14 Climates of Humans

Figure 14.1 On a very hot day in July, 2012, park users in St. Louis, United States, chose to sit in the shadow of the Gateway Arch, a slender sculpture that generates a narrow band of shade, rather than the adjacent sunlit grass (Credit: St. Louis Dispatch).

A commuter who walks to work leaves the comfort of home and embarks on a journey that may take her through areas that are: shaded or sunlit; next to walls that are warm; across grass that is cool; under trees that offer shelter from the rain; around a building corner where the wind suddenly accelerates; along roads where polluted air is inhaled and so on. As the individual encounters these different **microclimates**, the body responds by becoming warmer/cooler, shivering or sweating and reacts by changing pace, adjusting clothes, leaning into the wind or avoiding roads that are busy and polluted. Where individuals are stationary, they will tend to locate themselves in more favourable microclimates, such as the shelter of a building during windy weather. Figure 14.1 is a remarkable illustration of this behaviour in hot weather. Individuals have decided to avoid sunshine and gather in a narrow band of shade, exposed to the breeze off a nearby river; on the date of this image (July 4th, 2012) the city was in the middle of a **heatwave** and for the previous six days the maximum air temperature was $\geq$ 38°C. Persistent high temperatures can place great stress on the ability of the body to regulate its internal temperature, which is necessary for survival. The response of those outdoors here is to cluster within the shade, avoiding the nearby sunlit grass.

This chapter focuses on the bioclimates of humans with particular regard to the climates experienced in cities and on the outdoor thermal and wind environments. Air quality has been discussed in Chapter 11. Initially, we present the basic biophysical systems of humans and how they respond to variations in the ambient environment before discussing bioclimate and its parameters in more detail.

14.1 Basics

Humans make deliberate and imperceptible adjustments to an environment, which is in constantly in flux. One of the objectives of building and urban design is to manage this environment to minimize stress.

14.1.1 Managing Heat

Humans have a near constant deep body temperature of 37°C that is maintained by the body's thermoregulatory system, which ensures **homeostasis** under normal conditions. Thermoregulation incorporates a set of physiological and behavioural processes that manage heat exchange between the body and the ambient environment such that the net gain or loss of energy is close to zero. This is a complex feat that regulates the disposal of heat generated by internal metabolic processes in response to external environmental conditions including **radiation**, **sensible** and **latent heat** exchanges.

For an average adult at rest the heart beats 72 times a minute, causing 5,600 cm^3 of blood to flow through the body's circulatory system. This system is comprised of the pulmonary and systemic circuits; the former brings blood to the lungs for oxygenation and the latter transfers oxygenated blood to the body's tissues. This blood is carried via arteries that branch successively into smaller blood vessels until finally oxygen transfer occurs across the semi-permeable boundaries of capillaries into the adjacent tissue. While the blood leaves the heart through the aorta with radii of 10 mm at a rate of 0.3 m s^{-1}, it moves progressively slower as the blood vessels divide (becoming smaller) and the friction imposed by the vessel walls increases. The de-oxygenated blood is carried back to the heart in the veins.

The circulatory system also transfers heat from the body core to skin surface where heat exchange takes place either directly with the ambient atmosphere or indirectly via a layer of clothing. Thus, the energy balance of the body must account for heat exchanges internally (within the body) and externally (with the ambient environment).

The body can exert a considerable degree of control over the types and magnitudes of external exchanges through both automatic physiologic responses and voluntary actions. The former includes regulating blood flow, rates of sweating and metabolic activity. These can be complemented through a range of actions that require decisions, such as moving to a more comfortable place or altering clothing. Of course, spaces can also be designed to manage the ambient conditions (see Chapter 15); the most elaborate of these is the construction of buildings for shelter and comfort.

14.1.2 Maintaining Postural Balance

Humans control their postural balance while standing, walking or running by integrating the sensory, central nervous and muscular-skeletal systems. This process is complicated by the relatively small base (two feet) and location of the centre of body mass at approximately two-thirds of body height. The effect of the atmosphere on balance is related to wind, both its magnitude and variability.

The force (F_B) exerted by the wind on a person is related to the square of the mean wind velocity ($\overline{u}$),

$$F_B = \frac{\rho_a \overline{u}^2 C_D A_f}{2} \quad \left(\mathrm{kg\ m\ s^{-2}\ or\ N}\right) \qquad \textbf{Equation 14.1}$$

The drag coefficient (C_D) is a function of body shape and for the upright person is about 1.15 and 1.0 for front and side winds, respectively. However, C_D varies according to the nature of clothing and whether it 'hugs' the body or flaps about it. The area of the average body, projected in the direction of the wind (A_f) has a value of 2.4 m^2 and 1.6 m^2 for front and side winds, respectively.

An average adult pedestrian will begin to feel the force of a breeze at 6 m s^{-1}, which for a wind at the back corresponds to 62°N. Note that the force increases with the square of velocity; at 12 m s^{-1} walking becomes difficult and at 18 m s^{-1} an adult can be blown over. To adjust to this force, pedestrians lean into the breeze (see also Figure 4.1). In constant airflow, the angle (θ) required can be estimated from

$$\theta = \arctan\left(\frac{F_B}{m\, g}\right) \quad \text{(degrees)} \qquad \textbf{Equation 14.2}$$

The upright stability of the body is due to its mass (m) times the acceleration due to gravity (g) but when the mean wind $\overline{u}$ exceeds 15 m s^{-1} an adult pedestrian must lean 8° into a headwind, which is potentially unstable. However, in **turbulent** airflow where speed and direction change rapidly, maintaining stability at a much lower mean wind speed is more difficult (Bottema, 1993).

14.2 The Human Energy Balance

The energy balance of a human must account for: the transfer of heat from the body core to the skin surface and; between the skin surface and the ambient environment. The latter may be modulated by clothing.

14.2.1 Internal Energy Exchanges

The heat generated when metabolized food is chemically converted to fuel both internal (e.g. breathing) and external (e.g. running) physical activity is termed **metabolic heat**. While some of this energy is expended as mechanical energy (such as walking uphill), the great majority (> 95%) is converted to heat that must be dissipated to the ambient environment. The magnitude of the metabolic rate depends strongly on the level of exertion (Table 14.1). The lowest value occurs when an adult is sleeping (70 W) and is about 100 W when awake and comfortably at rest; however, it can be as high as 800 W during intense physical activity. Shivering describes involuntary muscular activity initiated when the body loses heat too quickly and increases the metabolic rate.

Table 14.1 The metabolic rate (Q_M in Equation 14.5) associated with different levels of physical activity (Source: ASHRAE, 2009).

Activity	Metabolic rate	
	(W)	(W m^{-2})
Resting		
Sleeping	70	40
Seated, quiet	110	60
Standing relaxed	130	70
Walking on a level surface		
Pace 0.9 m s^{-1}	210	115
Pace 1.2 m s^{-1}	270	150
Pace 1.8 m s^{-1}	400	220
Office		
Writing	110	60
Walking about	180	100
Lifting/packing	220	120
Occupational		
Cooking	170–210	95–115
Housecleaning	210–360	115–200
Handling 50 kg bags	420	235
Pick and shovel work	420–500	235–280
Leisure		
Dancing	250–460	140–255
Tennis	380–490	210–270
Basketball	520–880	290–440

Metabolic heat is transferred to the body's outer surface through the respiratory and circulatory systems. Rates of breathing vary with levels of exertion and oxygen demand (Table 14.2); an adult male at rest exchanges about 0.7 m^3 h^{-1}, so if the air temperature were 20°C, the sensible heat exchange would average just 4 W. Exhaled breath is also close to saturation at 37°C (about 44 g m^{-3}) but the heat transfer would depend greatly on the **relative humidity** of the ambient atmosphere; if the relative humidity were just 40% at 20°C, about 20 W would be transferred by breathing at rest. Naturally, these exchanges would increase in the same ambient conditions if the individual is engaged in heavy work and breathing more often (~3–4 m^3 h^{-1}). However, typically the dominant means of exchange internally is by blood flow,

$$Q_{core \rightarrow skin} = \frac{v_b C_b \left(T_{core} - \overline{T}_{skin} \right)}{A_{body}} \qquad (\mathrm{W\ m^{-2}})$$

Equation 14.3

where v_b and C_b are the flow rate (m^3 s^{-1}) and **heat capacity** of blood (3617 J m^{-3} K^{-1}), T_{core} is the temperature of the body core and $\overline{T}_{skin}$ is the average skin temperature. When the body is at rest and comfortable, $\overline{T}_{skin}$ is 34°C (about 3 K lower than T_{core}) and blood flow to the skin is between 3300 to 8300 mm^{-3} s^{-1} hence, between 36 and 90 W is exchanged.

One of the first responses of the body to excessive heat loss/gain is through **vasomotor control**, which regulates blood flow to the skin organ and thereby manages $\overline{T}_{skin}$. **Vasodilation** causes the blood vessels

Table 14.2 Human inhalation rates by activity level (Modified after: Moya et al., 2011).

Level of exertion	Resting (m^3 h^{-1})	Light (m^3 h^{-1})	Moderate (m^3 h^{-1})	Heavy (m^3 h^{-1})
Adult female	0.3	0.5	1.6	2.9
Adult male	0.7	0.8	2.5	4.8
Average adult	0.5	0.6	2.1	3.9
Child 6 years	0.4	0.8	2.0	2.4
Child 10 years	0.4	1.0	3.2	4.2

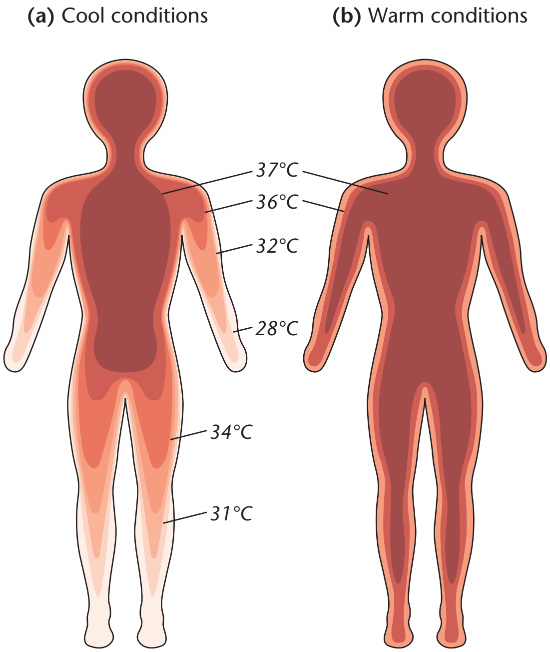

Figure 14.2 The temperature distribution in the body during cool and warm conditions. In cool conditions, the warmest temperature (37°C) is confined to the head and trunk only. The temperature of the subcutaneous tissue for the hands and feet is < 28°C. In a warm environment the warm core temperature is found over much of the body (Modified after: Mount, 1979).

to expand, increasing the rate of blood flow to the skin, while **vasoconstriction** does the opposite. In this way the body can manage heat loss by altering the **insulation** provided by the body tissue and regulating $\left(T_{\text{core}} - \overline{T}_{\text{skin}}\right)$. The effects of vasomotor control can be seen in Figure 14.2 which shows the temperature distribution in the body under cold and warm conditions. Note how much cooler the limbs become when the environment is cool and the body retains heat in its core; $\overline{T}_{\text{skin}}$ varies considerably, it is lowest where the potential heat loss to the ambient environment is greatest and the distance from the core is furthest.

