Chapter 2
Climate, Comfort and Sun

A well know American writer said once that, while everybody talks about the weather, nobody seems to do anything about it.
(Warner 1897).

2.1 Introduction

Sustainable design of building entails an understanding of climate of the given place and desirable comfort conditions:

Climatic conditions (Ambient conditions)	−	Indoor conditions (Thermal comfort)	=	Design strategies (Sustainable Design)

This chapter intends to present classification of climate, elements of climate, parameters of thermal comfort and solar geometry. Globally prevalent Köppen classification of climate and five climatic zones in India are discussed. The section on elements of climate presents sources and derivation of climatic data given in Chap. 5. The section on thermal comfort defines parameters of physiological thermal comfort and method to delineate comfort zone for a given city. The last section deals with solar geometry and method to draw sun-path diagrams.

2.2 Classification of Climate

Important characteristics of any planet are controlled by its climate. The word ‘climate’ comes from the Greek *klima*, which means the slope of the earth with respect to the sun. Climate is defined as ‘region with certain conditions of temperature, dryness, wind, light, etc. of a region,’ Oxford dictionary. Climate is also defined, ‘an integration in time of the weather conditions, characteristics of a certain

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geographical location.' As weather is the set of atmospheric conditions, including temperature, rainfall, wind, humidity and sky conditions prevailing at a given place and time. Climate on the other hand, is the general weather conditions over a long period of time. In totality, climate is the sum of all the statistical weather information that helps to describe a place or region.

Since Aristotle's time, attempts at climate classification have been done chiefly by biologists who realised that the natural vegetation represents a very good indication of the climate of a place. The well known vegetation-based classification of climates by Wladimir Köppen, a German biologist trained in St. Petersburg, was first published in 1900 and is still prevalent. The Köppen system is based on monthly mean temperature, monthly mean precipitation, and mean annual temperature. The five vegetation groups of Köppen distinguish between plants of the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E). A second letter in the classification considers the precipitation (e.g. Df for snow and fully humid), a third letter indicates the air temperature (e.g. Dfc for snow, fully humid with cool summer). The annual mean near-surface (2 m) temperature is denoted by T_{ann} and the monthly mean temperatures of the warmest and coldest months by T_{max} and T_{min}. P_{ann} is the accumulated annual precipitation and P_{min} is the precipitation of the driest month. Additionally P_{smin}, P_{smax}, P_{wmin} and P_{wmax} are defined as the lowest and highest monthly precipitation values for the summer and winter half-years on the hemisphere considered. All temperatures are given in °C, monthly precipitations in mm/month and P_{ann} in mm/year. In addition to these temperature and precipitation values a dryness threshold P_{th} in mm is introduced for the arid climates (B), which depends on $\{T_{ann}\}$ the absolute measure of the annual mean temperature in °C, and on the annual cycle of precipitation:

$P_{th} = \{$	$2\{T_{ann}\}$	If at least 2/3 of the annual precipitation occurs in winter
	$2\{T_{ann}\} + 28$	If at least 2/3 of the annual precipitation occurs in summer
	$2\{T_{ann}\} + 14$	Otherwise

Köppen classification enlist some 25 climate types, Fig. 2.1 and Table 2.1.

The Indian subcontinent is a big geographical unit, which has almost thirty degrees of latitudinal extent (between 6°N and 36°N) and the same amount of longitudinal extent (between 68°E and 98°E). With its vast size about 3.2 million square kilometers, India has sharp contrasts in its climatic conditions. The climatic map included in the National Building Code of India (BIS 2016) for the purpose of design of buildings distinguishes five climate zones (Fig. 2.2; Table 2.2):

1. Hot and dry
2. Warm and humid
3. Temperate
4. Cold
5. Composite

An extensive study in the book *Climatic zones and rural housing in India* by Bansal and Minke (1988) covered the climatic data of 32 stations along with 21

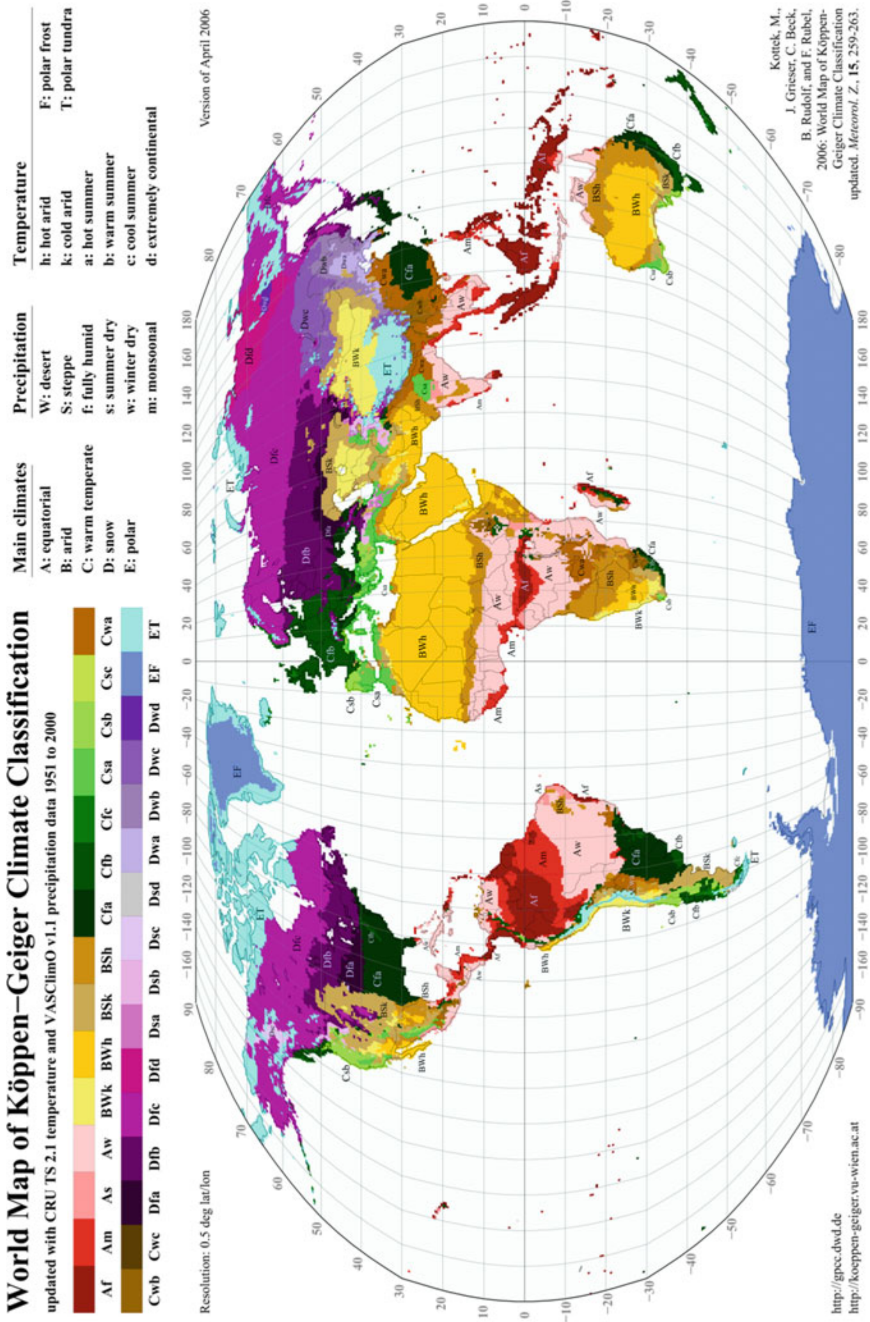

Fig. 2.1 World map of Köppen–Geiger climate classification. (Kottek et al. 2006)

Table 2.1 Köppen's major climates (Kottek et al. 2006)

