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MANUAL OF TROPICAL HOUSING AND BUILDING Climatic Design OH Koenigsberger Professor and Head, Development Planning Unit, School of Environmental Studies, University of London, UK TG Ingersoll former Deputy Head of the Housing and Research Unit, University of Science and Technology, Kumasi, Ghana Alan Mayhew Director of Development, University College of Cape Coast, Ghana SV Szokolay Senior Lecturer in Environmental Science, Polytechnic of Central London, UK 3. Universities Press (India) Private Limited Registered Office 3-6-747/1/A & 3-6-754/1, Himayatnagar, Hyderabad 500 029 (A.P.), INDIA e-mail: info@universitiespress.com Distributed by Orient Blackswan Private Limited Registered Office 3-6-752 Himayatnagar, Hyderabad 500 029 (A.P.), INDIA e-mail: info@orientblackswan.com Other Offices Bangalore, Bhopal, Bhubaneshwar, Chennai, Ernakulam, Guwahati, Hyderabad, Jaipur, Kolkata, Lucknow, Mumbai, New Delhi, Noida, Patna © O.H. Koenigsberger, T.G. Ingersoll, Alan Mayhew and S.V. 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Plant:Tropical daylight and sunlight University College, London, 1967 (duplicated) Fig 107 D. Paix:The design of buildings for daylighting Commonwealth Exp. Bldg. Stn. (Sydney) 1962 Fig 109 Illuminating Engr. Society, Technical Report No 10 Evaluation of discomfort glare Fig 128 Exp. Bldg. Stn. Notes on the Science of Bldg No 80: 'Some common noise problems' Fig 129 P. H. Parkin and H. R. Humphreys Acoustics, noise and buildings Faber, 1958 13. List of figures A absorption g glare (in general) or glare constant A area of surface HSI heat stress index a absorbance (absorption coefficient) h height AH absolute humidity l intensity AMR annual mean range la intensity of direct radiation AMT annual mean temperature ld intensity of diffuse radiation At total surface area 1o reference intensity (sound) b thickness (breadth) IRC internally reflected component C conductance K thermal diffusivity CET corrected effective temperature k conductivity CS contrast sensitivity L luminance Cnd conduction Lh luminance at horizon Cnv convection Lz luminance at zenith c specific heat Ly luminance at y altitude angle D dirt factor M mass per unit surface DBT dry bulb temperature Met metabolism DF daylight factor MF maintenance factor d density MRT mean radiant temperature 14. d distance (length) N number (of air changes per hour) E illumination (eclairage) NC noise criteria Ei illumination indoors (at defined) OT operative temperature point) P4SR predicted four hour sweat rate ΔEmax magnitude of illumination vector P pressure (atmospheric ~) En illumination of normal plane Pa partial pressure - dry air Eo illumination outdoors Ps stack pressure Es scalar illumination Pv partial pressure - vapour Eβ illumination on plane tilted by β Pvs saturation point vapour pressure degrees Pw wind pressure ECI equatorial comfort index p position index ERC externally reflected component Q heat flow rate ET effective temperature Qc conduction heat flow rate EW equivalent warmth Qe evaporative cooling rate Evp evaporation Qi internal heat gain, rate of ~ e emittance Qm mechanical heating/cooling rate F function of . . . Qs solar heat gain, rate of ~ F flux (flow) of light Qv ventilation heat flow rate Fl flux emitted by lamps q heat flow rate, density of ~ 15. Fr flux received (on working plane) R red (hue designation) FF framing factor Rad radiation f frequency RH relative humidity f surface or film conductance RT resultant temperature fi inside surface conductance R resistance fo outside surface conductance Ra air-to-air resistance G glare index Rc cavity resistance GF glazing factor r reflectance S total surface area v velocity s component surface areas WBT wet bulb temperature SC sky component α solar azimuth angle SH saturation point humidity β angle of incidence Tl transmission loss γ solar altitude angle Tm mean outside air temperature δ azimuth difference (=horizontai Ti inside air temperature shadow angle) To outside air temperature ∈ efficiency Ts sol-air temperature ∈ vertical shadow angle Tse sol-air excess temperature θ solar gain factor ΔT temperature difference λ wavelength 16. t transmittance (transmission μ decrement factor coefficient) ϕ time-lag U air-to-air transmittance ψ visual angle (solid angle) UF utilisation factor ρ visual angle V Munsell value ω wall azimuth angle (orientation) V ventilation rate 17. Preface and acknowledgements This book is intended as a textbook for students, as a reference work for practitioners and as an aid for their clients - investors, administrators and politicians. It is the result of the joint efforts of its authors, their fellow teachers and several generations of students who used successive drafts, recorded their reactions and experiences and provided material for revision and rewriting. I started working on the manual in 1952 to record the experience of twelve years of planning and building in India. The first draft provided the nucleus for a course in tropical architecture started in 1953 with E. Maxwell Fry as director at the Architectural Association in London*. It was designed to meet the demands of students from tropical countries for a syllabus centred on their specific needs. Some twenty to thirty architects, planners and builders from as many different countries assembled every year for a period of joint studies. The first draft of the Manual served to structure their discussions and was gradually developed and changed in the 'give and take' between teachers and students. After about ten years T. G. Ingersoll, a teacher in the department, revised and re-wrote the text to incorporate the most recent advances in a rapidly expanding subject. Alan Mayhew, also a former teacher, produced the third version designed especially to facilitate learning and teaching, and S. V. Szokolay prepared the manuscript for publication. He re-wrote some chapters and added others on the basis of his teaching experience in Africa and authoritative knowledge of building science. He also undertook and completed the - by no means negligable - task of translating and re- calculating formulas, tables, graphs and figures to fit into the new international system of measurements and notations. My fellow authors join me in recording their gratitude to the many colleagues and students who helped during the long gestation period of this manual. My particular thanks go to the trustees of the Halley Stewart Trust who had the foresight of financing the beginning of the work. August 1972 Otto Koenigsberger * Later 'Department of Development and Tropical Studies' and, since 1971, 'Development Planning Unit of the School of Environmental Studies, University College, London. 18. Introduction For most of the tropics, traditional housing is rural housing. Some of the countries of the arid belt of the northern hemisphere, notably Iraq, Egypt and the Maghreb countries, Iran, Rajastan, the Punjab and southern China have town-house traditions from which new urban building forms could develop. Yet, these are exceptions in the tropical world where the process of urbanisation has gathered momentum only in the last four or five decades. The majority of the people of the tropics still live dispersed in low density rural settlements and deal with their housing problems in the same manner as their fathers and forefathers have done. Traditional house types have developed in response to the needs of a predominantly peasant population. The surrounding country provides the building materials: in the humid tropics timber, bamboo and thatch; in arid zones stone, earth and bricks; and in composite climates a mixture of organic and inorganic materials. The rhythm of country life includes time for building as much as for tilling, sowing and harvesting. Everybody is a house builder as much as he is cultivator or herdsman. Traditional rural building is based on low investment and high maintenance. Monetary transactions are minimal. The assistance of relations, friends and neighbours is rewarded by food, drink and mutual help. Children and adults spend most of the day in the open. The functions of huts and houses are reduced to three: shelter from rain and spells of extreme heat or cold, minimal privacy and the safe storage of possessions. The safe storage of agricultural products receives as much — and often more — attention than shelter for human beings. Space is plentiful. Growing family or tribal units can be accommodated easily by the addition of huts, stores and enclosures as the need arises. Waste disposal and health problems are solved, or at least mitigated, by dispersal. There are a few exceptions. In the Nile Valley, in the hinterland of Peshawar, and in parts of Bengal and southern China, for instance, land is so fertile and so much in demand that villagers have to be as careful in its use as townsfolk. Yet in most rural communities, the land needs for housing are negligeable compared to those of agriculture. The traditional building forms of the rural tropics often include sound solutions of climatic problems. Given technological limitations and the always overriding considerations of safety, some of these solutions must be considered ingenious, and there can be no doubt that they deserve careful study. Yet the most pressing housing needs of the tropics are urban, and traditional forms because of their origin in the life and economy of rural societies are seldom suited to urban conditions. This is demonstrated convincingly by going through the above-described features of rural life and noting how few of them apply in towns and cities. Building materials for city needs cannot be taken from the surrounding countryside without, in the case of organic materials, denuding it of vegetation or, in the case of earth building, making borrow pits of dangerous dimensions. Building materials that have to be brought in over large distances cease to be cheap. The rhythm of city life does not include time for house building, least of all for the poorest, the unemployed, the casual or unskilled labourer who has to fight hard to stay alive and who cannot afford to miss a chance of finding a foothold in the urban economy. Even time for maintenance work becomes scarce and the townsman soon learns to value durable materials and methods that do not need frequent attention. He receives money for his labour and is 19. expected to pay cash for the services he requires including those of builders. His family, like that of the villager, spends a good part of the day in the open, but space for outdoor living is not as plentiful and suitable. Safe storage of possessions is even more important than in the open country. So is privacy, but both are more difficult to achieve. Yet it is space, a commodity so plentiful and so little valued in rural life, that becomes a major concern for the town-dweller. It is not a matter of the total amount of land available - although that too can be a problem in certain urban areas - but rather a question of location. Because he wants to be near to, work, schools and shops, the townsman must be content with a small piece of ground and adjust his life style, household size and building methods to proximity with others. Proximity makes major issues out of problems that the villager can afford to neglect. Fire hazards, waste disposal, sanitation, and noise pollution are typical urban problems that cannot be solved by going back to essentially rural traditions. They cannot be solved either by the adoption of Western technology and Western patterns that have their origin in different climates, different cultures and different economic conditions. It seems so obvious that house types and building materials from cold climates cannot solve the problems of cities where heat is the dominant problem and that solutions from communities with average per capita incomes of S7 000 per annum cannot work in communities where the income is less than S70. Yet the cities of the tropics are full of galvanised iron roofs, plate glass windows and buildings that could just as well stand in Manchester, Detroit or Montreal. The resulting urban environment is climatically and socially inadequate. A wealthy elite can escape the consequences of poor design through mechanical air- conditioning. The others suffer from living conditions that permit neither efficient work nor rest or enjoyment. It is the purpose of this manual to demonstrate that this need not be so, that it is possible to create cities that have pleasant indoor and outdoor living spaces and are suited to the social conditions of their inhabitants. 