Body Area

The intensity of exchanges at the body's outer surface (that is the energy **flux density**) is expressed in relation to the surface area of the body, which can be estimated using the DuBois relationship,

$$A_{\text{body}} = 0.007184 m^{0.425} H^{0.725} \qquad (\text{m}^2)$$

Equation 14.4

where m is mass (kg) and H is height (m) of the body. The surface area of an upright average adult male is about 1.8 m^2 based on a weight of 70 kg and a height of 1.65 m. Adult males are typically both taller and heavier (by up to 10%) than female; equivalent surface areas for a typical female and 10-year old child are 1.6 m^2 and 1.1 m^2, respectively. However, there is considerable variation across ages and cultures. In many studies the human form is represented by a cylinder with a height of 1.65 m and a radius of 0.12 m; this simplifies calculations and allows research on heat transfer from simple geometric shapes to be transferred to the study of human-environment exchanges.

The shape of the body and its parts (segments) plays an important role in managing heat exchange by controlling area of the outer surface exposed to the environment. For example drawing in the limbs and curling up converts the body shape from cylinder (area of about 1.8 m^2 for an adult male) into a more sphere-like shape (area of about 0.9 m^2); as the volume of the body remains the same, the effect of decreasing the outer surface is to minimize heat loss. Similarly, extending the limbs maximizes surface area and heat loss. The appendages (arms, legs, fingers and toes) are ideally suited to heat loss as they have a high area to volume ratio. As a result surface heat exchange is large but their capacity to store energy in the enclosed mass is small. Consider the implication for **heat storage**: the area to volume ratio for the torso is 17 but is 135 for the hands so for the same rate of heat loss the hands will cool eight times more quickly. Not surprisingly, it is the appendages (especially the fingers and toes) that experience the greatest temperature fluctuations and in extreme cold climates are the first to experience frostbite as the body withdraws blood flow in an effort to maintain core temperature.

14.2.2 External Energy Exchanges

The energy exchanges with the ambient environment occur across the outer surface of the body. These can be expressed in the form of an energy balance similar to those presented elsewhere in this book,

$$Q^* + Q_M = Q_H + Q_E + Q_G + \Delta Q_S \qquad (\text{W m}^{-2})$$

Equation 14.5

where each term is expressed as an average over the body's outer envelope, which may be the skin or the clothing surface. This energy balance is distinguished by internal energy supplied by the body's metabolism (Q_M), which varies according to the level of physical activity (Table 14.1). The healthy body regulates these fluxes so that heat storage is minimal ($\Delta Q_S \approx 0$). This control is necessary to ensure a near constant core temperature of approximately 37°C; the maximum allowable deviation of T_{core} is approximately ±3 K, with a greater tolerance on the cold side.

The sensible heat exchange via **conduction** (Q_G) is normally a relatively small term as typically just a small proportion of the body's surface area is in contact with a solid surface. However, there may be situations where the body is prone or immersed in water and this term is significant and must be included. For our purposes here it may be ignored.

Insulation/Resistance and Heat Transfer Coefficients

In biometeorological studies, energy fluxes employ insulation/**resistance** terms and transfer coefficients; the former are used to account for clothing which has a limited depth and the latter for exchanges with the ambient environment.

The effect of clothing is to trap a layer of still air against the skin surface, which impedes the transfer of sensible and latent heat (i.e. it offers resistance). A typical clothing ensemble (trousers, shirt and sweater) provides a thermal insulation (I_{cl}) of about 0.155 K m^2 W^{-1}. The equivalent thermal resistance can be assessed in relation to the properties of still air; at 20°C and 100 kPa, air has a heat capacity (C_a) of 1220 J K^{-1} m^{-3} and a thermal resistance (r_a) of 470 s m^{-1} (Monteith and Unsworth, 2008), so a 1 mm layer has an insulation value of 0.0385 K m^2 W^{-1} and the typical clothing ensemble is the equivalent of a cushion of 4 mm of still air. The resistance to **evaporation** provided by clothing (kPa m^2 W^{-1}) varies between 0.15 and 0.30 for common ensembles (Parsons, 2003).

At the outer surface of the body, energy exchanges with the ambient environment may be expressed using transfer coefficients (W m^{-2} K^{-1}) and an appropriate gradient, for example the **sensible heat flux density** (Q_H) can be expressed as:

$$Q_H = h_c \Delta T \qquad (\text{W m}^{-2})$$

Equation 14.6

where h_c is the convective heat transfer coefficient and ΔT is the difference in temperature between the **active surface** (here skin or cloth) and the ambient air. Values for these coefficients are established using thermal manikins to represent the human body (and its segments) in various postures and clothing ensembles. These manikins can be exposed to ambient conditions in a controlled laboratory environment where radiation, air temperature, humidity and airflow can be regulated and heat loss measured.

14.2.3 The Radiation Budget

The radiation budget of an individual is the same as that for the **surface radiation budget** of any natural surface, but its application to humans is made more complicated by body shape,

$$Q^* = (S + D)(1 - \alpha) + L_\downarrow - L_\uparrow \qquad (\text{W m}^{-2})$$

Equation 14.7

The direct **shortwave** radiation (S) received by an individual will depend on the area of the body as viewed from vantage point of the Sun. The intercepted solar radiation on an upright individual can be estimated by calculating the shadow area (A_s) generated by a cylinder that has the approximate dimensions of the human body,

$$A_s = (2rH)\cot\beta + \pi r^2 \qquad (\text{m}^2)$$

Equation 14.8

The controlling variable here is the **solar altitude** (β), which varies with latitude, time of year and time of day. If the Sun were directly overhead (β = 90º) then the only area in shade is directly underneath the body ($A_s = \pi r^2$) and all the available solar radiation would fall on the crown of the head and the shoulders. By comparison, when solar altitude decreases, the shadow area increases and S is spread over the illuminated limbs and torso. Moving from sunlight into shadow and *vice versa* will change the body's energy receipt significantly.

Diffuse irradiance (D) can be treated as though it originated from a notional 'hemisphere' that surrounds the body (Figure 14.3) where D is a function of the strength of the radiation source and the proportion of the flux leaving that source incident on the body surface (that is the **view factor**, ψ). If one were to treat these radiation sources as simply the sky and the surrounding surface environment, then

$$D = D_{sky} + D_{env} = D_0\,\psi_{sky} + K_\uparrow \psi_{env} \qquad (\text{W m}^{-2})$$

Equation 14.9

where D_0 represents diffuse radiation received on flat surface with $\psi_{sky} = 1$ and $K_\uparrow$ represents the

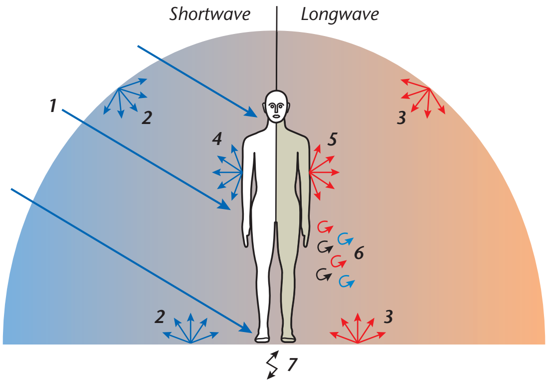

Figure 14.3 Energy exchanges at the surface of the human body. These include: (1) direct shortwave radiation that impinges on the sunlit part of the body; (2) diffuse shortwave radiation that originates from the sky as a result of scattering and from the ground as a result of reflection; (3) diffuse longwave radiation that is emitted from the sky vault and from the ground; (4) reflected shortwave radiation that is controlled by the albedo of the clothed body; (5) emitted longwave radiation which is a function of surface temperature; (6) convective heat loss by sensible and latent heat exchange with the ambient air that is partly a function of wind speed and; (7) conductive heat exchange with the ground through physical contact.

reflected radiation from the environment that impinges on the body. For an individual standing on an extensive horizontal surface ψ_{sky} and ψ_{env} will be approximately equal but this will not be the case in densely built urban environments. An individual walking through a city street intercepts $K_{\uparrow}$ from a variety of **facets** of a wide range of **fabrics** (glass, asphalt, concrete, grass, etc.) each with a unique solar radiation receipt and **albedo** (α). Integrating the diffuse radiation from all of these sources is a complex task but tools are available (e.g. Matzarakis et al., 2010).

The albedo (α) of skin regulates the **absorption** of solar radiation. α depends on pigmentation and skin blood flow. The spectral reflectivity of skin at visible wavelengths (0.4–0.7 μm) varies from 0.15 to 0.35 as pigmentation changes from dark to light and; between 0.8 and 1.2 μm, but increases sharply to 0.6 between 0.8 and 1.2 μm before falling at longer wavelengths. However, α can be readily changed through choice of clothing.

Longwave Radiation

Longwave radiation can be treated in the same way as diffuse shortwave radiation,

$$L_{\downarrow} = L_{\downarrow sky} + L_{\downarrow env} = L_{\downarrow 0}\, \psi_{sky} + L_{\uparrow}\psi_{env} \qquad (\mathrm{W\ m^{-2}})$$

Equation 14.10

where $L{\downarrow}_0$ represents **longwave** radiation receipt at a surface with ψ_{sky} = 1 and $L_{\uparrow}$ is that emitted by surrounding facets. $L_{\downarrow env}$ is a function of facet **emissivity** and surface temperature; at night, the contribution of $L_{\downarrow env}$ in cities is especially noticeable owing to the **surface urban heat island**. The human body reflects a very small proportion of $L_{\downarrow}$ (less than 3%) and consequently is a near perfect emitter at these same wavelengths.