Type	Main group-climates	Sub-group: precipitation	Second sub-group: temperature
A	Equatorial climates ($T_{min} \geq +18$ °C)		
Af		Equatorial rainforest, fully humid ($P_{min} \geq 60$ mm Rainy all seasons)	
Am		Equatorial Monsoon [$P_{ann} \geq 25$ $(100 - P_{min})$]	
Aw		Equatorial savannah with dry winter ($P_{min} < 60$ mm in winter)	
As		Equatorial savannah with dry summer ($P_{min} < 60$ mm in summer)	
B	Arid climates ($P_{ann} < 10$ P_{th})		
Bs		Semi-arid Steppe climate ($P_{ann} > 5$ P_{th})	
Bsh			Hot steppe/desert ($T_{ann} \geq +18$ °C)
Bsk			Cold steppe/desert ($T_{ann} \leq +18$ °C)
Bw		Desert climate ($P_{ann} \leq 5$ P_{th})	
Bwh			Hot steppe/desert ($T_{ann} \geq +18$ °C)
Bwk			Cold steppe/desert ($T_{ann} \leq +18$ °C)
C	Warm temperate climates (−3 °C < $T_{min} < +18$ °C)		
Cw		Warm temperate climate with dry winter ($P_{wmin} < P_{smin}$ and $P_{smax} > 10$ P_{wmin})	
Cwa			Hot summer ($T_{max} \geq +22$ °C)
Cwb			Warm summer (not 'a' and at least 4 $T_{mon} \geq +10$ °C)
Cs		Warm temperate climate with dry summer ($P_{smin} < P_{wmin}$, $P_{wmax} > 3$ P_{smin} and $P_{smin} < 40$ mm)	
Csa			Hot summer ($T_{max} \geq +22$ °C)
Csb			Warm summer (not 'a' and at least 4 $T_{mon} \geq +10$ °C)
Cf		Neither Cs nor Cw (Moist all seasons)	
Cfa			Hot summer ($T_{max} \geq +22$ °C)
Cfb			Warm summer (not 'a' and at least 4 $T_{mon} \geq +10$ °C)

(continued)

Table 2.1 (continued)

Type	Main group-climates	Sub-group: precipitation	Second sub-group: temperature
Cfc			Cool summer and cold winter (not 'b' and $T_{min} > -38$ °C)
D	Snow climates ($T_{min} \leq -3$ °C)		
Ds		Snow climate with dry summer ($P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm)	
Df		Snow climate, fully humid (neither Ds nor Dw)	
Dfa			Hot summer ($T_{max} \geq +22$ °C)
Dfb			Warm summer (not 'a' and at least 4 $T_{mon} \geq +10$ °C)
Dfc			Cool summer and cold winter (not 'b' and $T_{min} > -38$ °C)
Dfd			Extremely continental (like 'c' but $T_{min} \leq -38$ °C)
Dw		Snow climate with dry winter ($P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$)	
Dwa			Hot summer ($T_{max} \geq +22$ °C)
Dwb			Warm summer (not 'a' and at least 4 $T_{mon} \geq +10$ °C)
Dwc			Cool summer and cold winter (not 'b' and $T_{min} > -38$ °C)
Dwd			Extremely continental (like 'c' but $T_{min} \leq -38$ °C)
E	Polar climate ($T_{max} < +10$ °C)		
ET		Tundra Climate Short summer allows tundra vegetation (0 °C $\leq T_{max} < +10$ °C)	
EF		Frost climate (perpetual ice and snow) ($T_{max} < 0$ °C)	

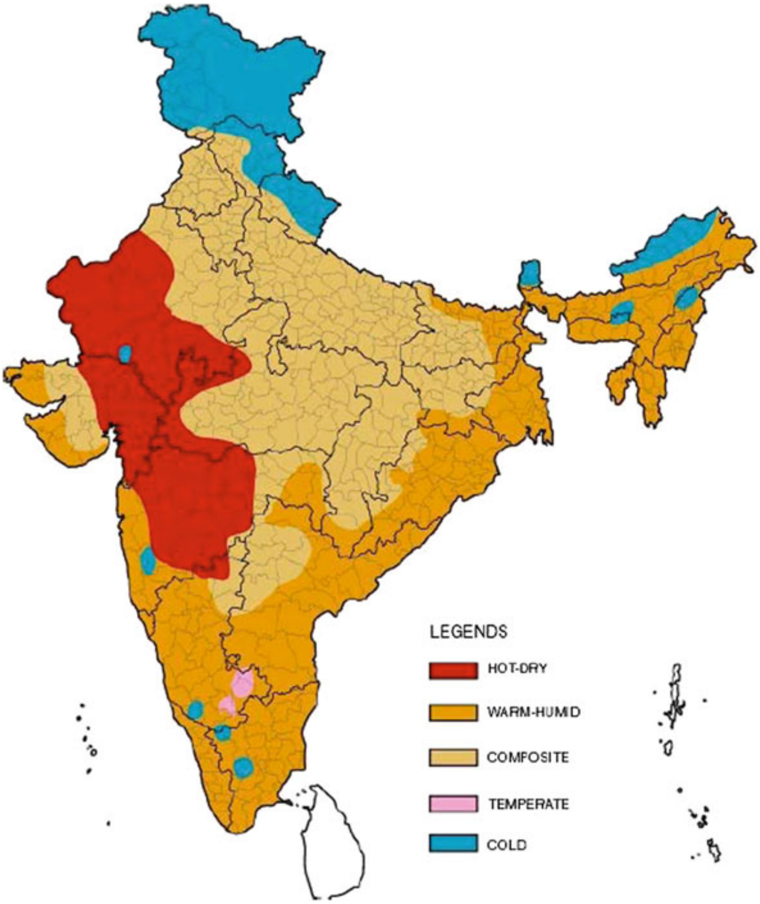

Fig. 2.2 Climatic zones of India, BEE (2017) and BIS (2016)

Table 2.2 Climatic zones of India

Climatic zone	Mean monthly maximum temperature (°C)	Mean monthly relative humidity (%)
Hot and dry	Above 30	Below 55
Warm and humid	Above 30	Above 55
	Above 25	Above 75
Temperate	Between 25 and 30	Below 75
Cold	Below 25	All values
Composite	Each climatic zone does not have same climate for the whole year; it has a particular season for more than six months and may experience other seasons for the remaining period. A climatic zone that does not have any season for more than six months may be called as composite zone.	

Source BIS (2016, Part 8 Building Services, Sect. 1: lighting and natural ventilation, clause 3.2 basic zones, Table 2) examples of rural housing across six climatic zones in India. *A design handbook for energy efficient buildings* by Krishan et al. (2001) and *Handbook on Energy Conscious Buildings* by Nayak and Prajapati (2006) present climatic data of six stations representing each climate zones of the country and the methodology of design, design tools, developments in energy efficient architecture and case studies. Chapter 5 presents climatic data of 62 cities across five climatic zones of India.

2.3 Elements of Climates

The main climatic elements regularly measured by meteorological organization and published in summary form. Further, climatic data are also obtained from satellites. In absence of observed climatic data, it can be also estimated based on standard algorithms. The following sections discuss the elements of climate needed for building design.

2.3.1 Temperature and Humidity

Air temperature is expressed by the dry bulb temperature (DBT), measured with a standard thermometer in the shade, usually in a ventilated box, the Stevenson screen, 1.2–1.8 m above ground level. The bulb of thermometer should not wet—if it were wet, the evaporation of moisture from its surface would affect the reading and give something closer to the wet bulb temperature. Air temperature can also be measured by thermocouple, or resistance temperature devices. Air temperature is usually given in degrees Celsius (°C) or Fahrenheit (°F), however its true SI unit is Kelvin (K). On the Kelvin scale 0 °K equals −273 °C. In conformity with the accepted usage of the SI system, the symbol C is used to denote a specified point on the temperature scale, but K (degree Kelvin) is used for a range, a span or a difference of temperature, i.e., a length of the scale, without specifying its position.

Humidity, can be expressed by six psychrometric parameters: (i) Wet bulb temperature (WBT, °C/°F); (ii) dew-point temperature (DPT, °C/°F), (iii) absolute humidity (AH, g/kg or lb/lb), (iv) humidity ratio (HR) (v) vapour pressure (p, kPa/psi), (vi) relative humidity (RH, %).