20. Section 1 Climate: The given conditions 1.1 Global climatic factors 1.2 Elements of climates 1.3 Classification of tropical climates 1.4 Site climate 21. 1.1 Global climatic factors 1.1.1 Climate and tropical climates 1.1.2 Solar radiation: quality 1.1.3 Solar radiation: quantity 1.1.4 Tilt of the earth's axis 1.1.5 Radiation at the earth's surface 1.1.6 The earth's thermal balance 1.1.7 Winds: thermal forces 1.1.8 Trade-winds: the Coriolis force 1.1.9 Mid-latitude westerlies 1.1.10 Polar winds 1.1.11 Annual wind shifts 1.1.12 Influence of topography 1.1.1 Climate and tropical climates Climate (from Greek: klima) is defined by the Oxford dictionary as 'region with certain conditions of temperature, dryness, wind, light, etc.'. A somewhat more scientific definition is: 'an integration in time of the physical states of the atmospheric environment, characteristic of a certain geographical location.' As weather is the momentary state of the atmospheric environment at a certain location, climate could be defined as 'the integration in time of weather conditions'. Tropical climates are those where heat is the dominant problem, where, for the greater part of the year buildings serve to keep the occupants cool, rather than warm, where the annual mean temperature is not less than 20°C. Before tropical climates can be examined in detail, we must survey the factors shaping the climates, on a global scale. 1.1.2 Solar radiation: quality 22. The earth receives almost all its energy from the sun in the form of radiation, thus the sun is the dominating influence on climates. The spectrum of solar radiation extends from 290 to 2 300 nm (nanometre = 10–9 m). According to human means of perception we can distinguish: a ultra-violet radiation, 290 to 380 nm, producing photo-chemical effects, bleaching, sunburn, etc. b visible light, 380 (violet) to 700 nm (red). c short infra-red radiation, 700 to 2300 nm, radiant heat with some photochemical effects. The spectral energy distribution varies with altitude, due to the filtering effect of the atmosphere. Some of the shorter wavelengths are absorbed by the atmosphere and reradiated at much longer wavelengths, e.g. long infra-red, up to 10000 nm. As the luminous efficiency of energy-radiation depends on its spectral composition, there is no constant relationship between radiation intensity and its lighting effect. However, as a general guidance, the value of 100 lumens/watt can be used for solar radiation. This would give an illumination of 100 lux for every W/m2 intensity or 100000 lux per kW/m2 1.1.3 Solar radiation: quantity The intensity of radiation reaching the upper surface of the atmosphere is taken as the solar constant: 1 395 W/m2, but it may actually vary ±2% due to variations in the output of the sun itself and it varies ±3.5% due to changes in the earth–sun distance. The earth moves around the sun in a slightly elliptical orbit. One revolution is completed in 365 days, 5 hours, 48 minutes and 46 seconds. This orbit results from the gravitational pull of the sun and the centrifugal force due to the earth's inertia and momentum. At aphelion the solar distance is 152 million km and at perihelion is is 147 million km. 1.1.4 Tilt of the earth's axis The earth rotates around its own axis, each rotation making one 24-hour day. The axis of this rotation (the line joining the North and South Poles) is tilted to the plane of the elliptical orbit, at an angle of 66.5° (i.e. a tilt of 23.5° from the normal) and the direction of this axis is constant. Maximum intensity is received on a plane normal to the direction of radiation. If the axis of earth were rectangular to the plane of the orbit, it would always be the equatorial regions which are normal to the direction of solar radiation. Due to the tilted position, however, the area receiving the maximum intensity moves north and south, between the tropic of Cancer (latitude 23.5°N.) and the tropic of Capricorn (latitude 23.5°S.). This is the main cause of seasonal changes. On 21 June areas along latitude 23.5°N. are normal to the sun's rays, the sun's apparent path goes through the zenith at this latitude, and the longest daylight period is experienced. At the same time latitude 23.5°S. experiences the shortest day and a radiation minimum. On 21 March and 23 September areas along the Equator are normal to the sun's rays and experience a zenith path of the sun. For all areas of the earth these are the equinox days (day and night of equal length). Figure 1 clearly explains this relationship. 23. Fig 1 The earth–sun relationship 1.1.5 Radiation at the earth's surface This earth–sun relationship affects the amount of radiation received at a particular point on the earth's surface three ways: 1 the cosine law, which states that the intensity on a tilted surface equals the normal intensity times the cosine of the angle of incidence. Figure 2 shows how the same amount of radiation is distributed over a larger area, therefore less radiation alls on unit area. Fig 2 The angle of incidence 2 atmospheric depletion, i.e. the absorption of radiation by ozone, vapours and dust particles in the atmosphere (a factor of 0.2 to 0.7). The lower the solar altitude angle, the longer the path of radiation through the atmosphere, thus a smaller part reaches the earth's surface. Figure 3 indicates this geometrical relationship and Figure 4 shows this effect in quantitative terms for points at different heights above sea-level. This atmospheric depletion is also affected by the momentary state of the atmosphere: its purity, vapour, dust, smoke, etc., content 3 duration of sunshine, i.e. the length of the daylight period [1]1 1.1.6 The earth's thermal balance The total amount of heat absorbed by the earth each year is balanced by a corresponding heat loss [2] Without this cooling the thermal balance of the earth could not be maintained, the temperature of the earth and its atmosphere would increase and would soon cease to be favourable to most forms of life. 24. Fig 3 Length of path through the atmosphere Figure 5 illustrates the distribution of incoming radiation and Figure 6 shows how the earth's surface releases heat by three processes: a by long-wave radiation to cold outer space (some 84% of this reradiation is absorbed in the atmosphere, only 16% escapes to space) b by evaporation: the earth's surface is cooled, as liquid water changes into vapour and mixes with air c by convection: air heated by contact with the warm earth surface becomes lighter and rises to the upper atmosphere, where it dissipates its heat to space 1.1.7 Winds: thermal forces Winds are basically convection currents in the atmosphere, tending to even out the differential heating of various zones.[2]2 The pattern of movements is modified by the earth's rotation. At the maximum heating zone (which is somewhere between the tropics of Cancer and Capricorn) air is heated by the hot surface, it expands, its pressure is decreased it becomes lighter, it rises vertically and flows off at a high level towards colder regions. Part of this air, having cooled down at the high level, descends to the surface in the subtropic regions, from where the cooler, heavier air is drawn in towards the Equator from both north and south. 25. Fig 4 Variation of direct solar intensity with height (Original by I S Groundwater in Btu/ft2h and ft units) 26. Fig 5 Passage of radiation through the atmosphere Fig 6 Heat release from the ground and the atmosphere 27. Fig 7 Global wind pattern The area where the air rises, where these northerly and southerly winds meet, where the tropical front is formed, is referred to as the inter-tropical convergence zone (ITCZ). This area experiences either completely calm conditions or only very light breezes of irregular directions and is referred to by sailors as 'doldrums'. The global pattern of thermal air movements is shown in Figure 7. The following explanation also relates to Figure 7. 1.1.8 Trade-winds: the Coriolis force The atmosphere rotates with the earth. As it is light in weight and behaves as fluid, held against the earth's surface only by gravity and friction, it has a tendency to lag behind the earth's rate of rotation where this rotation is the fastest, i.e. at the Equator. There is a slippage' at the boundary layer between the earth and its atmosphere caused by what is known as the 'Coriolis force'. The effect is experienced as a wind blowing in a direction opposite to that of the earth's rotation. The actual wind is the resultant of thermal forces and the Coriolis force (Figure 8): north- easterly winds north of the Equator and south-easterlies south of the Equator. These are known as North East and South Easttrade-winds [5], a term originated by round the world traders in the days of sailing-ships. 28. Fig 8 Wind parallelogram 1.1.9 Mid-latitude westerlies Around 30°N. and S. there are two bands of continually high barometric pressure (descending air). Winds in these zones are typically light and variable. Between 30 and 60°N. and S., however, strong westerly winds prevail, blowing in the same direction as the earth's rotation. The origin of these winds was for a long time in dispute, but it is now generally agreed that the mid-latitude westerlies can best be explained by the law of conservation of angular momentum.3 The total angular momentum of the earth–atmosphere system must remain constant. If it is reduced at the Equator by easterly winds, this must be compensated for by westerly winds elsewhere. If the air is moving from about 30° where it has a substantial circumferential velocity, towards 60° where the earth's radius of rotation, thus its circumferential velocity is much less, the faster rotating air will 'overtake' the earth's surface. 