Net Radiation

The diversity of the radiation environment is apparent in Figure 14.4, which shows two urban landscapes that are distinguished by the vegetative **surface cover**, the construction materials and built geometry. The patterns of sunlight and shade and the differing **surface energy balances** result in a great diversity of microclimates that are evident in the surface temperatures. Figure 14.4a and b shows a plaza where there is little shade and the surrounding surfaces have a nearly uniform temperature which is close to that of the people. Figure 14.4c and d shows a more complex urban setting comprised of warm (road and sunlit facades) and cool (grass and shaded pavements) surface that create a heterogeneous environment; the radiation experience of an individual will vary greatly depending on their position in this landscape.

For many practical purposes it can be useful to summarize the external radiative environment using a **mean radiant temperature** (T_{MRT}), the surface temperature of a perfect emitter (**blackbody**) that generates the same radiation as that absorbed by the body,

$$T_{\mathrm{MRT}} = \sqrt[4]{\left[\left(K_{\downarrow}\alpha\right) + \left(L_{\downarrow}\varepsilon\right)\right]/\sigma} \qquad (\mathrm{K})$$

Equation 14.11

Here, the albedo (α) and emissivity (ε) parameters are those for outer (clothed) surface of the body and σ is the Stefan-Boltzmann constant. The measurement of T_{MRT} is done using a globe thermometer that consists of a conventional thermometer housed in a spherical casing that has specific radiative properties. The resulting temperature is converted to T_{MRT} by solving the surface energy balance of the spherical enclosure.

Figure 14.4 Visible and infrared (thermal) images for two urban landscapes in Berlin, Germany illustrating the radiation environment (Credit: F. Meier; with permission).

In indoor situations where there is no shortwave radiation component, and little variation in surface temperatures, whole body **net allwave radiation** (Q^*) can be obtained from

$$Q^* = f_{cl}\, h_r (T_{0,cl} - T_{MRT}) \qquad (\mathrm{W\ m^{-2}})$$

Equation 14.12

where $T_{0,cl}$ is the surface temperature of the clothing and T_{MRT} is the mean radiant temperature. The coefficient of radiative heat transfer (h_r) is taken as 4.7 W m^{-2} K^{-1} for the whole body and f_{cl} is a clothing area factor. The latter is a simple ratio of the clothed surface area to that of the nude body (A_{body}); for standard work clothing f_{cl} equals 1.31. If ($T_{cl} - T_{MRT}$) were 10 K an individual in a typical work setting will lose 61 W m^{-2}.

14.2.4 Sensible Heat Flux

The sensible heat flux density (Q_H) occurs by breathing and by convective exchange at the skin surface, although the latter is modulated by clothing.

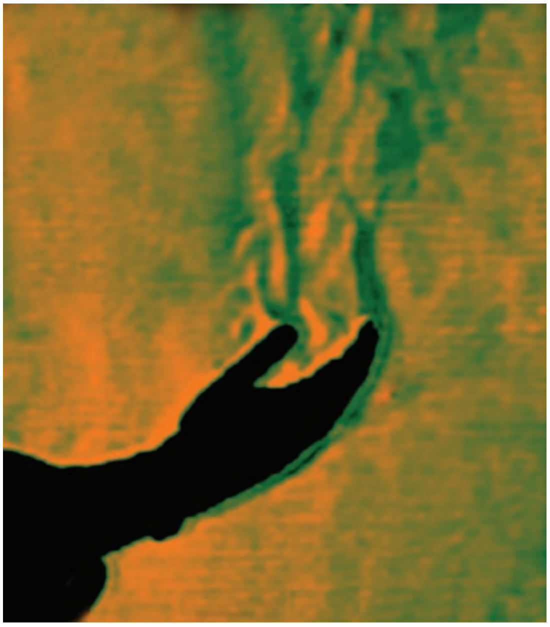

Figure 14.5 A Schlieren image, which shows distortions in optical depth produced by air currents reveal the nature of thermal turbulence generated by the extended hand in a still atmosphere (Credit: G. Settles; CC3.0).

The breathing rate is a function of activity levels (Table 14.2) but even an individual engaged in moderate activity (exchanging 2.1 m^3 h^{-1}) in an environment at 20°C will lose about 6 W m^{-2} or < 5% of the metabolic energy generated. So, the majority of sensible heat transfer occurs via the outer surface,

$$Q_H = f_{cl}\, h_c (T_{cl} - T_a) \qquad (\mathrm{W\ m^{-2}}) \qquad \textbf{Equation 14.13}$$

where h_c is the coefficient of heat transfer; its value varies according to: the magnitude of the temperature difference, which regulates thermal turbulence production (see Section 4.1.2) and; ambient airflow ($\overline{u}$), which causes mechanical turbulence production.

Thermal turbulence is generated as the human body warms adjacent air which becomes buoyant and rises forming a vertical stream of heated air (Figure 14.5). If there is little air motion thermal turbulence dominates but is not an effective means of heat loss. Increasing airflow disturbs the air around the body and generates mixing. Mechanical turbulence dominates once the ambient airflow exceeds > 0.2 m s^{-1}. Work on heat exchanges using a thermal manikin suggests that $h_c = 10.3\overline{u}^{0.6}$ that is suited for airflow $0.2 < \overline{u} < 0.8$ m s^{-1} in typical indoor situations (de Dear et al., 1997). Note that the value of h_c is not linear, at 0.2 m s^{-1} it equals 3.92 but at 0.8 m s^{-1} it equals 9.01 W m^{-2} K^{-1}; in other words, even low airflow dramatically improves heat loss. Consequently, simple appliances like electric fans can make individuals feel more comfortable in hot weather.

Net allwave radiation and sensible heat fluxes at the exterior of clothing can be combined (Parsons, 2003) by summing the heat coefficients for each and creating the operative temperature (T_o),

$$Q^* + Q_H = f_{cl}\, h (T_{cl} - T_o) \qquad (\mathrm{W\ m^{-2}})$$

Equation 14.14

where,

$$T_0 = \frac{h_r T_{\mathrm{MRT}} + h_c T_a}{h_r + h_c} \qquad (\mathrm{K}) \qquad \textbf{Equation 14.15}$$

and $h = h_r + h_c$. Similarly, the 'dry' heat exchange between the skin and T_o

$$Q^* + Q_H = \frac{(T_{skin} - T_o)}{I_{cl} + \left(\frac{1}{f_{cl} h}\right)} \qquad (\mathrm{W\ m^{-2}})$$

Equation 14.16

where the effects of clothing are captured by a single insulation value (I_{cl}).

14.2.5 Latent Heat Flux

Latent heat exchange (Q_E) occurs via **respiration** and via the skin. Exhaled air is close to saturation at core temperature (with a **vapour pressure** (e) of 91 kPa). If the ambient air temperature is 20°C and a relative humidity of 50%, then e_a = 16 kPa; a breathing rate of 2.1 m^3 h^{-1} would exchange approximately 75 g of water vapour, which would represent just 30 W m^{-2}.

At the skin surface, evaporation occurs by **diffusion** through the skin membrane and directly as water is secreted by the sweat glands. The former account for a small proportion of heat loss by evaporation, estimated at 6%. Regulatory sweating is the main avenue of Q_E but estimating its magnitude is complicated as the availability of water at the skin surface is governed by involuntary action,

$$Q_E = \frac{w(e_{skin} - e_a)}{I_{(v)cl} + \left(\frac{1}{f_{cl} h_v}\right)} \qquad (\mathrm{W\ m^{-2}}) \qquad \textbf{Equation 14.17}$$

where, e_{skin} and e_a are the vapour pressure at the skin and the ambient air, respectively; the former is treated as the saturation value of e at skin temperature. The insulation value of clothing with regard to vapour ($I_{(v)cl}$) is typically 0.015 m^2 kPa W^{-1} for work clothing. The latent heat transfer coefficient (h_v) is linked with that for sensible heat (h_c), via the Lewis Relation with a value of about 16.5 K kPa^{-1} for typical indoor conditions (Parsons, 2003). Hence, if airflow ($\overline{u}$) equals 0.5 m s^{-1}, h_c is approximately 6.80 W m^{-2} K^{-1} and h_v equals 112.13 W m^{-2} kPa^{-1}. The availability of water is represented by skin wettedness (w), which is calculated from the residual in the energy balance equation (Equation 14.5) when $\Delta Q_S \approx 0$. Essentially, w is the ratio of the latent heat required to balance the equation compared to the maximum allowable latent heat exchange in the ambient conditions (Parsons, 2003).

Regulatory sweating is the main means by which the body manages its heat exchanges at high ambient air temperatures. Approximately 85% of human skin can be made 'wet' through the excretion of water through sweat glands onto the skin surface. Over the trunk and limbs there are 1–2 glands per mm^2, for the palms of the hand and sole of the feet there are 20 per mm^2. However, the maximum sustainable heat loss through Q_E is about 380 W m^{-2} (equivalent to about 1 kg h^{-1} or 2.5% of the body's water content) if it is supplemented by water intake. A loss of 10.5 kg of water for a 70 kg man will cause circulatory failure and death; even half this loss results in headaches and loss of concentration.

14.2.6 Clothing

Exchanges between the skin surface and the atmosphere are modulated by clothing, which acts as a new 'surface' that intervenes between the skin and the ambient environment. Clothing modifies the shape of the body and acts as a barrier to solar radiation receipt by reflecting, absorbing and transmitting proportions of the intercepted flux. The magnitude of each depends on the incident flux and the colour and density of cloth. Clothing also exchanges longwave radiation with both the environment and the body it encloses. It also impedes the **turbulent fluxes** by introducing an additional resistance to transfer. Most clothing is designed to protect the body from excessive sensible heat loss and this is managed through the choice of clothing (the insulation values of various garments are listed in Table 14.3). Note that the values change with both the nature of the material and the extent of the body that it covers. The overall effect of clothing on the human energy balance is evaluated as a product of the ensemble, that is the shoes, socks, undergarments, trousers, shirt, etc. that fully clothe the person.

Table 14.3 The dry thermal insulation values (I_{cl}) for individual clothing garments and for selected work clothing ensembles (Source: Parsons, 2003). These data are also shown in the form of the equivalent depth of still air, 1 mm has a value of approximately 3.85×10^{-2} K m^2 W^{-1}.