It is usually measured by the wet-and-dry bulb (whirling) psychrometer or an aspirated psychrometer. These contain two thermometers; one has its bulb wrapped in gauze, which is kept moist from small water container. When whirled around (or the fan is operated) until their readings become steady to obtain maximum possible evaporation, this produces a cooling effect, showing the Wet bulb temperature (WBT). The other thermometer measures the air-or dry-bulb temperature (DBT). The difference DBT–WBT is referred to as the wet bulb depression and it is indicative of the humidity. Evaporation is inversely proportional to humidity. In saturated air there is no evaporation, no cooling thus WBT = DBT. In the dry air the moisture rapidly evaporates to produce a large depression which indicates of low humidity. In moisture-laden air evaporation is less and a small wet-bulb depression occurs; which indicates high humidity.

For any particular dry-bulb temperature there is only a certain amount of moisture vapour that can be absorbed in the air before it becomes saturated and precipitation occurs. The actual amount of moisture in the air is referred to as the absolute humidity (AH) and is measured in g/kg (or lb/lb). The dew-point temperature (°C/°F) refers to the maximum amount of moisture that the air can hold at a given temperature. The relative humidity (RH) is the ratio of the actual density of water vapour in air to the maximum density of water vapour that such air could contain, at the same temperature, if it were 100% saturated. Relative Humidity may be measured directly or derived from DBT and WBT. At 100% relative humidity, DBT and WBT are equal.

The main source of temperature and relative humidity data is the Indian Society for Heating Refrigerating Air Conditioning Engineers (ISHRAE 2014). The location's latitude, longitude and altitude above mean sea level are taken from these, as well as values of maximum and minimum temperature and relative humidity.

Both the graph and the table give the mean minimum and mean maximum temperatures. The monthly mean temperatures shown on the graph as well as in the table were calculated as

$$\overline{T} = \frac{T_{\text{mean max}} + T_{\text{mean min}}}{2} \tag{2.1}$$

Annual averages of all three temperatures values are given in the table, found as

$$\sum_{1}^{12} \frac{\overline{T}}{12} \tag{2.2}$$

Hourly values of temperature for a typical winter and summer day are given by the ISHRAE (2014).

The average diurnal range of temperatures is the difference between the monthly mean maximum and the monthly mean minimum. The annual mean range of temperature is the difference between the highest monthly mean maximum and the lowest monthly mean minimum.

The recommended outdoor "design conditions" (summer DBT and WBT and winter DBT) have been adopted from the BIS (2016, Part 8 Building Services—Sect. 3, Air Conditioning, Heating and Mechanical Ventilation, clauses 5 Table 2 Outside Design Conditions).

2.3.2 Cloud and Sunshine

Cloud cover, based on visual observation, expressed as a fraction of the sky hemisphere ('octas' eighths, or more recently tenths) covered by clouds. The cloud cover data for all the cities have been taken from the ISHRAE (2014).

Sunshine duration, i.e. the period of clear sunshine (when a sharp shadow is cast), measured by a sunshine recorder, in which a lens burns a trace on a paper strip; shown as hours per day or month. The sunshine data for 38 cities have been collated from the India Meteorological Department (IMD) and World Meteorological Organization (WMO). The sunshine duration was not available for 24 cities, so the values are estimated using standard algorithm (Muneer 2004, pp. 36–37):

$$n = \frac{N}{0.448}\left(\frac{\overline{G}}{\overline{E}} - 0.299\right) \tag{2.3}$$

where $\overline{G}$ and $\overline{E}$ are the monthly-averaged daily terrestrial and extraterrestrial irradiation on a horizontal surface (W/m^2), 0.299 and 0.448 are empirical coefficients based on data of 18 Indian cities (Hawas and Muneer 1983), n is the average daily hours of bright sunshine duration (hours) and N is the day length (hours), obtained by:

$$\omega_s = \cos^{-1}\left(-\tan \text{LAT} \times \tan \text{DEC}\right) \tag{2.4}$$

$$N = (2\omega_s/15) \tag{2.5}$$

where ω_s = sunset hour angle degrees, LAT = latitude degrees (southern hemisphere –ve), DEC = solar declination degrees (varies from a maximum value of +23.45 on June 22 to a minimum value of −23.45 on Dec. 22. It is zero on the two equinox days of Mar. 21 and Sept. 22)

Cooper (1969) has given the following simple equation for calculating declination on any day of year:

$$\text{DEC} = 23.45 \times \sin\left[\frac{360}{365}(284 + DN)\right] \tag{2.6}$$

where DN = Julian date, counted Jan. 1st DN = 1 to Dec. 31st as DN = 365.

Another more accurate expression is given by (Aydinli 1981)

$$\text{DEC} = 23.45 + \sum_{i=1}^{3} a_i \times \cos\left(i\frac{2\pi}{365}\text{DN} + b_i\right) \tag{2.7}$$

a_i and b_i are as follows:

i	a_i	b_i radians
1	−23.2559	0.1582
2	−0.3915	0.0934
3	−0.1764	0.4539

Another algorithm (Dogniaux 1975):

$$\mathrm{DEC} = 0.33281 + \sum_{i=1}^{3} a_i \times \cos\left(i\frac{2\pi}{366}\mathrm{DN}\right) + b_i \times \sin\left(i\frac{2\pi}{366}\mathrm{DN}\right) \tag{2.8}$$

where a_i and b_i are as follow:

i	a_i	b_i radians
1	−22.984	3.7872
2	−0.34990	0.03205
3	−0.13980	0.07187

The extraterrestrial irradiation, E may be calculated by:

$$E = \frac{0.024}{\pi} I_{\mathrm{sc}} \left[1 + 0.033 \times \cos\left(360 \times \frac{DN}{365}\right)\right] \times \left[\cos \mathrm{LAT} \times \cos \mathrm{DEC} \times \sin \omega_{\mathrm{s}} + \left(\frac{2\pi\omega_{\mathrm{s}}}{360}\right) \times \sin \mathrm{LAT} \times \sin \mathrm{DEC}\right] \tag{2.9}$$

In the above equation I_{sc} is the solar constant (= 1367 W/m^2).

Page et al. (1984) identified the particular day in each month for which the extra-terrestrial radiation is nearly equal to the monthly mean value, Table 2.3.

Table 2.3 Solar declination for representative dates, associated day number (DN) and recommended values of solar declination

Date	Day (DN)	Solar declination (DEC)	Date	Day (DN)	Solar declination (DEC)
Jan. 17	17	−20.71	Jul. 17	198	21.16
Feb. 15	46	−12.81	Aug. 16	228	13.65
Mar. 16	75	−1.80	Sep. 16	259	2.89
Apr. 15	105	9.77	Oct. 16	289	−8.72
May. 15	135	18.83	Nov. 15	319	−18.37
Jun. 11	162	23.07	Dec. 11	345	−22.99

Note: The values of monthly mean solar declination is the average of the individual daily values calculated using the algorithm given by Aydinli (1981). For use in the southern hemisphere the sign should be reversed (assuming that the latitude is given a positive value), Page et al. (1984)

These dates can be also taken for computing the monthly average values of instantaneous hourly radiation.

- Cloud over (table only) given in %, for some stations given in octas.
- Monthly mean sunshine hours (both table and graph).

2.3.3 *Irradiation*

Solar radiation, measured by a pyranometer (solarimeter), on an unobstructed horizontal surface and recorded either as the continuously varying irradiance in W/m^2, or through an electronic integrator as irradiation over the hour or day in Wh/m^2. If the hourly value of irradiation is given in Wh/m^2, it will be numerically the same as the average irradiance (W/m^2) for that hour. As an energy unit, the Wh (Watt-hour) is used for solar radiation, although it is only a "tolerated" unit in the SI.

Monthly irradiation data, as well as the hourly values of direct and diffuse irradiation for a typical winter and summer day (in Wh/m^2) for all the cities have been adopted from the ISHRAE (2014). Hourly values of irradiation for a typical winter and summer day are given by the ISHRAE (2014).

2.3.4 *Wind*

Air movement, i.e. wind, normally measured at 10 m above ground in open country, but higher in built-up areas, to avoid obstructions; both velocity and direction are recorded. Wind velocity and direction is measured by a cup-type or propeller anemometer.