1.1.10 Polar winds Further towards the poles from latitudes 60°N. and S. the air flow patterns come once more under the influence of thermal factors. The pattern is similar to that near the Equator. Air at the surface moves from the coldest to the slightly warmer regions, i.e. away from the poles. As the circumferential velocity of air at the poles is almost nil, the air will lag behind the rotating earth as it moves away from the poles. The northerly is deflected into north-easterly and the southerly (near the South Pole) into south-easterly polar winds. At the meeting point of cold polar winds and the mid-latitude westerlies, a band of low pressure – a subpolar front – is formed, with highly variable and strong winds. 1.1.11 Annual wind shifts During the course of each year the global wind pattern shifts from north to south and back again, remaining broadly symmetrical about the inter-tropical convergence zone. The location of the ITCZ follows the maximum solar heating, i.e. the zenith path of the sun, with a delay of about a month. Figure 9 gives the extreme north and south positions of the ITCZ in July (north) and in January (south). As a consequence of this annual shift most regions of the earth experience seasonal changes not only in temperature but also in wind directions and in rainfall (as a result of air movements which carry water vapour). 1.1.12 Influence of topography On a continental scale, wind and weather are the result of an interaction between broad global flow patterns and regional pressure and temperature patterns created by the sun's differential heating effect on land, forest and water. The force, direction and moisture content of air flows are strongly influenced by topography. Air can be diverted or funnelled by mountain ranges. Air flow deflected upwards, as it cools, releases its moisture content. A descending air mass will very rarely give any precipitation, therefore rainfall characteristics vary sharply between locations on windward and leeward slopes of mountain ranges. The humidity of air will vary with the rate of evaporation of moisture from the surface below, i.e. it depends on the availability of water to be evaporated. 29. Air movements can be generated on quite a small scale, e.g. between a lake and its shores, between a quarry and a nearby forest, between a town and the surrounding countryside or even between the sunny and shaded sides of a large building, but this will be examined in more detail in 1.4.11 [6]. Fig 9 Seasonal shifts of the inter-tropical convergence zone 30. 1.2 Elements of climates 1.2.1 Climatic information 1.2.2 Temperature: measurement 1.2.3 Temperature: data 1.2.4 Humidity: measurement 1.2.5 Vapour pressure 1.2.6 Humidity: data 1.2.7 Precipitation 1.2.8 Driving rain 1.2.9 Sky conditions 1.2.10 Solar radiation: measurement 1.2.11 Solar radiation: data 1.2.12 Wind: measurement 1.2.13 Wind: data 1.2.14 Special characteristics 1.2.15 Vegetation 1.2.16 Graphic representation 1.2.1 Climatic information The designer is interested specifically in those aspects of climate which affect human comfort and the use of buildings. They include averages, changes and extremes of temperature, the temperature differences between day and night (diurnal range), humidity, sky conditions, incoming and outgoing radiation, rainfall and its distribution, air movements and special features, such as trade-winds, thunder-storms, dust-storms and hurricanes. Climatic records as gathered at airports and meteorological stations are not primarily intended 31. for the use of designers. Publications frequently omit some of the aspects that interest the designer. It is often necessary to supplement such information with unpublished data obtained directly from meteorological stations. It is the designer's task to analyse climatic information and present it in a form that allows him to identify features that are beneficial or harmful to the future occupants of his building. 1.2.2 Temperature: measurement The temperature of the air is measured in degrees Celsius (°C), most often with a mercury thermometer. The dry-bulb or 'true air temperature' is a value taken in the shade, the thermometer being mounted inside a louvred wooden box, known as the 'Stevenson screen (Figure 10), at a height of 1.20 to 1.80 m above the ground [7]. Readings can be taken at specified times of the day, or if a maximum–minimum thermometer is used, one reading daily can give the momentary temperature as well as the maximum and minimum temperatures reached in the past 24 hours. Alternatively a thermograph can be used, which is based on a bimetallic thermometer and gives a continuous graphic recording of temperature variations. 1.2.3 Temperature: data All these readings would produce an unmanageable mass of data, thus some simplification is necessary. As a broad description, monthly mean temperatures can be given for each of the 12 months. The average is taken between each day's maximum and minimum and then the average of the 30 days' average is found (and possibly as many years' average for the same month). To give an indication of diurnal variations, this can be supplemented by monthly mean maxima and minima. (Monthly mean maximum is the average of 30 days' maximum temperatures.) These will establish the monthly mean range of temperatures. It may be useful to indicate the highest and lowest temperatures ever recorded for each month, i.e. the monthly extreme maxima and minima, to establish the monthly extreme range of temperatures. These five values for each of the 12 months would give a reasonably accurate picture of temperature conditions, on which the design work can be based (see Section 8). 1.2.4 Humidity: measurement The humidity of air can be described as absolute humidity (AH), i.e. the amount of moisture actually present in unit mass or unit volume of air, in terms of gramme per kilogramme (g/kg) or gramme per cubic metre (g/m3). The relative humidity (RH) is, however, a much more useful form of expression, as it gives a direct indication of evaporation potential. The amount of moisture the air can hold (the saturation- point humidity: SH) depends on its temperature (see appendix 1.1). Relative humidity is the ratio of the actual amount of moisture present, to the amount of moisture the air could hold at the given temperature – expressed as a percentage: 32. Fig 10 The Stevenson screen Humidity is usually measured with the wet-and-dry-bulb hygrometer. This consists of two ordinary mercury thermometers mounted side by side. The first one measures the air (dry-bulb) temperature (DBT). The bulb of the second one is covered with a gauze or wick and is kept wet. Moisture evaporating gives a cooling effect, thus the reading of the wet-bulb temperature (WBT) will be less than the DBT. As in dry air the evaporation is faster, the cooling is more pronounced and the difference between the two readings (the 'wet-bulb depression') is greater. In case of 100% RH the two readings will be identical, as there is no evaporation. The rate of evaporation, thus the wet-bulb depression, is a function of the relative humidity. Having made the two readings, the corresponding RH can be found from the psychrometric chart (Figure 12), from a table or a special slide-rule (see appendix 1.2). 1.2.5 Vapour: pressure Another indication or expression of atmospheric humidity is the vapour pressure, i.e. the partial pressure of water vapour present in the air. The 'atmospheric pressure' (P) is the sum of the 'partial pressure of dry air' (Pa) and the 'partial vapour pressure'(Pv): P = Pa + Pv The air is saturated when the vapour pressure (Pv) is equal to the pressure of saturated vapour of the same temperature (Pvs). Relative humidity can also be expressed as the ratio of actual vapour pressure to the 'saturation point vapour pressure': Fig 11 A hygrograph Vapour pressure is measured in the standard SI pressure unit, the Newton per metre square (N/m2): 1 millibar = 100 N/m2. The vapour pressure concept is rarely used in practical work. The relationship of all these quantities, i.e. of dry-bulb and wet-bulb temperature, absolute and relative humidity and of vapour pressure is shown by the psychrometric chart (Figure 12). 1.2.6 Humidity: data To give an indication of prevailing humidity conditions, it is sufficient to establish the monthly 33. mean maximum (the average of 30 days' maximum) and the monthly mean minimum relative humidity values for each of the 12 months. This is only possible, where continuous hygrograph4 recordings are available. Where these are not available, readings are made just before sunrise, e.g. at 6.00 hours (which is likely to be the maximum value), and at 15.00 hours (which is near the minimum value). As the early morning values are fairly high in any climate, the afternoon values are much more characteristic of a given location. They are often used alone, as a brief indication of humidity conditions. 1.2.7 Precipitation Precipitation is the collective term used for rain, snow, hail, dew and frost, that is, for all forms of water deposited ('precipitated') from the atmosphere [8]. It is measured by rain-gauges, i.e. calibrated receptacles, and expressed in millimetre per a time unit (mm/month, mm/day). 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. Ever recorded maxima and minima would give an indication of the reliability of rains or deviations from the average. The maximum rainfall for any 24-hour period is a useful guide for the predication of flooding, and for the design of surface drainage (roofs, paved areas, gutters and downpipes) the maximum hourly rainfall intensity (mm/h) should be known. 1.2.8 Driving rain The building designer may want to know whether intense rams are associated with strong wings, in other words what is the likelihood of driving rain [9]. The driving rain index [10] characterises a given location and expresses the degree of exposure. It is the product of annual rainfall (in m) and the annual average wind velocity (in metres per second: m/s) – thus its dimension is m2/s. Up to 3 m2/s the location can be considered as 'sheltered'. The exposure is 'moderate' if the index is between 3 and 7 m2/s and 'severe' if over 7 m2/s. Obviously this index only broadly classifies the given location, the actual rain penetration will depend on the instantaneous rain intensity and the simultaneous wind velocity. 1.2.9 Sky conditions Sky conditions are usually described in terms of presence or absence of clouds. On average, two observations are made per day, when the proportion of sky covered by cloud is expressed as a percentage (some records give cloud cover in 'tenths' or even in 'eighths' or 'octets', e.g. 50%, five- tenths or four-eighths would all indicate that half of the sky hemisphere is covered by cloud). Few records exist of night-time sky conditions [11]. It would be useful for the designer to know the time of day and frequency of observations. A single average figure giving the sky conditions for a typical day of a given month may conceal significant differences, e.g. between morning and afternoon conditions, which may affect the design of roofs, overhangs and shading devices. 