Garment	Insulation I_{cl} (K m^2 W^{-1})	Depth of still air (mm)
Individual clothing layers		
Underwear (e.g. underpants, T-shirt, slip)	0.03–0.10	0.15–0.52
Footwear (e.g. socks, slippers, boots)	0.02–0.10	0.10–0.52
Shirts/Blouses (e.g. short and sleeve shirt, sweatshirt)	0.15–0.30	0.78–1.55
Trousers (e.g. shorts, trousers, overalls)	0.06–0.28	0.31–1.45
Sweaters/Jackets	0.20–0.35	1.03–1.81
Dresses/skirts	0.15–0.40	0.78–2.07
Outdoor clothing (coat, parka)	0.55–0.70	2.84–3.62
Clothing ensemble		
Underwear with long sleeves and legs, shirt, trousers, jacket, socks, shoes	0.155	5.17
Underwear with short sleeves and legs, shirt, trousers, jacket, thermojacket and trousers, socks, shoes	0.225	7.50
Underwear with long sleeves and legs, thermojacket and trousers, parka with heavy quilting, socks, shoes, cap, gloves	0.395	13.17

The properties of traditional clothing usually reflect the climatic environment of the wearer. In hot climate where overheating is an issue, the objective is to limit heat gain and maximize heat loss. Where it is hot and humid, clothing that offers the least resistance to the transfer of heat and moisture is desirable; ideally, the fabric has a wide weave and is loose around the body to allow for circulation. In hot and dry climates, the primary purpose of clothing is to protect the body from solar radiation, which is best achieved through materials with a high **reflectivity**. Although it may appear counterintuitive, darker clothing can achieve the same effect if there is an additional layer beneath the outer layer, so that the heated fabric is not in contact with the skin surface. In these climates it is the head and shoulders that receive the brunt of solar radiation during the hottest period of the day so head cover is needed.

In colder climates, the emphasis shifts towards limiting heat loss so clothing ensembles that provide higher resistance values are desirable. In climates that are both cold and windy, heat loss is accentuated as the laminar layer adjacent to the skin surface is shallow and offers limited protection. Layers of clothing act to increase the depth of this layer by trapping air close to the skin. The coats of animals that have thick furs are also employed for the same purpose.

14.3 Thermal Stress and Body Strain

The terms in the energy balance equation (Equation 14.5) adjust continuously as the environment to which the body is exposed changes and the body responds. Altogether, there are six variables that regulate these exchanges: radiation, air temperature, humidity and wind speed, which represent the exposure environment and; metabolism and clothing, which represent the response of the individual. The combination of the environmental variables imposes a **thermal stress** to which the body responds, resulting in **thermal strain** as it seeks to ensure that ΔQ_S is close to zero. For example, in warm weather, low wind speed and a high relative humidity causes considerable stress to which the body responds by sweating. The degree of strain may be evident by the gleam of sweat that has been excreted onto the skin surface but has not evaporated resulting in a feeling of discomfort.

To understand the relationship between the stresses and strains, it is helpful to consider the case of a person placed in a controlled indoor setting (a climate chamber). In this setting, the ambient air temperature, humidity and velocity are fixed, the surrounding wall surfaces have a uniform temperature equal to the air temperature (that is, $T_{MRT} = T_a$) and the activity levels and clothing of the occupant are prescribed. In these conditions, the physiologic response of the occupant can be evaluated by modifying the temperature of the chamber only (Figure 14.6). A lightly clothed and sedentary individual when exposed to an environment with a wind speed of 0.1 m s^{-1}, a relative humidity of 50%, and T_a of 20°C experiences little

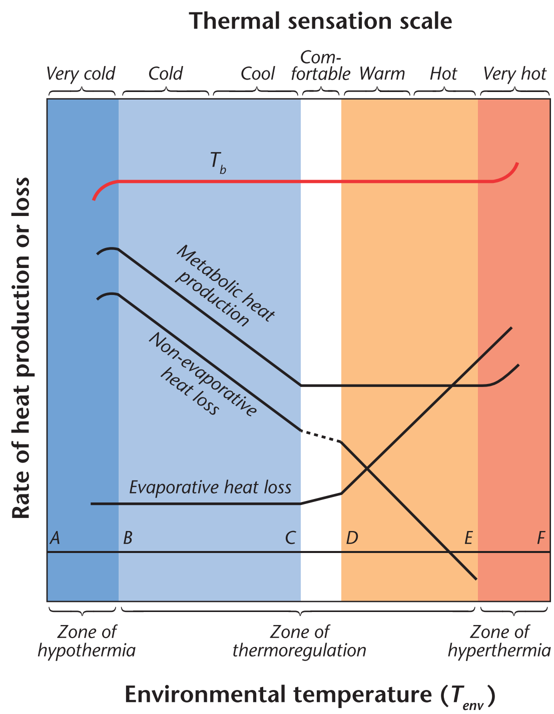

Figure 14.6 Simplified relationships between energy exchanges and a changing environment as represented by an environmental temperature, which represents the ambient conditions. To maintain a constant deep body temperature of 37°C the body must manage its exchanges. When the body is comfortable (C-D), the body has little difficulty in disposing of the metabolic heat (Q_M) it generates. When the ambient conditions cool (C to B) the body generates energy (Q_M) to compensate for radiative and sensible heat loss ($Q^* + Q_H$). When the ambient conditions warm (D to E), heat loss from the body via ($Q^* + Q_H$) diminishes and the body responds by increasing heat loss through regulatory sweating (Q_E). The thermal sensations associated with these changes are described in terms of varying degrees of cold or warm. At the extremes (B to A and E to F), the body cannot maintain a constant deep body temperature and experiences hypothermia or hyperthermia (Modified after: Mount, 1978).

strain. In these circumstances, the body does not sweat, Q_E is minimal and sensible heat loss (Q_H) dominates. Skin temperature is about 33°C. These conditions may be described as comfortable as most will express satisfaction with the environmental conditions.

Cold

Reducing T_a induces the thermal sensation of cooling and the body responds by managing heat loss while increasing heat generation. The first response will be to employ vasoconstriction to reduce skin temperature, which depresses Q_H and $L_\uparrow$, and the environment feels cool. If T_a continues to fall, it begins to feel cold ('goosebumps' appear on skin) and the body will take actions to increase Q_M such as shivering to offset heat losses. The temperature of the skin and subcutaneous tissue cools unevenly in response to heat loss (Figure 14.2): the lowest temperatures are found distant from the core, especially in extremities such as toes and fingers. A further temperature drop will be sensed as very cold: eventually the body will not be able to sustain heat loss ($\Delta Q_S < 0$) and T_{core} starts to fall leading to hypothermia.

Warm

On the warm side of comfort, the body must dispose of heat so internal heat generation (Q_M) is maintained at a base level. Vasodilation can enhance Q_H and $L_\uparrow$ by raising T_{skin} but this has a maximum value of 36°C, which limits the effectiveness of this response to conditions that feel slightly warm. The most effective mechanism for coping with warm and hot conditions is regulatory sweating and evaporation (Q_E). Eventually, increases in T_a will result in a net heat gain ($\Delta Q_S > 0$) as the body's ability to dispose of heat has been overwhelmed. These very hot conditions cause T_{core} to rise, which increases the metabolic rate and internal heat generated; if this continues the thermoregulation system fails and hyperthermia ensues.

The circumstances that govern the onset of hyper- and hypothermia will vary from individual to individual, depending primarily on their age and health. However, from a public health perspective, there is a clear relationship between mortality and air temperature. Figure 14.7 shows a U-shaped curve that captures the statistical relationship between daily mortality and daily maximum air temperature for Manhattan, United States, based on historical records. Notice that when temperature lies within the zone from 17.2 to 21.7°C, there is no discernible effect but outside these bounds, mortality is correlated with the magnitude of the deviation. This pattern is repeated in other places but the zone of no impact shifts higher (lower) in warmer (cooler) climate, which is taken to reflect a degree of adaption by the population to the climate at a place (Keatinge et al., 2000).

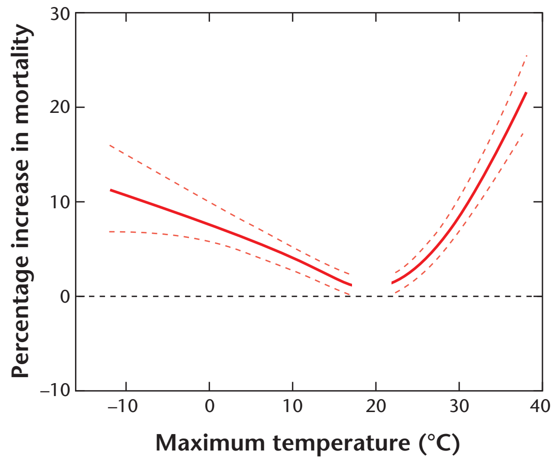

Figure 14.7 Exposure–response curve for temperature-related mortality in Manhattan, New York, United States. The solid line shows the central estimates. The dashed line shows the 95% confidence intervals (Source: Li et al., 2013; Reprinted by permission from Macmillan Publishers Ltd: Nature Climate Change, © 2013).

14.4 Thermal Comfort and Its Assessment

Thermal comfort is defined as *the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation*[1]. Thus a comfortable individual *feels* neither too warm nor too cold and has no desire to either alter their clothing/activity levels or to modify the environment to which they are exposed. Crucially, this definition highlights the role of psychology in assessing one's thermal state. It follows then that although thermal equilibrium may be a necessary condition for comfort, it is not a sufficient one. Moreover, deviations from comfort engender thermal sensations of 'warming' or of 'cooling' that is both a function of biophysical parameters (such as sweat rate or skin temperature) and individual

[1] ANSI/ASHRAE Standard 55-2010, Thermal Environmental Conditions for Human Occupancy

preferences, which may be associated with cultural contexts, thermal expectations and acclimatization. Much biometeorological research has focused on linking these expressed thermal sensations to measures of strains (body responses) and of stresses (environmental conditions).

14.4.1 Indoors

There has been exhaustive research carried out on comfort for the purpose of finding the ideal indoor climate that is suited to a particular occupation (such as office work) and the energy needed to create and sustain these conditions. This research is based on two distinct approaches that record the thermal sensations of individuals exposed to different climate conditions.

Climate Chamber Research

A climate chamber is an enclosed space within which all aspects of the ambient climate (surface and air temperature, relative humidity and airflow) can be managed precisely (Figure 14.6). Subjects are exposed to regulated climate settings wearing specified clothing ensembles and engage in activity levels that exemplify a given work setting. The physical responses and thermal sensations of the subjects are recorded in response to environmental settings. In these controlled settings, the measured physical responses (e.g. skin temperature) and expressed thermal sensations (e.g. warm or cold) are remarkably robust; they have provided a biophysical basis for delimiting conditions that are considered to be universally comfortable.