For all the cities wind data have been taken from the ISHRAE (2014). For building design wind data are best represented graphically in the form of wind rose.

Wind roses for 62 locations are drawn. These roses have eight sides, corresponding to the four cardinal and four semi-cardinal points of the compass, giving directions from which the wind comes. Each side has 12 lines, corresponding to the 12 months, from January to December in a clockwise direction, where the length of a line is proportionate to the frequency (% of observation) of wind from that direction in that month. Mean wind speed in m/s is shown in tables.

2.3.5 Precipitation

Precipitation, i.e. the total amount of rain, hail, snow or dew, measured in the tipping bucket rain gauges i.e. calibrated receptacles, and expressed in mm per unit time (day, month or year). Values indicating the total precipitation for each month of the year (and as many years' average) would show the pattern of dry and wet seasons. The mean monthly rain data have been obtained from the Indian Meteorological Department.

2.4 Thermal Comfort

A principal purpose of sustainable building design is to provide conditions for human thermal comfort, 'condition of mind that expresses satisfaction with the thermal environment' ASHRAE standard 55 (ASHRAE 2010). This definition emphasizes that judgement of comfort is a cognitive process involving many parameters influenced by physical, physiological, psychological, and other processes (ASHRAE 2009).

2.4.1 Heat Balance of Human Body

The human body continuously produces heat through metabolic processes that must be dissipated and regulated to maintain normal body temperatures. The heat output of a resting adult is about 100 W, but it can range from about 70 W (in sleep) to about 700 W in heavy activity (playing tennis). The deep body temperature is about 36.8 °C at rest in comfort and rises with activity to about 37.4 °C when walking and 37.9 °C when jogging. While as the skin temperatures associated with comfort at sedentary activities are 33–34 °C and decrease with increasing activity (Fanger 1967). The metabolic heat production can be of two kinds: *basal* metabolism, due to biological processes (assimilation and utilization of food) which are continuous and non-conscious and *muscular* metabolism, whilst carrying out work, which is consciously controllable (except in shivering). The heat is dissipated to the environment by conduction, convection, radiation or evaporation, Fig. 2.3.

The human body interacts with its thermal environment through sensible heat loss or gain by conduction, convection, radiation and through latent heat loss by evaporation. Thermal comfort is achieved when there is a balance between metabolic heat production and heat dissipation. The heat balance of human body; i.e. thermal interaction with its environment can be expressed as Eq. 2.10.

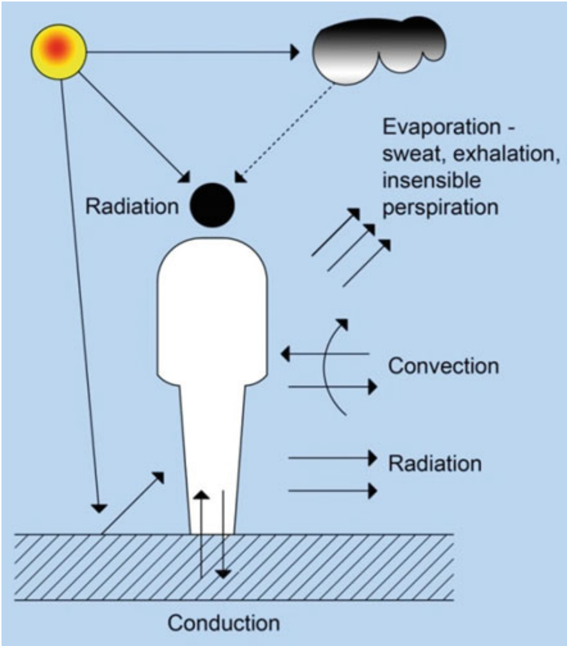

Fig. 2.3 Heat balance of the human body; thermal interaction with its environment

$$M - W \pm R \pm C \pm K - E = S \tag{2.10}$$

where M = rate of metabolic heat production W/m^2, W = rate of mechanical work accomplished W/m^2, S = any surplus or deficit heat stored W/m^2, C = sensible heat flow (loss or gain) by convection (including respiration) W/m^2, R = sensible heat flow (loss or gain) by radiation W/m^2, K = sensible heat flow (loss or gain) by conduction W/m^2, E = latent heat loss by evaporation (including respiration) W/m^2.

Thermal balance or comfort exists when external heat gains and heat produced by the body are fully dissipated to the environment and a condition of equilibrium prevails i.e. S is zero.

2.4.2 Parameters of Thermal Comfort

It is well established empirically that air temperature, relative humidity, radiant temperature and air speed all affect human thermal comfort. Several non-environmental factors like level of activity, clothing, acclimatisation etc. are also important for the determination of an optimum thermal environment. The parameters of thermal comfort are classified into three categories: personal, environmental and other, Table 2.4.

Table 2.4 Parameters of thermal comfort

Personal	Environmental	Other
Metabolic rate (level of activity)	Air temperature	Food and drink, living habits
Clothing insulation	Humidity	Body shape
State of health	Air speed	Subcutaneous fat
Acclimatisation	Radiant temperature	Age and gender

Metabolic activity is defined in terms of the rate of heat produced, expressed in W/m^2 of body surface. A unit used to express the metabolic rate per unit Du Bois area is the *met*, defined as the metabolic rate of a sedentary person (seated quite), 1 met = 58.2 W/m^2 (ASHRAE 2009). This is based on the average male with a skin surface area of about 1.8 m^2. Thus, the heat output of an average body is about 104.76 W. Metabolic rate varies over a wide range, depending on activity, person, and conditions under which the activity is performed. With higher levels of met, cooler environment will be preferred, to accelerate the heat dissipation.

Du Bois and Du Bois (1916) proposed the body surface area can be given as: BSA = 0.202 * weight$^{0.425}$ * height$^{0.725}$, where weight is in kg and height is in m.

Clothing is one of the dominant factors affecting heat dissipation. For the purpose of thermal comfort studies a unit has been advised, named the *clo*. A value of 1.0 *clo* corresponds to an insulating cover over the whole body of a transmittance (*U*-value) of 6.45 W/m^{2}K (i.e. a resistance of 0.155 m^{2}K/W). The insulating value of a normal business suit, with cotton underwear is 1.0 *clo*. The clothing may range from 0 to more than 3.5 *clo*. Clothing is an important adjustment mechanism if chosen freely, but if it is restricted in a warm environment, cooler environment will be preferred.

Acclimatization and state of health have strong influence, both physiologically and psychologically.

The environmental factors vary independently of each other, but the sensation of comfort or discomfort depends on the simultaneous effect of all these. Thermal environmental parameters that must be measured or otherwise quantified to obtain accurate estimates of human thermal response are divided into two groups: those that can be measured directly, e.g. (a) air temperature, (b) humidity (c) air speed and those calculated from other measurements, e.g. Mean Radiant Temperature.

Air temperature is the most significant environmental parameter of thermal comfort; it determines convective heat dissipation, together with air movement. Humidity determines heat dissipation by evaporation. At high humidity, too much skin moisture tends to increase discomfort as evaporation is prevented from the skin and in respiration, thus curb the heat dissipation mechanism. Low humidity can dry the skin and mucous surfaces (mouth, throat), thus cause discomfort. Air movement across the skin accomplishes heat dissipation by convective heat transfer (removing warm air close to the skin) as well as increases evaporation from the skin, thus produces a physiological cooling effect. In the presence of air movement the surface resistance of the body (or clothing) is reduced.

Precise relationships between increased air speed and improved comfort have not been established. Under hot conditions 1 m/s is pleasant and indoor air velocities up to 1.5 m/s are acceptable. Above this, light objects may be blown about, thus indirect nuisance effects may be created. Under cold conditions, in a heated room 0.25 m/s velocity should not be exceeded, but even in a heated room stagnant air (velocities <0.1 m/s) would be judged as "stuffy". A draft is an undesirable local cooling of the human body by air movement, and it is a serious comfort problem.