34. Fig 12 Psychrometric chart Sky luminance values are needed if daylighting in buildings is to be predicted. 1.2.10 Solar radiation: measurement A simple sunshine recorder will register the duration of sunshine, which can be expressed in number of hours per day, as an average for each month. A variety of more sophisticated instruments (solarimeter, heliometer, actinometer and pyranometer) are used for the quantitative recording of solar radiation, but reliable and comparable data is few and far between. Much of the available literature gives recorded intensities in Btu/ft2h5, in kcal/m2h or in langleys (cal/cm2) per hour, but the now accepted 35. international standard (SI) unit is the watt per metre square (W/m2). This is the instantaneous intensity, i.e. the incidence of energy in joules per square metre of the surface per second (W/m2 = J/m2s, as W = J/s). Total radiation received over a longer period, one day, for instance, will be expressed in J/m2day or the multiple MJ/m2day will be used (megajoule = 1 million joules) [12]. 1.2.11 Solar radiation: data Average daily amounts of solar radiation (MJ/m2day) for each month of the year would give a fair indication of climatic conditions, including seasonal variations. This could be supplemented by the highest and lowest daily totals for each month, to set the limits of variations which can be expected. For the purposes of detailed design, hourly totals (MJ/m2h), or rather hourly average intensities (W/m2), must be known for a typical day of each month – or at least for a typically high and a typically low radiation day of the year. Quantitative radiation data are not normally published by meteorological observatories, but are sometimes available on request or can be found in special publications [13]. The US Weather Bureau collects recordings of solar radiation intensity from all countries of the world. Appendix 2 gives a series of protractors for the calculation of radiation intensities under clear sky conditions, to be used in conjunction with the stereographic sun- path diagrams. Appendix 3 gives a method for estimating daily radiation totals on the basis of sunshine duration records. 1.2.12 Wind: measurement Wind velocity is measured by a cup-type or propeller anemometer, or by a Pitot tube (similar to the air-speed meters of aeroplanes), and its direction is measured by a wind vane. An anemograph can produce continuous recordings of wind velocity and directional changes. Free wind velocities are normally recorded in open flat country at a height of 10 m [14]. Measurements in urban areas are often taken at a height of between 10 and 20 m to avoid obstructions. Velocities near the ground are a good deal lower than the free wind speed. Directions can be grouped into eight or sixteen categories: the four cardinal (N., E., S. and W.) and four semi-cardinal compass points (NE., SE., SW. and NW.) and possibly the eight tertiary compass points (NNE., ENE., ESE., SSE., SSW., WSW., WNW. and NNW). Velocities ar measured in metres per second (m/s), but much data can still be found in obsolete units, such as ft/min, mph or knot (nautical mile per hour). A 'wind-force scale' developed by Beaufort in 1806, based on visual observation, is still in use in spite of its completely unscientific nature. The definitions of the twelve categories are given in appendix 4. 1.2.13 Wind: data The designer must try to determine whether there is a prevailing direction of winds, whether predictable daily or seasonal shifts occur and whether there is a recognisable pattern of daily or seasonal velocities. It is also important for him to note the calm periods in each month. All observatories record the occurrence of storms, hurricanes, typhoons or tornadoes. It is customary to tabulate winds according to their direction and velocity categories, in terms of their frequency of occurrence, over a significant time, generally 25 to 50 years. 36. Several methods of diagrammatic representation have been evolved, some of which re shown in Figures 13 and 14. Fig 13 Monthly wind frequency graph 1.2.14 Special characteristics Most regions experience conditions which are particularly unfavourable, such as hail and thunder- storms, line or arched squalls, earthquakes, tornadoes, hurricanes and dust-storms. Although such events may be rare, it is important to extract from meteorological data their frequency, likely duration and nature. The designer must classify rare events into those which affect human comfort and those which may endanger the safety of buildings and the lives of inhabitants. Discomfort – even if it impedes work or sleep – can be accepted if it is rare enough and lasts only for a few hours. Structural safety, on the other hand, must be guaranteed however infrequent the danger. 1.2.15 Vegetation The picture of climate is incomplete without some notes on the character and abundance of plant life. Although generally regarded as a function of climate, vegetation can in its turn influence the local or site climate. It is an important element in the design of out-door spaces, providing sun- shading and protection from glare. This section of the climatic survey may range from a few notes about local species of plant life to a lengthy compendium of the major native plants and trees – their shape and colour, also their preferred orientation and situation. 1.2.16 Graphic representation It is not easy to understand the nature of a particular climate by merely looking at the vast amount of data published in the records of the nearest meteorological station. It is necessary to sort, summarise and simplify available data with reference to the objectives and requirements of climatic design. This is accomplished best by adopting a standardised method of graphic presentation. Figure 15 illustrates a graphic method that was developed especially to facilitate environmental design. For the purposes of showing the diurnal variations of one climatic parameter (e.g. temperature) throughout the year, an isopleth chart can be used such as that shown in Figure 16. 37. Fig 14 Annual wind frequencies (Nairobi) To understand a new and unfamiliar climate one must relate it to a familiar one then measure and note essential differences. This is best done by using the standard graphic presentation first for the climate of one's own home-town and then for the strange climate being investigated. When the two graphs are placed side by side (or superimposed if one is transparent) similarities and differences become apparent and characteristic features can be identified. Even the comparison of simplified climate graphs (such as those shown in Figure 17) can reveal the most important differences. 38. Fig 15 Climate graph (Nairobi) – tropical upland climate Fig 16 Temperature isopleths 39. Fig 17 Comparison of climates 40. 1.3 Classification of tropical climates 1.3.1 Climatic zones 1.3.2 Tropical climates 1.3.3 Warm-humid climate 1.3.4 Warm-humid island climate 1.3.5 Hot-dry desert climate 1.3.6 Hot-dry maritime desert climate 1.3.7 Composite or monsoon climate 1.3.8 Tropical upland climate 1.3.1 Climatic zones The interaction of solar radiation with the atmosphere and the gravitational forces,together with the distribution of land and sea masses, produces an almost infinite variety of climates. However, certain zones and belts of approximately uniform climates can be distinguished. It is essential for the designer to be familiar with the character and location of these zones, as they are indicative of the climatic problems he is likely to encounter. Boundaries of climatic zones cannot be accurately mapped. One zone merges gradually and almost imperceptibly into the next. It is, nevertheless, easy to identify the zone, or the transition area between two zones, to which a particular settlement belongs. The present work concerns itself with tropical climatic zones only, as defined in 1.1.1. The subdivision of tropical climates into climatic zones should be looked upon as a useful tool of communication. It is a code that conveys a great deal of information for those who are familiar with it. Its usefulness increases with the increase of the number of people familiar with it, who accept and use it. 1.3.2 Tropical climates The classification given below was suggested by G A Atkinson in 1953. It has since been widely accepted and proven useful. The basis of this classification is given by the two atmospheric factors 41. which dominantly influence human comfort: air temperature and humidity (as it will be shown in Section 2). The main criterion is: what extremes of these two factors are likely to cause discomfort. Accordingly the tropical regions of earth are divided into three, major climatic zones and three subgroups: 1 Warm-humid equatorial climate – subgroup: warm-humid island or trade-wind climate Fig 18 Climate graph (Mombasa, Kenya) – warm-humid climate 42. Fig 19 Climate graph (Phoenix, Arizona) - hot-dry desert climate 2 Hot-dry desert, or semi-desert climate - subgroup: hot-dry maritime desert climate 3 Composite or monsoon climate (combination of 1 and 2) – subgroup: tropical upland climate These groups are referred to throughout the text. Detailed description of each zone is given below (many of the values taken from Atkinsons publication) [15]. 1.3.3 Warm-humid climate Warm-humid climates are found in a belt near the Equator extending to about 15°N. and S. Examples of cities in this zone: Lagos, Dar-es-Salam, Mombasa, Colombo, Singapore, Jakarta, Quito and Pernambuco. Figure 18 shows a climate graph for Mombasa. There is very little seasonal variation throughout the year, the only punctuation being that of 43. periods with more or less rain and the occurrence of gusty winds and electric storms. Air temperature, i.e. DBT, in the shade reaches a mean maximum during the day of between 27 and 32 °C, but occasionally it may exceed the latter value. At night the mean minimum varies between 21 and 27 °C. Both the diurnal and annual ranges of temperature are quite narrow. Humidity, i.e. RH, remains high, at about 75% for most of the time, but it may vary from 55 to almost 100%. Vapour pressure is steady in the region of 2500 to 3000 N/m2. Precipitation is high throughout the year, generally becoming more intense for several consecutive months. Annual rainfall can vary from 2000 to 5000 mm and may exceed 500 mm in one month, the wettest month. During severe storms rain may fall at the rate of 100 mm/h for short periods. Sky conditions are fairly Cloudy throughout the year. Cloud cover varies between 60 and 90%. Skies can be bright, a luminance of 7000 cd/m2 or even more when it is thinly overcast, or when the sun illuminates white cumulus clouds without itself being obscured. When heavily overcast, the sky is dull, 850 cd/m2 or less. Solar radiation is partly reflected and partly scattered by the cloud blanket or the high vapour content of the atmosphere, therefore the radiation reaching the ground is diffuse, but strong, and can cause painful sky glare. Cloud and vapour content also prevents or reduces outgoing radiation from the earth and sea to the night sky, thus the accumulated heat is not readily dissipated. Wind velocities are typically low, calm periods are frequent, but strong winds can occur during rain squalls. Gusts of 30 m/s have been reported. There are usually one or two dominant directions. Vegetation grows quickly due to frequent rains and high temperatures and it is difficult to control. The red or brown laterite soils are generally poor for agriculture. Plant-supporting organic substances and mineral salts are dissolved and washed away by rain-water. The subsoil water table is usually high and the ground may be waterlogged. Little light is reflected from the ground. Special characteristics: high humidity accelerates mould and algal growth, rusting and rotting. Organic building materials tend to decay rapidly. Mosquitoes and other insects abound. The thunder-storms are accompanied by frequent air-to- air electrical discharges. 