The widely employed **Predicted Mean Vote** (PMV) model of Fanger is based on this research. PMV is based on a derivation of the energy balance which quantifies the deviation of the body's net energy flux in the exposure environment from that if the body experienced minimal strain (i.e. comfort) doing the same activity and wearing the same clothes (van Hoof, 2008). This deviation is correlated with the thermal sensation expressed as a 'vote' by subjects to create a linear scale. PMV values range from very cold (−3) to very hot (+3); these scores identify the thermal sensation expressed by the majority of those exposed to these conditions (Table 14.4). For example, PMV values of ±0.5 are comfortable, as less than 10% of the population should perceive those conditions as either too warm or too cool. Figure 14.8a shows this zone plotted on a psychrometric chart, with air temperature and humidity. The value of this work is that it outlines universal comfort zones suited to particular work practices. For example, a design climate suitable for an office is one in which wind velocity is low (< 0.2 m s^{-1}), air temperature is between 20°C and 24°C and relative humidity is 40–60%.

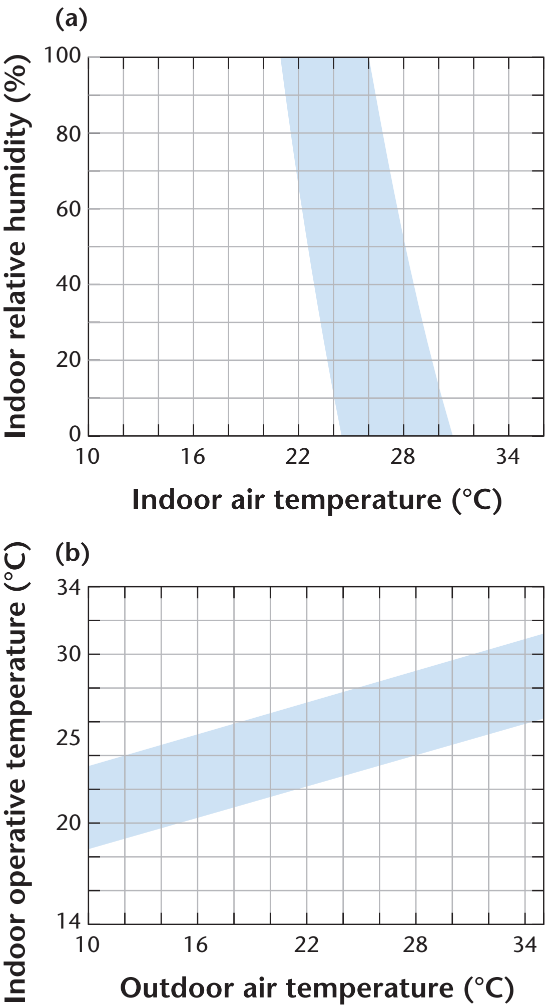

Figure 14.8 Comfort zone in blue, representing 90% acceptability, plotted according to ASHRAE standards: **(a)** based on Predicted Mean Vote (PMV) values of ±0.5 and plotted according to air temperature and humidity (i.e. a psychrometric chart) and **(b)** based on the adaptive method and plotted according to indoor operative temperature and prevailing mean outdoor temperature. The targets shows the same set of circumstances on each (Source: CBE Thermal Comfort Tool for ASHRAE 55 http://comfort.cbe.berkeley.edu/; CC3.0)

Table 14.4 Ranges of the thermal indexes Predicted Mean Vote (PMV) and physiological equivalent temperature (PET) for different grades of thermal perception by human beings and physiological stress on human beings (Modified after: Matzarakis et al., 1999).

PMV	PET	Thermal perception	Grade of physiological stress	Universal Thermal Climate Index (UTCI) (°C) range	Physiological responses
		Very cold	Extreme cold stress	< 40	Decrease in core temperature
−3.5	4			−27 to −40	Shivering, average skin temperature will fall below 0°C if exposure is sustained
−2.5	8	Cold	Strong cold stress	−13 to −27	Face temperature < 7°C (numbness), core to skin temperature gradient increases
		Cool	Moderate cold stress	0 to −13	Vasoconstriction, exposed skin temperature < 15°C
−1.5	13	Slightly cool	Slight cold stress	+9 to 0	Localized cooling, need for gloves
−0.5	18				
		Comfortable	No thermal stress	+9 to +26	Comfortable, sweat rate < 100 g h^{-1}
0.5	23				
1.5	29	Slightly warm	Slight heat stress	+26 to +32	Slight heat stress
		Warm	Moderate heat stress	+32 to +38	Positive change in rate of sweating, and of skin temperature
2.5	35	Hot	Strong heat stress	+32 to +38	Sweat rate > 200 g h^{-1}
3.5	41			+38 to +46	Small core to skin temperature gradient (< 1 K). Sweat rate increase (> 650 g h^{-1} at limit)
		Very hot	Extreme heat stress	> 46	Increase in core temperature

Naturally Ventilated Buildings

A complementary approach measures the environmental conditions and the thermal sensations of subjects in actual work settings selected to represent different climate settings, cultural contexts and building types. This work has shown a significant difference between the responses of individuals in office buildings that have heating and cooling systems from those that are naturally ventilated (de Dear and Brager, 2002). While the responses of the former group conform closely to the results of climate chamber work, those of the latter are closely linked to outdoor air temperature. These differences are explained by a process of cultural and psychological acclimatization that adjusts the human 'thermostat' so that individuals are prepared to accept lower/warmer temperatures in winter/summer and adjust accordingly. In strongly managed climates (represented by the climate chamber approach), these adjustments do not occur; thus effect of managing climates to narrow parameter values is to heighten expectations. The key finding from this work has been establishing a link between the outdoor temperature, the indoor temperature and expressed satisfaction (Figure 14.8b). This approach has informed the development of models of adaptive comfort, which allow for greater thermal tolerance by building occupants; this work has significant implications for assessments of building energy demand (Halawaa and van Hoof, 2012).

14.4.2 Outdoors

Although there have been many attempts to transfer the knowledge and techniques of indoor comfort to the outdoor environment, the process is fraught with difficulty for a number of reasons.

Firstly, the outdoor environment is a great deal more variable over space and time so that conditions are rarely static. As a consequence, the body's biophysical systems do not come into equilibrium with the environment and are constantly adjusting. This process is readily observed in Figure 14.9, which shows the ambient environment of an individual on a path (a **Lagrangian** perspective) through the urban landscape on a warm summer day (Nakayoshi et al., 2015). Note the great variation in air temperature experienced by the pedestrian outdoors when compared to that recorded at a nearby meteorological station and the impact of moving indoors; T_a (and T_{MRT}) rises and falls by up to 12°C (20°C) instantaneously on leaving/entering buildings. The changes in wind, humidity and T_{MRT} are equally dramatic; the reader should compare this thermal experience with the outdoor air quality experience depicted in Figure 11.7. Where the indoor space is air-conditioned, the environment is static and there is little temporal variation in variables but when outside, microscale spatial and temporal variation in all of the weather elements is the norm.

Secondly, the activities of those in the outdoors (walking, sitting, running, etc.), their demographic make-up and their clothing decisions are far more diverse (Figure 14.10). This means that it is not generally possible to create outdoor climates that meet narrow objectives. On the other hand, the climate expectations of individuals (that is the psychological component of comfort) are far less stringent; a draught may be unacceptable inside a building but a moderate wind may be perfectly acceptable and even desirable when outdoors. A design goal for outdoor urban spaces is to moderate, to varying degrees, its undesirable properties. So, in a cold and windy environment, one would seek to provide shelter from the wind. Although this is unlikely to make the space comfortable, it will make it less stressful and extend the period of usage.

Measurement

Acquiring information on the human climate outdoors is extremely difficult. Ideally one needs to gather information on radiation, wind, temperature and humidity in the exposure environment but this is complicated by the great number of microclimates in cities. In addition, it is necessary to link these to indicators of the biophysical and psychological response of the person, which depends on activity levels, clothing, age, health and so on.

Figures 3.10a, 3.11b and 3.11c show instrument systems that are designed to make observations at pedestrian height; note that radiation instruments are arranged to provide information on the exchanges at the sides of an imaginary box. Each instrument combination is oriented perpendicular to the others and records short- and longwave radiation. Typically, these systems are located in an environment that is likely to see public use and a sample of people are interviewed to provide data on clothing and activity levels and their personal assessment of the thermal environment. This information may be supplemented by observations of the public use of the space. Subsequently, this response information is correlated with the environmental data to determine temporal and spatial patterns of use. Figure 14.11 shows a different approach, which is made possible by technological advances that allow instruments to be miniaturized and placed directly onto the human body. Rather than relocating the instruments to the places where outdoor users are located, the user becomes the platform for measuring the ambient environment. Even still, it is necessary to record the thermal sensation of the wearer to assess comfort and stress (Nakayoshi et al., 2015).

Modelling

The PMV model predicts thermal sensation based on the deviation between the energy exchange that is required to solve the energy balance in given conditions against that required during comfort. It was designed for indoor spaces and its relations are based on empirical studies carried out with subjects in a climate chamber. More general **numerical models** of the human energy balance can simulate the thermophysical responses of the human (e.g. skin temperature and sweat rate) to environmental stimuli that change rapidly; these transient conditions require non-steady state responses. Typically, these models segment the body into parts that are represented by simpler shapes (e.g. a sphere to represent the head and cylinders of different dimensions to represent the torso, arms, legs, fingers and toes) for which view factors and exchange coefficients are known. Each segment is connected via a modelled circulatory system and the energy exchange from the core to the outer skin surface is simulated at a series of nodes that represent layers of tissue. Clothing is included as a new surface layer and the energy exchange between the node at the skin surface and that at the cloth surface is simulated. These models can be used to create *rational* indices of environmental stress by comparing ambient conditions against a standard (see next section).