An additional effect is that with no air movement practically a saturated air layer is formed at the body surface, which prevents (reduces) further evaporation. Air movement would remove this saturated air envelope. The skin is surrounded by a thin, still air layer which is close to skin temperature and insulates the body from its surroundings. Air movement decreases the thickness of this insulating layer and thus gives a cooling effect provided that the vapour pressure of air is lower than the skin vapour pressure, even if the dry bulb temperature is higher than the skin temperature within a certain limit. Increased air movement reduces the amount moisture laden air close to the skin thereby increasing evaporation. The effect of air movement is, therefore, two-fold: the convection heat loss coefficient of the body (or clothing-) surface (h_c) is a function of air velocity and evaporation from the skin, thus the evaporation heat loss coefficient (h_e) is also increased by moving air.

Radiation exchange depends on the mean radiant temperature (T_{mrt}), the average temperature of the surroundings surfaces, each weighted by the solid angle it subtends at the measurement point. If the temperature of the surrounding surfaces is lower than skin temperature then the body will radiate heat. Surroundings which are hotter than skin temperature will radiate heat causing skin temperature to increase, (Vernon 1932). This effect is accentuated when lighter clothing is worn, (for example in summer). Radiation exchange with the surroundings can have a significant effect on human comfort. Measurements of globe temperature (T_g), air temperature (T_a) and air velocity (v) can be combined to estimate the mean radiant temperature. The globe thermometer is a mat black copper sphere, usually of 150 mm diameter, with a thermometer located at its centre. Positioned in a room, after equilibrium is reached (in 10–15 min) the globe will respond to the net radiation to or from the surrounding surfaces. If radiation is received, then $T_g > T_a$; $T_g < T_a$ indicates that the surrounding surfaces are cooler than the air, radiation is emitted. In still air $T_{mrt} = T_g$, but a correction for air movement of v velocity (in m/s) is possible:

$$T_{mrt} = T_g \times \left(1 + 2.35\sqrt{v}\right) - 2.35 \times T_a\sqrt{v} \tag{2.11}$$

In warm climates (with light clothing) the mean radiant temperature is twice as important as dry bulb temperature, which is accounted in environmental temperature (CIBSE 1999):

$$T_{\text{env}} = \frac{2}{3}T_{\text{mrt}} + \frac{1}{3}T_{\text{ai}} \tag{2.12}$$

However, in cooler climates (with heavier clothing) the mean radiant temperature has the same influence as the dry bulb temperature, which is expressed as the dry resultant temperature (T_{drt}) :

$$T_{\text{drt}} = 0.5 \times T_{\text{ai}} + 0.5T_{\text{mrt}} \tag{2.13}$$

In addition to independent personal and environmental parameters influencing thermal comfort, other factors may also have some effect. Food and drink consumed may have an influence on metabolism, thus have an effect on heat production and dissipation. Body shape is significant in that heat production is proportional to body mass, but heat dissipation depends on body surface area. Age and gender may have modicum influence in preferred temperature.

2.4.3 Thermo-Regulation

The human thermo-regulatory system attempts to maintain a constant deep body temperature of 36.8 °C. The *hypothalamus*, located in the brain, controls various physiological processes to regulate body temperature. Its control behavior is primarily proportional to deviations from deep-body temperatures with some integral and derivative response aspects. The most important and often-used physiological process is regulating blood flow to the skin: *vasodilation* (in extreme heat when internal temperatures rise above a set point), more blood is directed to the skin, to transport internal heat to elevate the skin temperature and increase heat dissipation to the environment. *Vasoconstriction* (in extreme cold when body temperatures fall below the deep-body temperature), skin blood flow is reduced to conserve heat. The effect of maximum vasoconstriction is equivalent to the insulating effect of a heavy sweater.

At temperatures less than the set point, muscle tension increases to generate additional heat; where muscle groups are opposed, this may increase to visible shivering, which can increase resting heat production to 4.5 met. At elevated internal temperatures, sweating occurs. This defence mechanism is a powerful way to cool the skin and increase heat loss from the core.

Insufficient heat loss leads to overheating (hyperthermia), and excessive heat loss results in body cooling (hypothermia).

2.4.4 Thermal Neutrality

Adaptive models predict the almost constant conditions under which people are likely to be comfortable in buildings. In general, people naturally adapt and may also make various adjustments to themselves and their surroundings to reduce discomfort and physiological strain. Auliciems (1981 and 1982) proposed psycho-physiological model of thermal perception, which is the basis of the adaptive models. It has been empirically established that, through adaptive actions, an acceptable degree of comfort in residences and offices is possible over a range of air temperatures from about 17 to 31 °C (Humphreys and Nicol 1998). An ASHRAE sponsored study (de Dear et al. 1997) compiled an extensive database from past field studies to study, develop, and test adaptive models (ASHRAE 2009).

Adaptive adjustments are typically conscious actions such as altering dress codes, posture, flexible activity schedules or levels, rate of working, diet, ventilation, air movement, and local temperature. They may also include unconscious long-term changes to physiological set points and gains for control of shivering, skin blood flow, and sweating, as well as adjustments to body fluid levels and salt loss after a few days of exposure up to about six months. In a hot climate this may consist of increased blood volume, which improves the effectiveness of vasodilation, enhanced performance of the sweat mechanism, as well as the readjustment of set point. In cold climate the vasoconstriction may become permanent, with reduced blood volume, whilst the body metabolic rate may increase (Szokolay 2008). The adjustment of seasonal preferences can be quite significant, even over a period of a month.

The term 'thermal neutrality' refers to a specific value of the indoor thermal environmental index (e.g. operative temperature) corresponding to a mean thermal sensation vote of zero on the seven-point scale (i.e. *neutral*). Values of thermal neutrality were calculated by using an empirical correlation function developed by de Dear and Brager (2002) as an improved version of the function earlier proposed by Auliciems (1981) and Humphreys (1978). Thermal neutrality (T_c) is expressed as a function of mean monthly temperature ($\overline{T}_o$):

$$T_c = 17.8 + 0.31 \times \overline{T}_o \tag{2.14}$$

with the limitation that 17 ºC < T_c > 31 ºC (Humphreys and Nicol 1998).

If mean monthly outdoor temperature is less than 10 °C or greater than 33.5 °C, this option may not be used (ASHRAE 2010).

2.5 Environmental Indices and Comfort Zone

The comfort zone is defined in terms of a range of thermally acceptable conditions within which the average person would feel comfortable. The environmental conditions required for comfort are not the same for everyone. However, extensive laboratory and field data have been collected that provide the necessary statistical data to define conditions that a specified percentage of occupants will find thermally comfortable. The comfort parameters are derived usually to satisfy about 80–90% people in a space.

As thermal comfort is influenced by four environmental parameters, attempts have been made to create a single index. An environmental index combines two or more parameters (e.g. air temperature, mean radiant temperature, humidity, air velocity) into a single variable to express the thermal response. Indices simplify description of the thermal environment and the stress it imposes. Since the early 1900s large number of thermal indices has been developed in various countries throughout the world. Environmental indices may be classified according to how they are developed. Empirical indices are based on field measurements with subject under defined environmental conditions or simplified relationships that do not necessarily follow theory. Rational or analytical indices are based on the theoretical concepts of the thermal exchanges with the environment i.e. heat flow paths from metabolic heat production to the environment and resistances to such flows.

The earliest empirical index, Effective Temperature, was developed at ASHVE Pittsburgh research laboratories (Houghten and Yaglaglou 1923a, b). It is defined as the temperature of a still, saturated atmosphere, which would, in the absence of radiation, produce the same effect as the atmosphere in question. It is represented by a set of equal *comfort lines* drawn on the psychrometric chart. There are about 30 different such indices developed over the years by various research workers, all based on different studies, all with different derivations and names (Auliciems and Szokolay 2007).

Effective Temperature (ET*) is an analytical index and it has the widest range of application in practice. It is defined as the temperature (DBT) of a uniform enclosure at 50% relative humidity, which would produce the same net heat exchange by radiation, convection and evaporation as the environment in question. It combines temperature and humidity into one single index, so two environments with the same ET* should evoke the same thermal response even though they have different temperatures and humidities, as long as they have the same air velocities. Because ET* depends on clothing and activity, it is not possible to generate a universal ET* chart.