1.3.4 Warm-humid island climate Islands within the equatorial belt and in the trade-winds zone belong to this climate type. Typical examples are the Caribbeans,the Philippines and other island groups in the Pacific Ocean. Seasonal variations are negligible. Air temperature, i.e. DBT, in the shade reaches a day-time mean maximum between 29 and 32°C and rarely rises above skin temperature. Night-time mean minima can be as low as 18°C, but it is normally between this figure and 24°C. The diurnal range is rarely more than 8 degC and the annual range is only about 14 degC. Humidity, i.e. the RH, varies between 55 and almost 100%, the vapour pressure being between 1 750 and 2500 N/m2. Precipitation is high, 1 250 to 1 800 mm per annum, and 200 to 250 mm in the 27 wettest month. Up to 250 mm may fall in a single storm of a few hours' duration. Spray is driven nearly 44. horizontally on windward coasts. Sky conditions are normally clear or filled with white broken clouds of high brightness, except during storms, when the skies are dark and dull. Clear blue skies are of low luminance, between 1 700 and 2500 cd/m2. Solar radiation is strong and mainly direct, with a very small diffuse component when the sky is clear, but varies with the cloud cover. Winds: the predominant trade-wind blows at a steady 6 to 7 m/s and provides relief from heat and humidity. Much higher velocities occur during cyclones (see below). Vegetation is less luxuriant and of a lighter green colour than in the warm-humid zones. It varies with the rainfall. Sunlight reflected from light coloured coral, sand and rock can be very bright. The soil is often dry with a fairly low water-table. Special characteristics are the tropical cyclones or hurricanes with wind velocities from 45 to 70 m/s, which constitute a serious seasonal hazard. The high salt content of the atmosphere encourages corrosion in coastal areas. 1.3.5 Hot-dry desert climate These climates occur in two belts at latitudes between approximately 15 and 30° north and south of the Equator. Examples of settlements in this zone: Assuan, Baghdad, Alice Springs, and Phoenix. Figure 19 shows a climate graph for the last-named. Two marked seasons occur: a hot and a somewhat cooler period. Air temperature, i.e. DBT, in the shade rises quickly after sunrise to a day-time mean maximum of 43 to 49 °C. The ever-recorded maximum temperature of 58 °C was measured in Libya in 1922. During the cool season the mean maximum temperature ranges from 27 to 32 °C. Night-time mean minima are between 24 and 30°C in the hot season and between 10 and 18°C in the cool season. The diurnal range is very great: 17 to 22 degC. Humidity, i.e. the RH, varies from 10 to 55%, as the wet-bulb depression is large (rapid evaporation). The vapour pressure is normally between 750 and 1 500 N/m2 Precipitation is slight and variable throughout the year, from 50 to 155 mm per annum. Flash- storms may occur over limited areas with as much as 50 mm rain in a few hours, but some regions may not have any rain for several years. Sky conditions are normally clear. Clouds are few due to the low humidity of the air. The sky is usually dark blue, with a luminance of 1 700 to 2500 cd/m2, and further darkened during dust or sand-storms to 850 cd/m2 or even less. Towards the end of the hot period, dust suspended in the air may create a white haze, with a luminance of 3 500 to 10000 cd/m2, which produces a diffuse light and a painful glare. Solar radiation is direct and strong during the day, but the absence of cloud permits easy release of the heat stored during the day-time in the form of long-wave radiation towards the cold night sky. Diffuse radiation is only present during dust haze periods. Winds are usually local. The heating of air over the hot ground causes a temperature inversion, and as the lower warm air mass breaks through the higher cooler air, local whirlwinds are often created. Winds are hot, carrying dust and sand – and often develop into dust-storms. 45. Vegetation is sparse and difficult to maintain because of the lack of rain and low humidities. The soil is usually dusty and very dry. Strong sunlight illuminating a highly reflective light coloured and dry ground can create a luminance of 20000 to 25000 cd/m2. Soils dry quickly after rain and would generally be fertile if irrigated. The subsoil water-table is very low. Special characteristics: during certain months dust and sand-storms may be frequent. The high day-time temperatures and rapid cooling at- night may cause materials to crack and break up. 1.3.6 Hot-dry maritime desert climate Maritime desert climates occur in the same latitude belts as the hot-dry desert climates, where the sea adjoins a large land mass. These are regarded to be amongst the most unfavourable climates of the earth. Typical examples are Kuwait, Antofagasta and Karachi. There are two seasons: a hot one and somewhat cooler one. Air temperature, i.e. DBT, in the shade reaches a day-time mean maximum of about 38°C, but in the cool season it remains between 21 and 26°C. The night-time mean minimum temperatures of the hot season range from 24 to 30°C and of the cool season from 10 to 18°C. The diurnal mean range varies between 9 and 12 degC, the larger diurnal variation occurring during the cool season. Humidity, i.e. the RH, is steadily high, between 50 and 90%, with vapour pressures of 1 500 to 2 500 N/m2, as the strong solar radiation causes strong evaporation from the sea. The moisture is, however, not precipitated but remains suspended in the air, creating intensely uncomfortable conditions. Precipitation, as in other desert regions, is very low. Sky conditions are as for hot-dry desert climates, a little more cloud may occur in the form of a thin, transparent haze, which is likely to cause glare. Solar radiation is strong, with a higher diffuse component than in desert climates, due to the thin clouds and suspended moisture. Winds are mostly local, coastal winds, caused by the unequal heating and cooling of land and sea surfaces. These tend to blow off the sea towards the land during the day and in the reverse direction during the night. Vegetation is sparse, not more than some dry grass. The ground and rocks are brown or red; it is dry and dusty throughout the year. Ground glare can be intense. Special characteristics: dust and sand-storms may occur. The salt laden atmosphere accelerates corrosion. 1.3.7 Composite or monsoon climate These climates usually occur in large land masses near the tropics of Cancer and Capricorn, which are sufficiently far from the Equator to experience marked seasonal changes in solar radiation and wind direction. Examples of cities with composite climates: Lahore, Mandalay, Asuncion, Kano and New Delhi. The latter is shown as an example in Figure 20. Two seasons occur normally. Approximately two-thirds of the year is hot-dry and the other third is warm-humid. Localities further north and south often have a third season, best described as cool-dry. 46. Air temperature, i.e. DBT, in the shade is as follows: Humidity, i.e. the RH, is low throughout the dry periods at 20 to 55%, with a vapour pressure of 1 300 to 1 600 N/m2. During the wet period it rises to 55 to 95%, with a vapour pressure of 2000 to 2500 N/m2. Precipitation: the monsoon rains are intense and prolonged; occasionally 25 to 38 mm can fall in an hour. Annual rainfall varies from 500 to 1 300 mm with 200 to 250 mm in the wettest month. There is little or no rain during the dry seasons. Sky conditions markedly vary with the seasons. The sky is heavily overcast and dull during the monsoons, and clear, with a dark blue colour, in the dry seasons. Towards the end of the hot-dry seasons the sky becomes brighter with frequent dust haze. The intensity of sky glare varies accordingly. Solar radiation alternates between conditions found in the warm-humid and the hot-dry desert climates. Winds are hot and dusty during the dry period. Directional changes in the prevailing winds at the beginning of the warm-humid season bring rain-clouds and humid air from the sea. Monsoon winds are fairly strong and steady. 47. Fig 20 Climate graph (New Delhi) – composite or monsoon climate Vegetation, which is sparse – characteristic of a hot-dry region – with brown and red barren ground, changes rapidly and dramatically with the rain. The landscape becomes green and fertile within a few days. Plants grow quickly. In the cooler period vegetation covers the ground, but diminishes as the temperature rises. The soil is damp during the rains but it dries out quickly. There is a risk of soil erosion during monsoons. In the dry season strong ground glare may be experienced. Special characteristics: seasonal changes in relative humidity cause rapid weakening of building materials. Dust and sand-storms may occur. Termites are common. Occasional condensation problems. 