Human energy balance models are distinguished by their sophistication in representing aspects of the

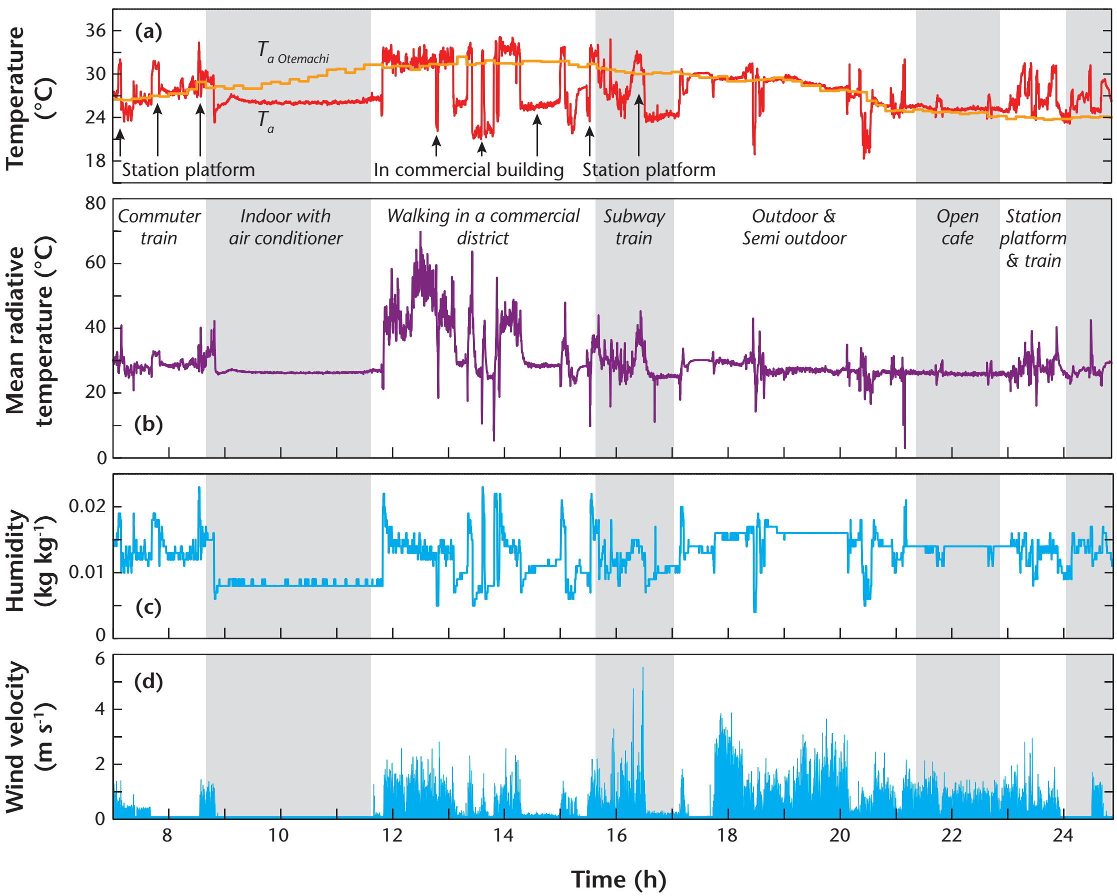

Figure 14.9 The ambient environment as recorded by an instrumented pedestrian (Figure 14.11) when walking through an urban environment. The variables recorded are: **(a)** air temperature as recorded at a nearby weather station ($T_{a\ \mathrm{Otemachi}}$) and by the individual (T_a); **(b)** mean radiant temperature (T_{MRT}); **(c)** humidity (as mixing ratio) and; **(d)** wind speed (m s^{-1}). The shading indicates the indoor, outdoor and semi-outdoor environments experienced during the walk (Data source: M. Nakayoshi; with permission).

energy balance. The Munich Energy-Balance Model for Individuals (MEMI) solves three sets of equations: the energy balance of the whole body; the heat flux from the core to the skin surface and; the heat flux through the layers of clothing. More sophisticated models have realistic descriptions of the body form and of internal transfers. As an example, the UCTI-Fiala model treats the body as composed of 12 compartments: head, face, neck, shoulders, thorax, abdomen, upper and lower arms, hands, upper and lower legs and feet. The transfer of heat within and between body compartments is calculated at 187 nodes that allow for detailed simulation of the variations in skin temperature associated with asymmetric heat gains and losses at the skin surface (Fiala et al., 2012).

One of the obstacles to using such models is the availability of data on the ambient environment. Observations from conventional meteorological stations will often have little in common with microclimate circumstances experienced in cities among buildings. Computer models are ideally suited to dealing with these situations by allowing routine calculations of solar access, and **sky view factor** in urban areas using building morphology data (e.g. Lindberg, 2007). The RayMan model simulates the short- and longwave radiation absorbed by an individual located in complex urban setting. It does this by dividing the urban landscape into surface elements, computing the radiation flux originating for each and calculating the view factor between the recipient and the source of radiation. The results of the

Figure 14.10 A typical outdoor urban environment (Curitiba, Brazil) which illustrates the varied use of outdoor spaces and micro-climatic experiences. While some are walking or sitting in sunlight, others are situated in shade, some next to fountains (Credit: G. Mills).

computation are converted into a mean radiant temperature (T_{MRT}) suitable for biometeorological purposes (Matzarakis et al., 2010).

14.4.3 Thermal Indices

A great number of indices have developed that link thermal responses to measures of ambient stresses and body strains (Epstein and Moran, 2006). Some are based on readily available meteorological data so that they have the advantage of ease of calculation; others are based on measures of thermal strain such as skin temperature or sweat rate. The most comprehensive are based on the human energy balance. For practical purposes, many of these indices are calibrated against a suite of ambient climatic, activity and clothing conditions that represent an imaginary setting in which only air temperature is allowed to vary. The 'equivalent' air temperature is calculated that would exert the same stress (or cause the same strain) in these circumstances as the conditions to which the body is currently exposed; this provides a single measure of the thermal environment.

Direct Indices

These are based on routinely available meteorological data and are of value in assessing extreme temperatures that may have public health consequences. However, these indices do not provide any detailed examination of the factors contributing to thermal stress and are consequently of limited diagnostic value. As examples the Humidex and Wind Chill Index (WCI) for warm and cold conditions, respectively, are used by the Canadian meteorological service,

$$\text{Humidex} = T_a + 0.5555\,(e - 10.0) \qquad (^\circ\text{C})$$

Equation 14.18

$$\text{WCI} = 13.12 + 0.6215\,T_a - 11.37\,\overline{u}^{\,0.16} + 0.3965\,T_a\,\overline{u}^{\,0.16} \qquad (^\circ\text{C})$$

Equation 14.19

where e is vapour pressure (hPa) and $\overline{u}$ is wind speed (in km hr^{-1}) measured at 10 m above the ground (that is, a conventional weather station). Both indices produce values that can be linked to a temperature scale and include just two of the environmental variables governing either warm stress (temperature and humidity) or cold stress (temperature and wind). On a warm (30°C) and very humid (30 hPa) day, the Humidex would be close to 40, indicating that the effect on a person is nearly the same as if the air were dry and T_a almost 40°C; the associated advice is 'great discomfort, avoid exertion'. By contrast, WCI is applicable when $T_a \leq 10$°C and $V \geq 5$ km hr^{-1} and again indicates the equivalent temperature in calm conditions that would produce the same effect.

Rational Indices

These are based on the energy balance (Equation 14.5) which is a complete description of the biophysical processes that underpin thermal state of the body. It can be applied generally once the meteorological inputs (wind velocity, air temperature and humidity

Figure 14.11 An outdoor Lagrangian measurement system suitable for evaluating the biometeorological environment. The antennae attached to the hat measure radiation, air temperature and humidity and wind speed; the instruments attached to the skin surfaces record skin temperature and heart rate and; the data-loggers recording the ambient environment and thermophysical responses are attached to the body (Credit: M. Nakayoshi; with permission).

and radiation terms) are available. This model is best applied to indoor situations where environmental and behavioural circumstances can be treated as constant and as a consequence, the body can be assumed to be in thermal equilibrium. It is less suited for outdoor conditions that are transient in nature, the radiation environment is far more complex and the response of individuals is variable.

The physiological equivalent temperature (PET) describes the exposure environment in terms of the air temperature that would be required in reference conditions (using the MEMI model) to produce the same thermal response (Höppe, 1999). These reference conditions correspond to a person located indoors, wearing office attire and engaged in light work. In this setting, $T_a = T_{\mathrm{MRT}}$, V is 0.1 m s^{-1} and e equals 12 hPa (relative humidity of 50% at 20°C). In essence, the model is solved for the actual exposure conditions, the calculated mean core and skin temperature are re-entered as fixed values for the reference indoor conditions and a new T_a is obtained that ensures a heat balance; this is the PET. Similarly the **Universal Thermal Climate Index** (UTCI) is based on the UTCI-Faisla model (Krzysztof et al., 2013) which in addition to its more complex treatment of the human energy balance selects an outdoor reference where the individual is walking, $T_a = T_{\mathrm{MRT}}$, V is 0.5 m s^{-1} and relative humidity is 50% (e is capped at 20 hPa).

14.5 Wind and Comfort

Apart from its role in thermal comfort, the mechanical effect of wind itself can generate discomfort, depending on the outdoor activity (ASCE, 2004). Typically, the attributes of wind are expressed in terms of the mean wind speed ($\overline{u}$) and its fluctuation (u'), where the latter are fluctuations of between 1 and 5 seconds,

$$u = \overline{u} + u' \qquad (\mathrm{m\ s^{-1}}) \qquad \textbf{Equation 14.20}$$

Typical gust conditions ($\hat{u}$) over a period of time are evaluated using the statistics of wind at a place,

$$\hat{u} = \overline{u} + f_p\,\sigma_u \qquad (\mathrm{m\ s^{-1}}) \qquad \textbf{Equation 14.21}$$

where σ_u is the standard deviation of $\overline{u}$ and f_p is a peak factor; if $f_p = 0$ then gusts are ignored, at $f_p = 1.5$ we can expect the gust speed to be exceeded 10% of the time and, at $f_p = 3.5$, just 0.01% of the time. Discomfort can occur as a result of either strong winds or gustiness so it can be useful to derive a gust equivalent speed (u_{GEM}) that can be compared directly with $\overline{u}$,

$$u_{\mathrm{GEM}} = \hat{u}/f_{p,\mathrm{fixed}} \qquad (\mathrm{m\ s^{-1}}) \qquad \textbf{Equation 14.22}$$

where $\hat{u}$ is based on a gust factor of 3.5 (i.e. a 3-second long gust exceeded about once every 5–10 minutes) and $f_{p,\mathrm{fixed}}$ is a representative fixed peak factor (1.85). If either u_{GEM} or $\overline{u}$ exceed some established criterion, then the overall assessment is uncomfortable. Table 14.5 provides wind ranges for different activities that would be acceptable if met more than 80% of the time; note that the acceptable ranges increase with activity level, that is, the conditions comfortable for walking may be uncomfortable for sitting.