A standard set of conditions representative of typical indoor applications is used to define a standard effective temperature SET*, defined as the equivalent air temperature of an isothermal environment at 50% relative humidity in which a subject, wearing clothing standardized for the activity concerned, has the same heat stress and thermoregulatory strain as in the actual environment. It is interpreted as a sub-set of ET* under standardized conditions: clothing standardised for given activities. At sea level, under the above standard environmental conditions SET = ET*. The SET thus defined combines the effect of temperature and humidity, the two most important determinants. The slope of the SET lines indicates that at higher humidities the temperature tolerance is reduced, whilst at lower humidities higher temperatures are acceptable.

ASHRAE used the psychrometric chart for the definition of the comfort zone since 1966. Current and past studies periodically reviewed to update ASHRAE Handbook of Fundamentals, which specifies conditions or comfort zones where 80% of sedentary or slightly active persons find the environment thermally acceptable. The 1966 version gave the temperature limits by DBT (vertical) lines and the humidity limits by two RH curves. In 1974 the side boundaries changed to ET* lines and the humidity boundaries were defined in terms of vapour pressure (or the corresponding AH or RH (horizontal) lines.

The ASHRAE Handbook of Fundamentals (2009) specifies summer and winter comfort zones, Fig. 2.4, appropriate for clothing insulation levels of 0.5 [0.078 (m^2 K/W)] and 1 clo [0.155 (m^2 K/W)] respectively. It is assumed that a winter business suit has about 1 clo of insulation, and a short-sleeved shirt and trousers has about 0.5 clo. This is justified by needing an "objective" reason, rather than a nebulous notion of 'acclimatisation'. The warmer and cooler temperature borders of the comfort zones are affected by humidity and coincide with the lines of constant ET*. In the middle of a zone, typical person wearing the prescribed clothing would have a thermal sensation at or very near neutral. Near the boundary of the warmer zone, a person would feel about +0.5 warmer on the ASHRAE thermal sensation scale; near the boundary of the cooler zone, that person may have a thermal sensation of −0.5. In general, comfort temperature for other clothing levels can be approximated

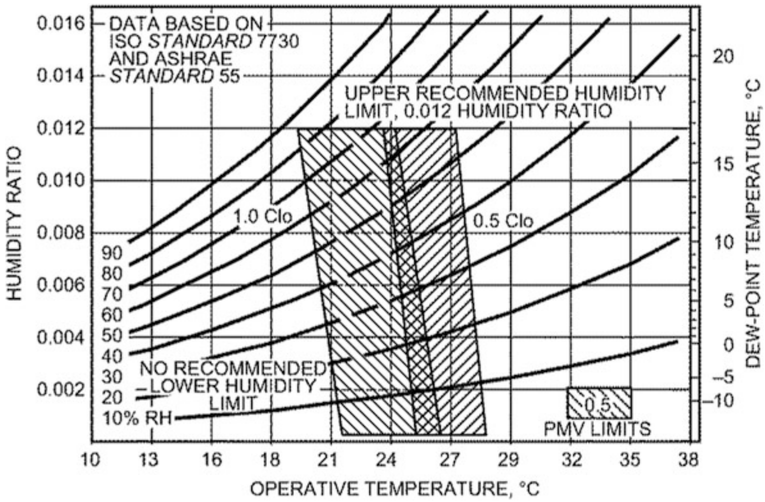

Fig. 2.4 ASHRAE summer and winter comfort zones. © ASHRAE, www.ashrae.org, (2009) ASHRAE Handbook of Fundamentals

by decreasing the temperature border of the zone by 0.6 K for each 0.1 clo increase in clothing insulation and vice versa. Similarly, a zone's temperatures can be decreased by 1.4 K per met increase in activity above 1.2 met.

ASHRAE (2009) specifies the upper humidity ratio limit of 0.012 $kg_w/kg_{dry\ air}$ because it restrict the evaporation and thus the cooling effect. There is no lower limit specified, but the accepted lower humidity limit is 4 g/kg for non-thermal comfort factors such as skin drying, irritation of mucus membranes, dryness of the eyes, and static electricity generation (Liviana et al. 1988).

The comfort zone can be plotted on this chart that will vary with the climate and be different for each month. The procedure may be as follows:

The thermal neutrality temperature (T_c) as Eq. (2.14): $T_c = 17.8 + 0.31 \times T_o$ is used as a threshold to articulate comfort zone for both the summer and the winter month. The temperature limits of such a comfort zone is taken as ($T_c - 2.5$) °C to ($T_c + 2.5$) °C for 90% acceptability. The SET coincides with DBT at the 50% RH curve; these points are marked on the 50% RH curve. These will define the 'side' boundaries of the comfort zone as the corresponding SET lines. The humidity limits (top and bottom) will be 12 and 4 g/kg respectively (1.9 and 0.6 kPa vapour pressure).

Up to 14 °C the SET lines coincide with the DBT. Above that the slope of these isotherm lines is progressively increasing, with the slope coefficient taken as DBT/AH × 0.023 x (DBT − 14) which gives the deviation from the corresponding vertical DBT line for each g/kg AH, positive below the 50% and negative above it (Szokolay 2008).

Figures 2.5 and 2.6 shows the summer and winter comfort zones for Mumbai and Jaipur respectively. It is noteworthy that Mumbai has very little seasonal variation (a warm–humid climate), while as in Jaipur (a composite climate) there is a large difference between winter and summer.

2.6 Cooling and Heating Degree-Days

Degree-days (DD or Kd, Kelvin-days) is relatively simple forms of climatic data, useful as an index of climatic severity as it affects energy use for space cooling or heating. Degree-days are calculated as the difference between the prevailing external, dry bulb temperature and a 'base temperature'. Traditionally used base temperatures to calculate HDD and CDD are 18.3 °C in the United States (ASHRAE 2009). This is the external temperature at which, in theory, no artificial cooling (or heating) is required to maintain an acceptable internal temperature. If the mean temperature of a day is $\overline{T}_o$, then for day we have $T_b - \overline{T}_o$ degree days. (When $\overline{T}_o = T_b$) the degree-day number is zero). This number can then be summed for any given period, e.g. a month or a year. The number multiplied by 24 gives the degree-hours number. Degree-days are used in energy estimating methods.

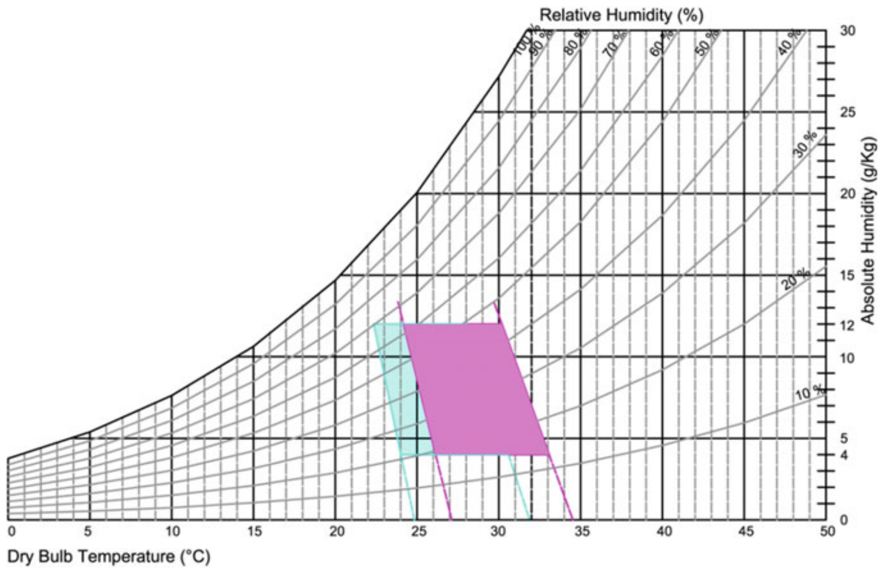

Fig. 2.5 Summer (*magenta*, *dark*) and winter (*cyan*, *light*) comfort zones for Mumbai

