass participation in athletic competition. The 'city-to-surf' race. *Med. J. Aust.*, **2**, 127–133.

Taylor, P. F., 1956: Middle east trials: Meteorological observations (July–August, 1955). Rep. No. 67, Clothing and Stores Experimental Establishment, Directorate of Physiological and Biological Research, Ministry of Supply, U.K.

Terjung, W. H., and S. Louie, 1971: Potential solar radiation climates of man. *Ann. Assoc. Amer. Geogr.*, **61**, 481–500.

Weiner, J., and M. Khogali, 1980: A physiological body-cooling unit for treatment of heat stroke. *The Lancet,* **1**, 507–509.