14.6 The Urban Effect on Human Climates

From the perspective of human health and well-being, it is conditions within the **urban canopy layer** (UCL) that are most relevant. Here the ambient environment is dynamic and highly variable over very short distances (Figure 14.4 and Figure 14.9). The following text focuses on the outdoor environment and thermal and airflow effects of cities and is arranged according to the scale of the urban effect in this layer.

14.6.1 Microclimates

Given the variety of urban microclimates, most systematic work has been done on common urban configurations such as streets, parks and plazas. This research relies on the methods described above; here we present some examples of this work and leave general discussion of design to the following chapter.

Table 14.5 Wind criteria (applicable to both $\overline{u}$ and u_{GEM}) for different levels of activity based on a 20% probability of exceedance (Source: ASCE, 2004; © ASCE, with permission).

Activity	Comfort ranges (m s^{-1})
Sitting	0–2.5
Standing	0–3.9
Walking	0–5.0
Uncomfortable	> 5.4

Thermal Environment

The role of street geometry on the climate experienced by pedestrians can be examined using Figure 14.12 which shows the cross-section of canyon that is partly in shade. While T_a is nearly constant owing to mixing (see Figure 7.23), the surface temperatures of the facets vary considerably. The surfaces in shadow are relatively cool, whereas those in direct sunlight are warm. On the shaded side of the street, a pedestrian receives no direct shortwave radiation and the bulk of the intercepted longwave radiation will be sourced from the shaded side of the street, which occupies the larger view factor. However, all these exchanges change as the individual crosses the street to the sunlit side, receives **direct-beam irradiance** and intercepts more of the radiation emitted by the warmer surfaces; the T_{MRT} captures the radical change in the radiation environment when crossing from the shaded to sunlit part of the street. The PET index follows the path of T_{MRT}, illustrating the importance of the radiation environment to human (dis)comfort in the outdoors.

Johansson (2006) measured surface and air temperature, wind and humidity in typical streets that characterize Fez, Morocco (33°N), a city that experiences hot summers and cold winters. The old city has a compact design where narrow streets (high H/W) separate buildings (similar to that of Marrakech, see Figure 5.1) but the newer part has a more dispersed urban design and is characterized by lower H/W ratios. Figure 14.13 shows PET values calculated for

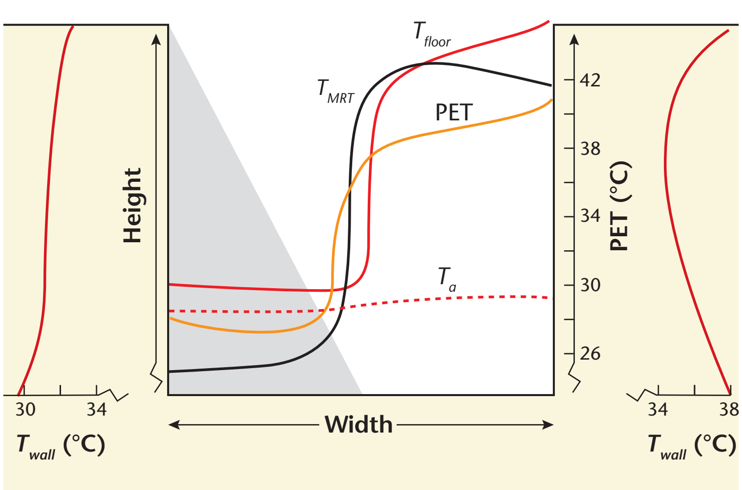

Figure 14.12 A cross-section of an urban canyon showing simulated variations in wall (T_{wall}) and floor (T_{floor}) temperatures; air temperature (T_a) and mean radiant temperature (T_{MRT}). Note the impact of sunshine and shade (in grey) on the surface values (Source: G. Jenritzky; with permission).

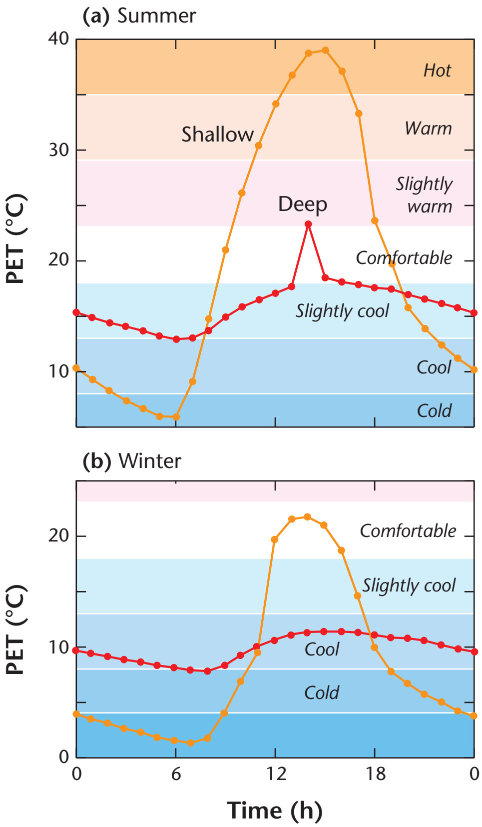

Figure 14.13 Physiologically equivalent temperature (PET) at the mid-point of a deep and shallow street canyon for summer and winter periods in Fez, Morocco (Source: Johansson, 2006; © 2005 Elsevier, used with permission).

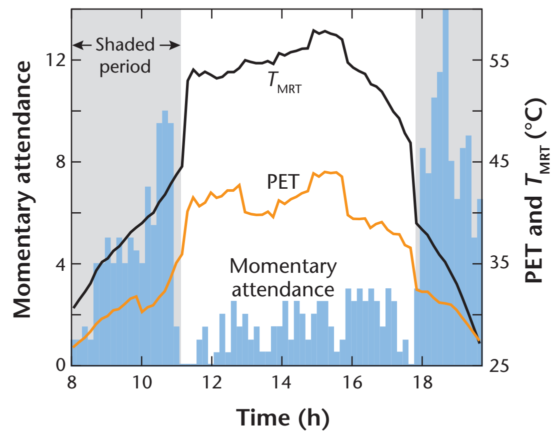

Figure 14.14 Assessment of the influence of daily shadings pattern on human thermal comfort and attendance in Rome during summer period (Source: Martinelli et al., 2015; © Elsevier, used with permission).

two streets (one deep and one shallow) that represent these neighbourhoods, respectively. During the summer period the deep canyon remains comfortable throughout the day. Here the surface facets remain in shade and surface temperatures are relatively low, hence the low PET. By comparison, the shallow canyon experiences very high PET values and offers little shade from the Sun. At night, the pattern is reversed with higher PET values in the deep canyon. During winter, the same patterns occur but, as the winter climate is cool, access to sunshine is desirable and the shallow canyon is more comfortable during the daytime. On the other hand, the deep canyon retains heat at night and remains relatively warm.

Parks and plazas are both places set aside for outdoor public use and have received some attention. Figure 14.14 shows the results of a study on the public use of a square in central Rome, Italy (Martinelli et al., 2015). The researchers divided the square into subareas based on the pattern of shade as it moved over the course of a sunny and warm August day. Those in place (not walking through) for 10 minutes or more (momentary attendance) were counted according to their position in the different subareas. The results show a clear correspondence between the choices of those in attendance, the shaded period and recorded T_{MRT} and PET. Evidently, most preferred shade whenever possible and relocated when it was no longer available at that location.

Wind Environment

The overall effect of cities is to reduce the mean wind speed while simultaneously increasing gustiness at pedestrian level but the wind environment in any given location is controlled by the interaction between the ambient airflow and the immediate geometry of the built environment. Tall buildings in particular present problems as they displace faster moving air from above to ground level and can cause problems for vehicles and pedestrians in their vicinity (Section 4.2.4). Figure 14.15 shows the effects of **turbulence** on the gait of a pedestrian near a tall building. As the wind shifts the body must redistribute its weight by altering footstep patterns to maintain balance.

Although each building has a unique impact on airflow, Figure 14.16 shows a range of building types

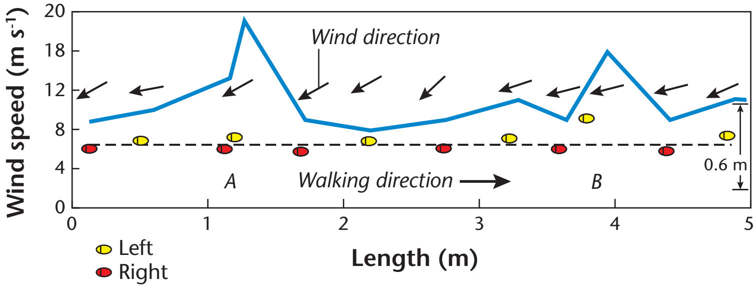

Figure 14.15 Observed footsteps and wind speed at 1 m height near a high rise building. The distance between the steps reflects the difficulty that the pedestrian experiences while walking in a turbulent urban environment (Source: Murakami, 1982).

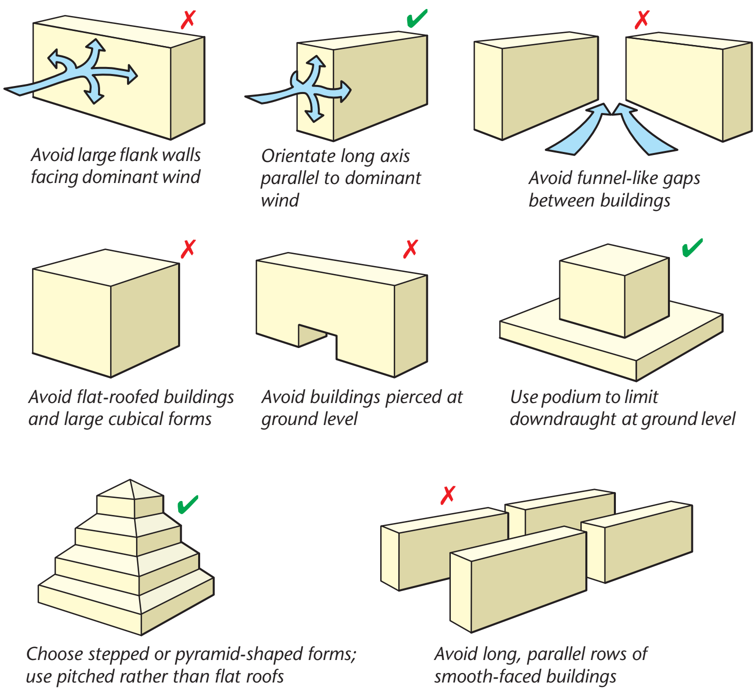

Figure 14.16 Guidelines for reducing the wind sensitivity of buildings (Source: Littlefair et al., 2000; © IHS, reproduced with permission from BRE BR 380).

and arrangements and their wind effect. In general, tall buildings that present a wide face to the oncoming flow should be avoided; similarly, long smooth-faced buildings aligned along the path of airflow offer no shelter. A common solution to such problems is to raise the tall tower on a larger base (podium) that protects the wind environment at street level. The separation distance between buildings may also be relevant as airflow will accelerate as it squeezes through the gap; large slab-like faces with narrow separation gaps that channel airflow are problematic. For these types of situations, wind shelter at the ground in the form of windbreaks is often needed to make the outdoor space useable. On the other hand, tall buildings that taper with height or present a narrow face to the oncoming flow offer less resistance to above roof winds and are less likely to cause unfavourable winds at the ground.