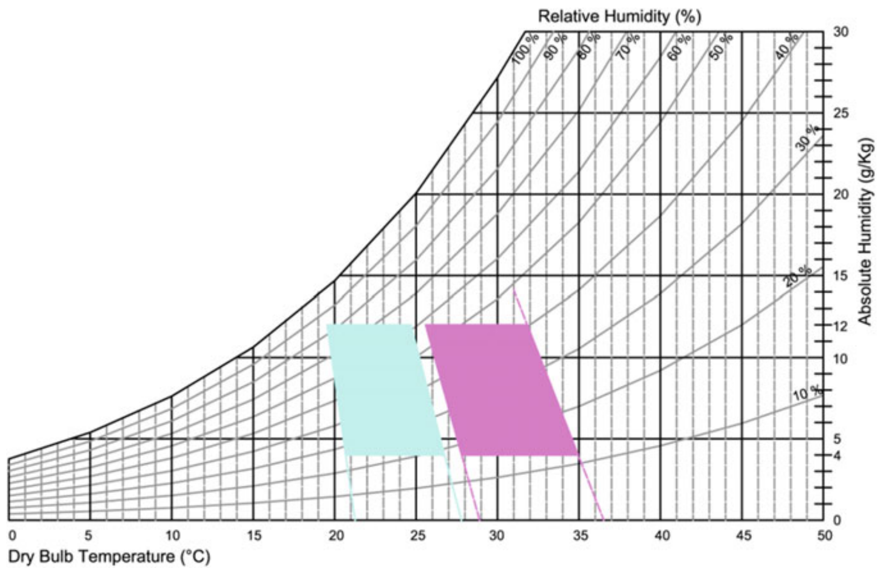

Fig. 2.6 Summer (*magenta*, *dark*) and winter (*cyan*, *light*) comfort zones for Jaipur

Two types of degree-days are used in building design. The cooling degree-days (K-day) or cooling degree-hours (K-h), indicate the warmth of the summer and hence cooling requirements. The heating degree-days (K day) indicate the severity of the winter season and therefore heating energy requirements.

Cooling and heating degree-days (base 18.0 °C) are calculated as the sum of the differences between daily average temperatures and the base temperature. The number of cooling degree-days (CDD) is defined as "cumulative temperature excess" above an agreed reference level or base temperature. For example the number of cooling degree-days (CDD) in the month is calculated as

$$\mathrm{CDD} = \sum_{i=1}^{N} (\overline{T}_{\mathrm{o}} - T_{\mathrm{b}})^{+} \tag{2.15}$$

The concept of heating degree days is rather similar to the cooling degree-days, but here the definition would be: "cumulative temperature deficit" below an agreed reference level or base temperature (T_b).

The number of monthly heating degree-days (HDD) are calculated as:

$$\mathrm{HDD} = \sum_{i=1}^{N} (T_{\mathrm{b}} - \overline{T}_{\mathrm{o}})^{+} \tag{2.16}$$

where N is the number of days in the month, T_{b} is the reference temperature to which the degree-days are calculated, and T_{o} is the mean daily temperature calculated by adding the maximum and minimum temperatures for the day, then dividing by 2. The + superscript indicates that only positive values of the bracketed quantity are taken into account in the sum.

The main source of cooling and heating degree-days (base 18.0 °C) data is the ISHRAE (2014).

2.7 Solar Geometry

The earth is almost spherical in shape, some 6371 km in radius and it revolves around the sun in a slightly elliptical (almost circular) orbit. The earth–sun distance is approximately 150×10^6 km, varying between:

152.10×10^6 km (at *aphelion*, on July 1) and

147.09×10^6 km (at *perihelion*, on January 1)

The full revolution takes 365.24 days (365 days 5 h 48' 46" to be precise) and as the calendar year is 365 days, an adjustment is necessary: one extra day every four years (the 'leap year'). This would mean 0.25 days per year, which is too much. The excess 0.01 day a year is compensated by a one day adjustment per century.

The plane of the earth's revolution is referred to as the *ecliptic*. The earth's axis is not normal to the plane of its orbit, but tilted by 23.45°. Consequently the angle between the earth's equatorial plane and the earth–sun line (or the ecliptic, the plane of the earth's orbit) varies during the year (Fig. 2.7). This angle is known as the declination (DEC) and varies as

- +23.45° on June 22 (northern solstice)
- 0° on March 21 and September 22 (equinox dates)
- −23.45° on December 22 (southern solstice).

Geographic latitude (LAT) of a point on the earth's surface is the angle subtended between the plane of the equator and the line connecting the centre with the surface point considered. The latitude of the equator is LAT = 0°, the north pole is +90°and the south pole −90°. The convention is to use negative sign for southern hemisphere latitudes. The extreme latitudes where the sun reaches the zenith at mid-summer are the 'tropics' (Fig. 2.8)

LAT = +23.45 is the tropic of Cancer and

LAT = −23.45 is the tropic of Capricorn.

The *heliocentric* view as given above is necessary for explaining the sun and earth relationship, but the *lococentric* view is essential to solve building design problems. In this view the observer's location is at the centre of the sky hemisphere, on which the sun's position can be determined by two angles (Fig. 2.9):

solar altitude (ALT): measured upwards from the horizon, 90° being the zenith

solar azimuth (AZM): measured in the horizontal plane from north (0°), through east (90°), south (180°) and west (270°) to north (360°)

Sun-path diagrams or solar charts are the simplest practical tools for depicting the sun's apparent movement. The sky hemisphere is represented by a circle (the horizon). Solar azimuth angles (i.e. the direction of the sun) are given along the perimeter and solar altitude angles (from the horizon up) are shown by a series of concentric circles, 90° (the zenith) being the centre. Several methods are in use for the construction of these charts: orthographic, equidistant, wall diagram, stereographic. The stereographic projection (developed by Phillips 1948) is widely used.

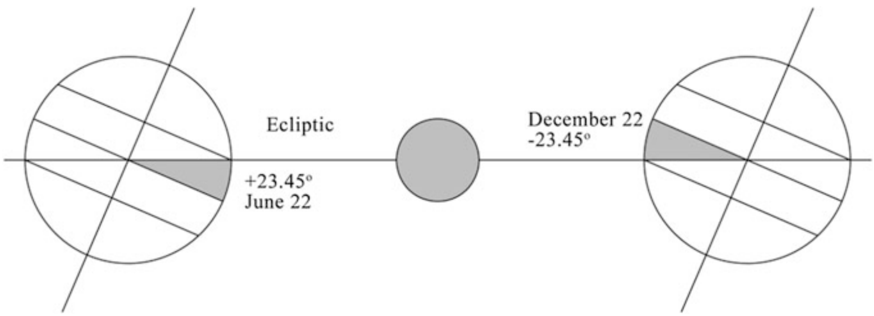

Fig. 2.7 Elevation section of the earth's orbit and solar declination (DEC)

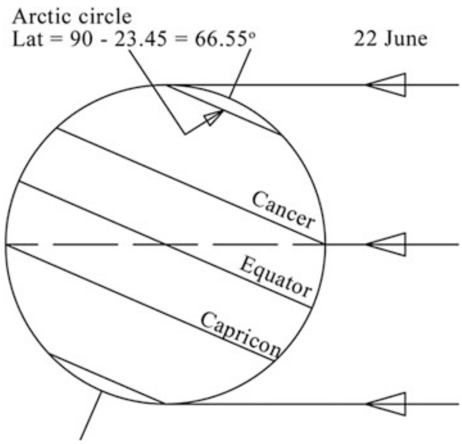

Fig. 2.8 Definitions of tropics

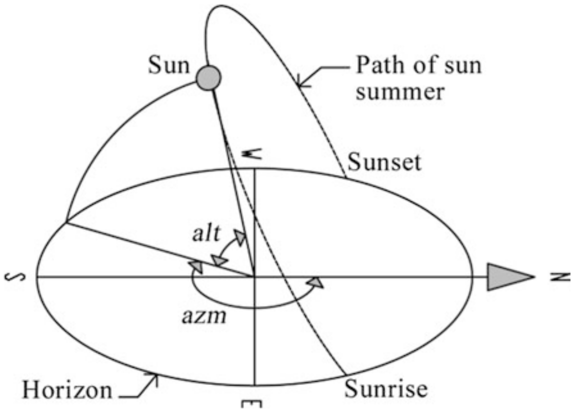

Fig. 2.9 Altitude and azimuth angles

These are constructed by a radial projection method (Fig. 2.10), in which the centre of projection is vertically below the observer's point, at a distance equal to the radius of the horizon circle (the nadir point). The sun-path lines are plotted on this chart for given latitude for the solstice days, for the equinoxes and for any intermediate dates. The date-lines (sun-path lines) are intersected by hour lines. The vertical line at the centre is noon. The solar time (local apparent time) is used on solar charts, which coincides with clock time only at the reference longitude of each time zone.