1.3.8 Tropical upland climate 48. Mountainous regions and plateaux more than 900 to 1 200 m above sea-level experience such climates, between the two 20°C isotherms. Examples of cities in such regions: Addis Ababa, Bogota, Mexico City and Nairobi. A climate graph for Nairobi has been given in Figure 15. Seasonal variations are small in upland climates near the Equator, but when further away from the Equator, the seasons follow those of the nearby lowlands. Air temperature, i.e. the DBT, in the shade decreases with altitude. At an altitude of 1 800 m the day-time mean maxima may range from 24 to 30°C and the nighttime mean minima are around 10 to 13°C. At some locations it may fall below 4°C and ground frost is not uncommon. The diurnal range is great. The annual range depends on latitude: at the Equator it is slight; but at the tropics of Cancer and Capricorn it may be 11 to 20 degC. Humidity, i.e. the RH, varies between 45 and 99% and the vapour pressure between 800 and 1 600 N/m2. Precipitation is variable, but rarely less than 1 000 mm. Rain often falls in heavy concentrated showers, reaching an intensity of 80 mm per hour. Sky conditions are normally clear or partly cloudy, to the extent of about 40%. During the monsoon rains the sky is overcast – and the clouds are heavy and low. Solar radiation is strong and direct during the clear periods, stronger than at the same latitude, but at sea-level. Ultra-violet radiation especially is stronger than at lower altitudes. It becomes more diffuse as cloud cover increases. Winds are variable, predominantly north-east and south-easterlies, but may be drastically deflected by local topography. Wind velocity rarely exceeds 15 m/s. Vegetation is green although not very luxuriant during the wet season but it may wither in the dry season, when the ground can turn brown or red. The soil may be damp in the rains but dries quickly. Special characteristics: heavy dew at night. Strong radiation loss at night during the dry season, which may lead to the formation of radiation fog. Thunder-storms with a fair proportion of electric discharges – air to ground. Hail may also occur. 49. 1.4 Site climate 1.4.1 Deviations within the zone 1.4.2 Site climate 1.4.3 The designer's task 1.4.4 Local factors 1.4.5 Air temperature 1.4.6 Temperature inversion 1.4.7 Humidity 1.4.8 Precipitation 1.4.9 Sky conditions 1.4.10 Solar radiation 1.4.11 Air movement 1.4.12 Special characteristics 1.4.13 Vegetation 1.4.14 Urban climate 1.4.15 Site climatic data 1.4.1 Deviations within the zone Knowledge of the climatic zone to which a town or settlement belongs and possession of published regional climatic data does not eliminate the need for careful investigation of site climatic conditions. It does, however, usually provide enough information for the designer to make a preliminary assessment of the climate and may be sufficient to form the basis of sketch designs. Every city, town or village and even a precinct in a town may have its own climate, slightly different from the climate described for the region – the macroclimate. Information published by the nearest meteorological observatory describes the macroclimate. Such information may be a useful guide to the climate of the site, but is seldom sufficient in accuracy as conditions can vary 50. considerably within a short distance from the point of observation. 1.4.2 Site climate The term 'site climate' has been chosen deliberately rather than the synonymously used' term 'microclimate'. The latter can imply any local deviation from the climate of a larger area, whatever the scale may be. The botanist may consider the 'microclimate' of a single plant leaf, with its temperature and moisture conditions, its population of insects and micro-organisms, on the scale of a few centimetres. For the urban geographer the term 'microclimate' may mean the climate of a whole town. 'Site climate' establishes the scale: whatever the size of the project, it implies the climate of the area available and is to be used for the given purpose, both in horizontal extent and in height. 1.4.3 The designer's task If a large site is available, the first task of the designer is to identify the area most suitable for habitation. In all cases, however, he must design the building(s) in such a way as to take advantage of the favourable and mitigate the adverse characteristics of the site and its climatic features. The opportunity is rarely given to carry out on site observations and measurements for any length of time. The best approach is to start with regional data and assess the likely deviations. Valuable advice may be obtained from an expert, an experienced observer, who may be able to predict climatic deviations on the basis of visual inspection of the site. For a large project it is certainly worthwhile to seek expert advice, as many users of the building may have to endure the consequences of climatic design decisions for a long time. The nature and extent of climatic deviations – also the likely effects of the intended building – should be assessed early in the design stage, before one is committed to a certain solution which may later prove to be difficult to rectify. It is the purpose of the present section to give an understanding of local factors, which should enable the reader to make his own assessment of a given site climate with reasonable accuracy. 1.4.4 Local factors The factors governing the climate of a zone have been surveyed in the previous sections. Factors which may cause local deviation from this are: Topography, i.e. slope, orientation, exposure, elevation, hills or valleys, at or near the site. Ground surface, whether natural or man-made, its reflectance, permeability and the soil temperature, as these affect vegetation and this in turn affects the climate (woods, shrubs, grass, paving, water, etc.). Three-dimensional objects, such as trees, or tree-belts, fences, walls and buildings, as these may influence air movement, may cast a shadow and may subdivide the area into smaller units with distinguishable climatic features. A logical method will be to follow the sequence of climatic elements examined in the previous section and see how each of these may be affected by the above mentioned factors. 1.4.5 Air temperature 51. At any point near the ground the air temperature is dependent upon the amount of heat gained or lost at the earth's surface and any other surfaces with which the air has recently been in contact. Heat exchange at surfaces varies between night and day, with the season, latitude and the time of year, always influenced by the amount of cloud cover. During the day, as surfaces are heated by solar radiation, the air nearest to the ground acquires the highest temperature. In calm conditions the air within 2 m of the ground remains stratified in layers of differing temperatures. Mixing of the hotter and cooler layers takes place as the heat build-up of the lowest layer becomes great enough to cause an upward eddy of warmer, lighter air [16]. At night, particularly on clear nights, the ground loses much heat by radiation and soon after sunset its temperature falls below that of the air. The direction of heat flow is reversed: from the air to the ground. The lowest layer of air becomes cooler. Figure 21 shows the typical diurnal changes at various heights. 1.4.6 Temperature inversion This phenomenon is referred to as temperature inversion, as the day-time situation of decreasing temperature with increase of height is taken as normal. This is a much more stable situation than the 'normal' day-time temperature strata – there are no thermal forces tending to cause disturbances or upward eddies. Cold air tends to settle in the deepest depressions and behaves as a liquid. It does not flow quite as readily as water, rather like a highly viscous liquid. If it flows down the hill and along the floor of a long, sloping valley it can add up to a 'katabatic 33 wind': a concentrated and accelerating flow of a cold mass of air [17]. Fig 21 Formation of temperature inversion Topography can thus strongly influence air temperature [18], a difference of 7 to 8 m in height can cause a difference of 5 to 6°C in air temperature, under still air conditions. 1.4.7 Humidity 52. The relative humidity depends as much on the air temperature as on the actual amount of water vapour present in the air. During the day, as the lowest layer of air is being heated by the ground surface, its RH is rapidly decreased. With a lower RH the rate of evaporation is increased, if there is water available to be evaporated. An open surface of water or rich vegetation would provide an abundant supply of water – in such a case strong evaporation would increase the AH of the lower layers of air. The following situation is likely to arise, if the air is still: With air movement the rate of evaporation is increased, but with the mixing of air the temperature and humidity differences tend to be evened out. At night the situation is reversed. Especially on a clear night with still air, as the lowest layer (of the highest AH) cools, its RH increases, the point of saturation is soon reached and with further cooling the excess moisture condenses out in the form of dew (hence the term 'dewpoint'). When the dewpoint temperature is reached the formation of fog will start, and if there is no further rapid cooling and no air movement, a deep layer (up to 40 to 50 m) of fog can develop near the ground. 1.4.8 Precipitation When moisture bearing winds occur frequently from the same direction, the effect of hills on rainfall patterns can be very pronounced. Where the ground changes level by more than 300 m, the windward slope can be expected to receive a rainfall more 34 than the regional average, and the leeward slope correspondingly less (Figure 22).With the increase of height or steepness of the hill formation, the effect will be more pronounced. In an extreme case it can happen that on a large site located on the top of a hill and extending down to both slopes, the leeward half receives only 25% of the rain received by the windward side. Fig 22 Precipitation on hills The cause of the above phenomenon is that the hill forces the air mass to rise, as it rises it cools and can no longer support the moisture carried. Conversely, a descending air mass increases in temperature and it can absorb more moisture, rather than to precipitate any. A similar situation can develop over towns, where the more absorbent surfaces reach a high temperature and can produce an upward air movement. Such an upward current may divert any horizontal air movement in an upward direction, with similar effects to a hill slope. 53. Fig 23 Precipitation over towns Actually a number of workers have reported a higher frequency of rains of the cloudburst type over city centres (Figure 23). (A factor contributing to this, may be the presence of solid particles in urban atmospheres.) If rainfall generally occurs associated with high wind velocities, resulting in 'driving rain', the effect will be more pronounced on the windward side than on the leeward slope, as explained by the parallelogram of forces in Figure 24. 