14.6.2 Neighbourhood

Given the diversity of urban microscale environments, generalizations at the scale of a neighbourhood are not simple. A neighbourhood may be described as an urban landscape with a degree of homogeneity in terms of building dimensions, separation distances, **impermeable** and vegetative cover, etc. (see Chapter 2).

Table 14.6 Frequency of occurrence of climatic event days in the LCZs (see Figure 2.9) in Oberhausen, Germany during the measurement period 1 August 2010–31 July 2011 (Modified after: Müller et al., 2014).

Local Climate Zone (LCZ)	$T_{a\,(\max)} \geq 30°C$	$T_{a\,(\max)} \geq 25°C$	$T_{a\,(\min)} \geq 20°C$	$T_{a\,(\max)} \leq 0°C$	$T_{a\,(\min)} \leq 0°C$
LCZ 2: Compact mid-rise	3	35	2	12	51
LCZ 3: Compact low-rise	3	24	2	12	55
LCZ 5: Open mid-rise	3	26	1	9	60
LCZ 6: Open low-rise	3	29	0	8	69
LCZ 8: Large low-rise	3	25	2	12	59
LCZ 9: Sparsely built	3	19	0	6	61
LCZ A: Dense trees	2	16	0	5	64
LCZ D: Low plants	3	23	0	5	72

Different neighbourhood types have a 'typical' mixture of microclimates (e.g. streets, plazas, parks, gardens, etc.) that distinguish it from other neighbourhoods. Moreover, as these types are often associated with particular functions such as commercial or residential activities, they will have distinct patterns of indoor and outdoor use.

Thermal Environment

The design of a neighbourhood affects every meteorological variable that influences human biometeorology; the magnitude of the urban effect on each is closely related to characteristics of the urbanized landscape and the 'natural' landscape that it replaced. However, it is important to note that the body responds thermally to the integrated urban effect rather than any one variable in isolation. Thus, for example, raising T_a and lowering $\overline{u}$ together reduces heat loss, which may make the neighbourhood more comfortable (if cold) or less comfortable (if already warm); similarly, raising T_a while lowering T_{MRT} (through shading) may have little net impact.

Table 14.6 shows the thermal climate of Oberhausen, Germany, over a year (1 August 2010 to 31 July 2011) based on observations made at eight stations representing different **Local Climate Zones** (see Figure 2.9). Note that, in general the urban areas experience warmer air temperatures by day and by night in the summer and fewer cold days during the winter. Figure 14.17 shows the diurnal pattern of PET curves for July 11, which was especially warm. Note the mid-rise compact LCZs, which represent the higher building density with the least vegetation exert the greatest thermal stress during the day. Although vegetation (to provide shade and evaporation) were important regulators of PET, the greatest influence was near-surface wind speed.

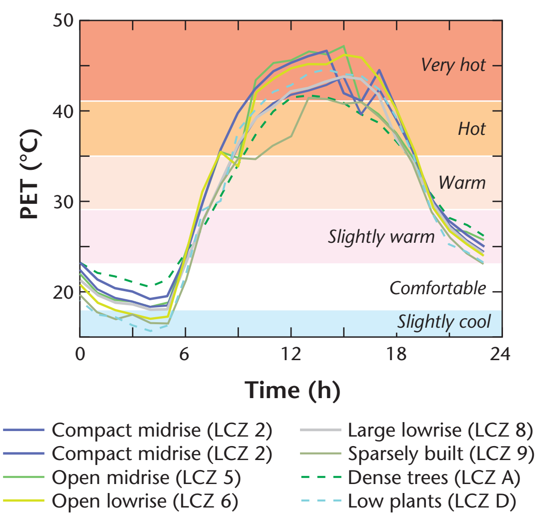

Figure 14.17 Diurnal variation of physiologically equivalent temperature (PET) values at the climate stations of the monitoring network in Oberhausen, Germany on 10 July 2010, based on measurements of the station monitoring network. (Source: Müller et al., 2014; © The Authors 2013, open access from Springer).

Wind Environment

More so than any other atmospheric property the statistics of air velocity are extremely variable in time and space within the UCL. In general, the degree of shelter at ground level is closely related to the packing density of buildings (see Figure 4.24). Where buildings are closely spaced, compactly organized and of uniform height, the space below roof level may be aerodynamically sheltered from the ambient airflow above roof level. However, where buildings are widely spaced, aligned along flow paths or of variable heights faster moving eddies from above roof level can be drawn into the UCL where they may pick up loose debris, and cause discomfort for citizens.

14.6.3 Urban Scale

At this scale, the average **urban climate** effect is to raise air and surface temperature (the urban heat island), lower relative humidity (largely as a result of air temperature changes) and retard airflow. With the exception of air quality, the urban effect can be beneficial depending on the background climate; when the climate is cold and windy, cold stress and building heating needs can be lessened but, where the climate is already warm and humid, heat stress (and building cooling demand) will increase. However, it is concerns for urban warming that has dominated research. This can be explained by: the increased energy demand for building cooling systems, even in cool climates; the emergence of very large cities in tropical climates where the background climate is already warm and; projections of global warming and increased frequency of heatwave events (see Section 12.3.3 and Table 13.6).

Managing the urban heat island generally is discussed in the following chapter, but it is worth reiterating the integrated nature of the environmental variables that create outdoor heat stress. As an example, the development of Hong Kong as a very densely built and occupied city in a warm and humid tropical setting has added to thermal stresses that residents would experience naturally. The pattern of building has worsened the climate by creating a line of closely spaced tall building that are parallel to the coastline and obstructs the movement of **sea breezes** into the city. These thermal circulations are strongest during the same calm and clear weather associated with the UHI and could provide respite from stressful conditions by bringing cooler and cleaner air into the city. To strike a balance between urban development and environmental concerns, the city has a development strategy that aims to create ventilation corridors between buildings that offer passage for coastal air (Ng, 2009).

14.7 Indoor Climates

Although the focus of this book has been on the climate outdoors, there is an intimate link with the indoor climate of buildings, which are an outcome of internal and external energy gains and losses (Section 6.5.2). The internal gains are associated with the metabolic heat released by occupants and that added by appliances (e.g. computers), lighting and heating systems. The external gains are those that enter the building via the envelope and include: radiation transmitted through windows and sensible and latent heat transfer across the wall and roof facets via conduction and through openings via convection. Maintaining a desirable indoor climate involves managing these exchanges each of which has distinct diurnal and seasonal patterns associated with occupation patterns. However, the same outcome could be achieved by different means (envelope design, material choice, energy demand and so on), each of which will have a different impact on the outdoor climate. Figure 14.18 shows a large low-rise building that has a retail function and is located in a hot and arid environment. Part of its energy management strategy is to reduce solar gain via the large roof surface, by increasing its albedo (a **cool roof**) while at the same time converting some of the solar energy to electricity. The combined strategy reduces the cooling energy demand within the building and provides an alternative and renewable source of energy. However, this example also shows the limits of such actions at a building scale, a theme that is picked up in the following Chapter 15.

Figure 14.18 A large retail shop in Arizona, United States, that has taken steps to reduce its energy demand by using a white-coated roof to reflect solar radiation and installing solar panels to generate a portion of the building's energy needs (Source: Walmart; CC2.0).

Summary

Concern for the climates of humans is at the heart of much of urban climate research, much of which is concerned with the application of scientific knowledge to the design of cities. The basic energy balance that underpins our understanding of human climates is discussed extensively in this book: it includes the **radiative** and **convective exchanges at the skin surface** and accounts for **heat transfer within the body**. However, the involuntary responses of the human system to these exchanges and the role of psychology in regulating thermal sensitivity distinguish the human climate from those of inanimate objects.

There are **six variables that** govern **the energy balance terms**. The environmental variables include the wind velocity, air temperature, relative humidity and radiation. The latter is encapsulated by the **mean radiant temperature** (T_{MRT}), which expresses the short- and long-wave radiation absorbed at the outer surface of the body. The terms that are intrinsic to humans are levels of activity and of clothing. Overall, the body must achieve balance so that the deep body temperature is constant.

- The combination of environmental variables results in **thermal stress**, which causes the body to respond by experiencing strain. The zone of minimum stress (and strain) is referred to as comfortable. Cold thermal stress causes the body to generate internal heat while limiting heat losses. Warm thermal stress causes the body to maximize heat loss.
- There are a great **number of thermal indicators** which are based on simple measures of the environment and of thermal stresses but the most useful indicators are based on the energy balance that link exchanges to physical (dis)comfort.
- Cities create myriad microclimates within the UCL. Indoor microclimates tend to be less variable and exposure can be treated as a steady state problem for occupants. **Outdoor microclimates are extraordinarily diverse** in space and time and **exposure is transient in nature**. A variety of tools have developed to understand the complex relationship between humans, climate and the use of outdoor spaces but much is still unknown.
- The creation of **comfortable indoor spaces** is a primary concern for building engineers and decisions on how to best achieve this **has ramifications for urban energy use** (Chapter 13) and the **anthropogenic heat flux** (Chapter 6). Sustainable architecture attempts to achieve this goal through good design that makes best use of the background climate resources. Even still, there is an ongoing debate on the importance of psychological controls in determining the best indoor climate for a given place and purpose.

All of the environmental variables relevant to human climates are modified in the city. While some of these changes may be beneficial, others are deleterious (e.g. dangerous winds, poor air quality). The thermal effect of the city has received most attention: the urban heat island raises surface and air temperature and in hot climates (or weather) will add to thermal stresses but, in cold climates (or weather) may be beneficial. Managing the urban climate through design solutions for the benefit of humans is the focus of Chapter 15.