The local apparent time can be obtained from the standard time observed on a clock by applying two corrections. The first correction arises because of difference between the longitude of a location and the meridian on which the standard time is based. The correction has a magnitude of 4 min for every degree difference in longitude. The second correction called the equation of time correction is due to the

Fig. 2.10 Stereographic projection method for sun-path diagram

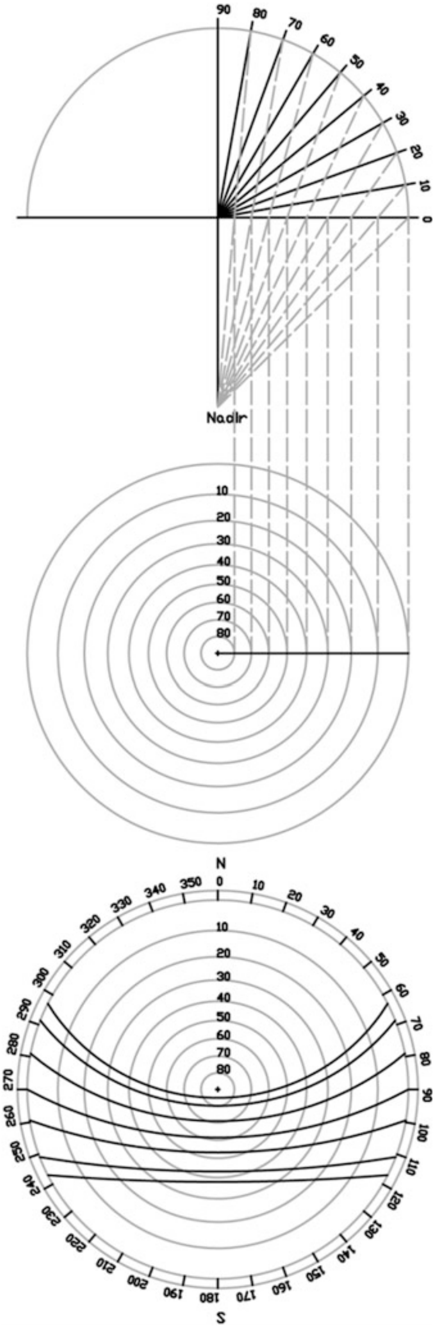

Table 2.5 Equation of time correction

Day	1–5	6–10	11–15	16–20	21–25	26–30	31
Jan	−3′14″	−5′33″	−7′41″	−9′34″	−11′10″	−12′28″	−13′26″
Feb	−13′35″	−14′09″	−14′22″	−14′16″	−13′51″	−13′11″	
Mar	−12′39″	−11′37″	−10′24″	−9′02″	−7′34″	−6′03″	−4′32″
Apr	−4′14″	−2′45″	−1′21″	−0′03″	+1′06″	+2′04″	
May	+2′50″	+3′22″	+3′41″	+3′46″	+3′37″	+3′14″	+2′38″
Jun	+2′29″	+1′41″	+0′45″	−0′17″	−1′21″	−2′26″	
Jul	−3′28″	−4′24″	+5′11″	−5′47″	−6′11″	−6′22″	−6′18″
Aug	−6′15″	−5′53″	−5′15″	−4′23″	−3′18″	−2′01″	−0′35″
Sep	−0′17″	+1′20″	+3′03″	+4′49″	+6′35″	+8′19″	
Oct	+9′59″	+11′33″	+12′58″	+14′11″	+15′10″	+15′52″	+16′16″
Nov	+16′19″	+16′20″	+16′01″	+15′21″	+14′19″	+12′56″	
Dec	+11′16″	+9′19″	+7′08″	+4′47″	+2′20″	−0′10″	−2′38″

Source Smithsonian meteorological tables (List 2000, pp. 445–446)

fact that the earth's orbit and rate of rotation are subject to small perturbations, Table 2.5. Thus,

$$\begin{aligned}\text{Local apparent time} = \text{Standard time} \pm 4\,(&\text{standard time longitude} \\ &- \text{longitude of location}) + \text{Equation of time correction}\end{aligned} \tag{2.17}$$

The negative sign in the first correction is applicable for the eastern hemisphere, while the positive sign is applicable for the western hemisphere.

For example to find LAT for Jodhpur (Long. 73°01′E) at 1330 h IST on 11th June

The Indian standard time (IST) is the mean solar time for longitude 82.5°

Difference in longitude between Jodhpur and standard meridian (S.M.) 82°30′ − 73°01′ = 9°29′

Correction for obtaining LMT at Jodhpur = 9°29′ × 4 min = 37.9 min

Since Jodhpur is to the west of SM = −37.9 min = −37 min 54 s

Local Mean Time (LMT) = 1330 – 37 min 54 s = 12 h 52 min 6 s

Equation of Time on 11th June as read from the table = 0 m 45 s

LAT 12 h 52 min 6 s + 0 min 45 s = 12 h 52 min 51 s ~ 12.88 h

The path of the sun across the sky on any day is a circle on the stereographic projection whose radius (R_s) and position of its centre (D_s) depend on the latitude of the place for which the diagram is drawn and the declination of the day. These and the radius and the distance of hour circles (R_h and D_h^1, D_h^2) can be computed from the equations given below (Lim et al. 1979):

$$R_s = \frac{R \times \cos \text{DEC}}{\sin \text{LAT} + \sin \text{DEC}} \tag{2.18}$$

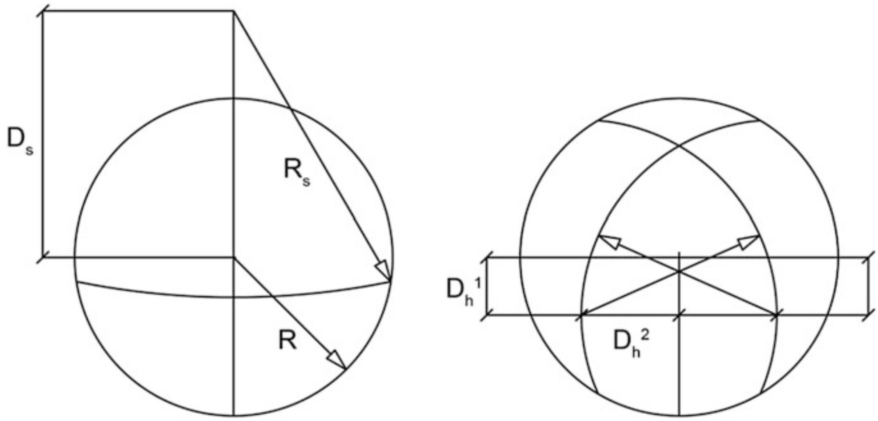

Fig. 2.11 Drawing of stereographic sun-path diagram

$$D_s = \frac{R \times \cos \text{LAT}}{\sin \text{LAT} + \sin \text{DEC}} \tag{2.19}$$

$$R_h = \frac{R}{\cos \text{LAT} \times \sin \omega} \tag{2.20}$$

$$D_h^1 = R \times \tan \text{LAT} \tag{2.21}$$

$$D_h^2 = \pm \frac{R}{\cos \text{LAT} \times \tan \omega} \tag{2.22}$$

where DEC = declination, LAT = latitude, ω = hour angle (noon = 0), R = Radius of the stereographic projection of the horizon circle. Fig. 2.11 illustrates drawing of stereographic sun-path diagram.

Chapter 5 presents sun-path diagrams of 62 cities in India drawn using the software Winshade (Kabre 1999).

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