1.4.9 Sky conditions Normally sky conditions do not vary perceptibly over short distances, unless there is an abrupt and considerable change in topography, which may lead to an almost permanent cloud formation. The flag-like permanent cloud on the leeward side of the Rock of Gibraltar is a good example, but it is rather rare. Fig 24 Driving rain parallelograms 1.4.10 Solar radiation The amount of solar radiation may be influenced by local factors three ways: 1 the intensity on a theoretical horizontal plane above the ground is affected by local variations in the transparency of the atmosphere. Atmospheric pollution, smoke, smog or dust and local cloud formations can produce substantial reductions 2 the intensity on the actual ground surface is influenced by the slope and orientation of the site, this effect being negligible around the Equator, but increasingly important towards higher latitudes. At mid-latitudes a site sloping towards the pole will receive much less radiation than one sloping towards the Equator 3 the daily total amount of radiation may also be influenced by the slope (later sunrise and earlier sunset for a northern slope on the northern hemisphere) but also by nearby hills or even trees and existing buildings, which may cast a shadow over the site at certain times of the day. This effect is most pronounced when such obstructions lie on the east or west of the site. When the sun is on these sides, it is at low angle and casts a long shadow 54. Radiation on a vertical building surface will be affected by its orientation, but not by the slope and orientation of the site. The factors under 1 and 3 above will still show an effect. The magnitude of thermal effects of such incident radiation will, of course; depend on the surface qualities of the recipient ground or objects (see 1.4.5). If it is vegetation, some of the solar energy is converted into chemical energies and the heating is also mitigated by evaporation, but a stone, concrete or especially an asphalt surface can reach a temperature up to 44 degC higher than the surrounding air temperature. 1.4.11 Air movement Wind speed can be reduced after a long horizontal barrier by 50% at a distance of ten times the height and by 25% at a distance of twenty times the height. In addition to this, air flowing across any surface is subject to frictional effects. The type of ground cover affects the wind speed gradient. Near the ground the wind speed is always less than higher up, but with an uneven ground cover the rate of increase in speed with height is much more than with an unbroken smooth surface, such as water (Figure 25). On a hilly site the greatest wind speeds will be experienced at the crests of hills. Small valleys and depressions will normally experience low velocities, except in cases where the direction of the valley coincides with the direction of wind. The more pronounced the form of the valley, the greater is its effect both in sheltering the valley floor from cross-winds and in funnelling the parallel winds. The effect of long, tall slabs or rows of buildings may be similar to this. In regions where wind can provide a welcome relief from sultry heat, the crests and windward slopes are preferable as building sites to the leeward sides of hills. The day-time heating of air over barren ground often gives rise to local thermal winds, especially in hot-dry regions. These may be whirlwinds or local breezes, normally hot and carrying fine dust. Observations can usually reveal a pattern of their course during certain seasons of the year. Large stretches of water can give rise to local coastal breezes. On-shore breezes (from water to land) during the day may lower the maximum temperature by as much as 10 degC, but are likely to increase the humidity. On lake shores these breezes are rarely effective beyond about 400 m inland, but on the sea coast the effect may reach much further inland if topography is favourable [9]. Fig 25 Wind velocity gardients 55. 1.4.12 Special characteristics Thunder-storms are macroclimatic phenomena, but local topography can influence their path, their intensity and even their frequency. Local features particularly affect the accompanying electrical phenomena. Tops of hills are mostly subjected to lightning strikes and a tall building, which is the highest object of a large area, even on level ground, may be an attractive target for lightning. Precautionary measures must be taken accordingly. Dust and sand-storms are influenced by local factors, both by the ground surface providing sand and dust to be carried by the wind, and by topography in funnelling or diverting the wind or by causing local eddies. Sand is only drifting along the surface even in strong winds, so small barriers will effectively stop its movement. It will be deposited at locations where the wind speed is reduced or where local turbulences or eddies are formed. Smaller dust particles being in suspension in the air stream are carried more freely and may reach a height of 1 500 m or more. Dust- storms of this magnitude are macroclimatic phenomena, not directly affected by local factors. Their effect is most adverse in positions exposed to high wind velocities. Barriers, natural or artificial, can provide adequate protection, but will exclude the possibility of utilising the air movement for cooling purposes Smaller dust-storms of the 'willy-willy' type may be generated on quite a small scale. At the time of maximum solar heating (14.00 to 15.00 h) the lowest and hottest layer of air may burst through the overlaying cooler air with violent suddenness in the form of a whirlwind and carry much dust with it. Both the birth and the path of such whirlwinds can depend on small-scale local features: topography and surface qualities. Earthquakes, although not strictly climatic phenomena, must be considered here. They mostly occur in well-defined areas – seismic zones. Macroseismic information is available everywhere and, even in the absence of local instrumental recordings, in the light of geological evidence (e.g. location of fault lines), the seismic danger zones can be pinpointed on quite a small scale. 'Isoseismal maps', i.e. maps showing lines of equal earthquake risk, are available in many locations. If not, and if the given site is in or near a major seismic zone, expert advice should be sought, either regarding the least risky part of a large site or just to establish the degree of risk, so that appropriate precautionary measures can be taken. 1.4.13 Vegetation Trees and vegetation form an intermediate layer between the earth's surface and the atmosphere. Their moderating effect on the site climate has already been referred to in the context of air temperature, humidity, radiation and air movement. By covering the ground with vegetation, the surface of contact is transferred to a higher layer and is increased four to twelve times. In all hot and dry regions of the earth the beneficial climatic effect of even the lightest plant cover is quite considerable. Valuable information for siting and landscaping can be obtained from the observation of existing vegetation. With a working knowledge of the soil, water, sun and wind requirements of common plants, the designer should be able to identify the major areas of differences in site climate, as indicated by the existing vegetation. 1.4.14 Urban climate Man-made environments can create microclimates of their own, deviating fromUrban climate The 56. macroclimate of the region to a degree depending on the extent of man's intervention. Such intervention with the natural environment is greatest in large towns or cities, thus it is justifiable to speak of an 'urban climate'. The factors causing deviations of the urban climate from the regional macro- climate are the following: a changed surface qualities (pavements and buildings) – increased absorbance of solar radiation; reduced evaporation b buildings – casting a shadow and acting as barriers to winds, but also channelling winds possibly with localised increase in velocity or by storing absorbed heat in their mass and slowly releasing it at night c energy seepage – through walls and ventilation of heated buildings; the output of refrigeration plants and air conditioning (removing heat from the controlled space to the outside air); heat output of internal combustion engines and electrical appliances; heat loss from industry, especially furnaces and large factories of atmospheric pollution – waste products of boilers and domestic and industrial chimneys; exhaust from motor-cars; fumes and vapours, which both tend to reduce direct solar radiation but increase the diffuse radiation and provide a barrier to outgoing radiation. The presence of solid particles in urban atmosphere may assist in the formation of fog and induce rainfall under favourable conditions The extent of deviations may be quite substantial. Air temperature in a city can be 8 degC higher than in the surrounding countryside and a difference of 11 degC has been reported. Relative humidity is reduced by 5 to 10%, due to the quick run-off of rain-water from paved areas, to the absence of vegetation and to higher temperature. Wind velocity can be reduced to less than half of that in the adjoining open country, but the funnelling effect along a closely built-up street or through gaps between tall slab blocks can more than double the velocity. Strong turbulences and eddies can also be set up at the leeward corners of obstructions. 1.4.15 Site climatic data Data relating to the regional macroclimate is available almost everywhere. A method summarising such data in graphic and tabulated form has been given in 1.2.16. Rarely will similarly reliable measured data be available for a given site. As the climatic parameters for a site are the same as for a region, it is best to start with the summary of regional data and, in a subsequent step, examine which of the parameters will be affected by local specific factors and what the extent of such deviations is likely to be. The climate graph and the values included in the tables can be changed accordingly. Where such deviations are not certain, this fact can be shown. In most cases the regional data may be used with only some qualitative remarks regarding local deviations. This may be quite satisfactory, as the conclusions to be drawn from such information will most often be qualitative only. 57. 1. Figures in square brackets refer to the bibliographical list on p. 275 et seq. 2. It has been calculated [4] that if the atmosphere were still, the average temperature at the Equator would be 33°c in lieu of 27°c and at the North Pole it would be -40°c, instead of -17°c,as it is now. 3. 'Since the direction of the rotation of the earth is from west to east ail easterly winds have a braking effect on the earth s surface, whereas all westerly winds have an accelerating effect. But the law of conservation of angular momentum requires that the sum of angular momentum in the system "earth + atmosphere" remains constant. In the easterly wind regions surface friction does indeed transfer westerly angular momentum from the earth to the atmosphere, whereas in westerly wind regions the opposite occurs, and the more rapidly rotating atmosphere transfers angular momentum to the earth. This is possible only when the atmosphere transfers angular momentum from the tropics and also to a much smaller extent from the polar caps to the middle latitudes.'[3]. 4. This is an instrument based on the moisture movement of human hair, which is proportionate to the relative humidity. The expansion and contraction of this is transmitted through a lever mechanism to a pen, which draws a continous graph of humidity variation on a paper stretched over a clockwork-driven cylinder (see Fig 11) 5. For definition of units, see p.69 58. Section 2 Comfort: The desirable conditions 2.1 Thermal comfort factors 2.2 Thermal comfort indices 2.3 Effective temperature – its use 59. 2.1 Thermal comfort factors 2.1.1 Introduction 2.1.2 The body's heat production 2.1.3 The body's heat loss 2.1.4 Regulatory mechanisms 2.1.5 Heat loss in various thermal environments 2.1.6 Calm, warm air, moderate humidity 2.1.7 Hot air and considerable radiation 2.1.8 Hot air, radiation and appreciable air movement 2.1.9 Saturated, still air, above body temperature 2.1.10 Effects of prolonged exposure 2.1.11 Subjective variables 2.1.1 Introduction Our daily life cycle comprises states of activity, fatigue and recovery. It is essential that the mind and body recovers through recreation, rest and sleep to counterbalance the mental and physical fatigue resulting from activities of the day [19]. This cycle can be and is often impeded by unfavourable climatic conditions and the resulting stress on body and mind causes discomfort, loss of efficiency and may eventually lead to a breakdown of health. The effect of climate on man, is therefore, a factor of considerable importance [20]. The task of the designer is to create the best possible indoor climate (it is not feasible to regulate out-door conditions). The occupants of a building judge the quality of the design from a physical as well as an emotional point of view. Accumulated sensations of well-being or discomfort contribute to our total verdict on the house in which we live and the school, office or factory where we work. It is a challenge for the designer to strive towards the optimum of total comfort, which may be defined as the sensation of complete physical and mental well-being. Considerable information has by now been published on the physical side; but far less on the emotional aspects of our environment. 60. Criteria of total comfort depend upon each of the human senses. In the following paragraphs, while the subjective-emotional relationships with our environment may be mentioned, the main emphasis is placed upon human thermal comfort, which is the dominant problem in tropical climates. The physiological responses to specific climatic conditions, here described, can be verified by controlled experiments. Interest in establishing thermal comfort criteria dates back in Europe about 150 years, to the beginning of the nineteenth century, when it started with the movement for the reform of conditions in industry and housing. Basic warmth criteria were first established in the mining, metal and textile industries, as accidents and illness due to heat and humidity stresses were formerly quite common. Human response to the thermal environment does not depend on air temperature alone. It has been established beyond doubt that air temperature, humidity, radiation and air movement all produce thermal effects, and must be considered simultaneously if human responses are to be predicted. To appreciate the effect of these climatic factors, it is necessary to examine briefly the basic thermal processes of the human body. 2.1.2 The body's heat production Heat is continuously produced by the body. Most of the biochemical processes involved in tissue- building, energy conversion and muscular work are exotherm, i. e. heat producing. All energy and material requirements of the body are supplied From consumption and digestion of food. The processes involved in converting foodstuff into living matter and useful form of energy are known as metabolism [20]. The total metabolic heat production can be divided into basal metabolism, i.e. the heat production of vegetative, automatic processes which are continuous, and the muscular metabolism, i.e. the heat production of muscles whilst carrying out consciously controlled work. Of all the energy produced in the body, only about 20% is utilised, the remaining 80% is 'surplus' heat and must be dissipated to the environment. This excess heat production varies with the overall metabolic rate, and depends on the activity. The following table indicates the rate of excess heat output of the body in various activities. Activity watts Sleeping min. 70 Sitting, moderate movement, e.g. typing 130–160 Standing, light work at machine or bench 160–190 Sitting, heavy arm and leg movements 190–230 Standing, moderate work, some walking 220–290 Walking, moderate lifting or pushing 290–410 61. Intermittent heavy lifting, digging 440–580 Hardest sustained work 580–700 Maximum heavy work for 30-minutes duration max. 1100 (Average values of data published in many sources) 2.1.3 The body's heat loss The deep body temperature must remain balanced and constant around 37°C. In order to maintain body temperature at this steady level, all surplus heat must be dissipated to the environment [21]. If there is some form of simultaneous heat gain from the environment (e.g. solar radiation or warm air) that also must be dissipated. The body can release heat to its environment by convection, radiation and evaporation – and to a lesser extent by conduction (Figure 26) [22]. Convection is due to heat transmission from the body to the air in contact with the skin or clothing which then rises and is replaced by cooler air. The rate of convective heat loss is increased by a faster rate of air movement, by a lower air temperature and a higher skin temperature. Radiant heat loss depends on the temperature of the body surface and the temperature of opposing surfaces. Evaporation heat loss is governed by the rate of evaporation, which in turn depends on the humidity of air (the dryer the air, the faster the evaporation) and on the amount of moisture available for evaporation. Evaporation takes place in the lungs through breathing, and on the skin as imperceptible perspiration and sweat. Fig 26 Body heat exchange Conduction depends on the temperature difference between the body surface and the object the body is in direct contact with. 2.1.4 Regulatory mechanisms 62. The thermal balance of the body is shown by Figure 27 [22] and can be expressed by an equation. If the heat gain and heat loss factors are: Gain: Met = metabolism (basal and muscular) Cnd = conduction (contact with warm bodies) Cnv = convection (if the air is warmer than the skin) Rad = radiation (from the sun, the sky and hot bodies) Loss: Cnd = conduction (contact with cold bodies) Cnv = convection (if the air is cooler than the skin) Rad = radiation (to night sky and cold surfaces) Evp = evaporation (of moisture and sweat) then thermal balance exists when Met – Evp ± Cnd ± Cnv ± Rad = 0 Fig 27 Thermal, balance of the body As soon as this sum is more than zero, vasomotor adjustments will take place: blood circulation to the skin surface is increased, more heat is transported to the surface and the skin temperature is elevated – all forms of heat loss processes are accelerated. Conversely, if the sum of the above equation is less than zero, the blood circulation to the skin is reduced, skin temperature is lowered and the heat loss processes are slowed down. If the vasomotor regulation is still insufficient, and overheating continues, sweating will start. The rate of sweating may vary from about 20 g/h to 3 kg/h during periods of physical effort combined with hot environmental effects [23].1 If, in a cold environment, underheating continues in spite of vasomotor adjustments, violent shivering may occur, which can cause a ten-fold increase in metabolic heat production for short periods. Long-term, endocrine adjustments constitute the acclimatisation process. These may involve the change in the basal metabolic heat production, an increase in the quantity of blood (to produce and maintain a constant vaso- dilation) and an increase in sweat rate. 2.1.5 Heat loss in various thermal environments In classifying tropical climates into six categories (1.3.2) and in discussing deviations of the site climate, the importance of the four basic factors has been emphasised which would directly affect 63. human comfort, namely: air temperature, humidity, air movement and radiation. The importance of these factors should now be obvious: each influences in some way the heat exchange processes between the human body and its environment; each may aid or impede the dissipation of surplus heat from the body. For example, high air temperature is a definite obstacle to heat dissipation by convection (it may even produce a heat input, if warmer than the skin), and simultaneous high humidity may impede the heat loss by evaporation [24]. The following paragraphs will examine how these four climatic variables affect the heat dissipation processes of the human body for various indoor conditions. 2.1.6 Calm, warm air, moderate humidity In a temperate climate, indoors, when the air temperature is around 18°C, when the air is calm, i.e. air velocity does not exceed 0.25 m/s, and when the humidity is between 40 and 60%, a person engaged in sedentary work will dissipate the surplus heat without any difficulty, in the following ways: by radiation 45% by convection 30% by evaporation 25% if the temperature of bounding surfaces is approximately the same as the air temperature [25]. 2.1.7 Hot air and considerable radiation The normal skin temperature is between 31 and 34°C. As the air temperature approaches skin temperature, convective heat loss gradually decreases. Vasomotor regulation will increase the skin temperature to the higher limit (34°C), but when the air temperature reaches this point, there will be no more convective heat loss. As long as the average temperature of opposing surfaces is below skin temperature, there will be some radiation heat loss, but as the surface temperature increases, radiation losses are diminished. Radiant heat from the sun or a hot body (a radiator or fire) can be a substantial heat gain factor. When both the convective and radiant elements in the heat exchange process are positive, bodily thermal balance may still be maintained by evaporation (but only by evaporation) up to a limit, provided the air is sufficiently dry to permit a high evaporation rate. 2.1.8 Hot air, radiation and appreciable air movement When the air is hot (equal to or above skin temperature) so that the convection element is positive, when the surface temperatures are warm or there is a substantial radiant heat source, so that the radiant element is also positive, and when the air is humid (but less than 100% RH) the movement of air will accelerate evaporation, thus increase heat dissipation, even if its temperature is higher than that of the skin. The mechanism is as follows: if the air is at approximately 90% RH, it will take on some humidity by evaporation from the skin, but the thin (1 to 2 cm) layer of air in immediate contact with the skin soon will become saturated and this saturated air envelope will prevent any further evaporation from the skin. Moving air will remove this saturated air envelope and the evaporation process can continue. It has been estimated [26] that over 2000 N/m2 vapour pressure, every 1 m/s increase in air velocity will compensate for an increase of 300 N/m2 in

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