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Urban bioclimatology in developing countries

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Abstract. A brief review of the literature on urban human bioclimatology in the tropics is undertaken. Attempts to chart human bioclimatic conditions on the regional/local scale have been made in several developing countries. The effective temperature scheme (with all its limitations) is the one that has been most frequently applied. The possibilities of application of bioclimatic models based on human heat balance for the tropical urban environment are discussed.
Key words. Tropical urban climatology; developing countries; human biometeorology.

Introduction

Human bioclimatology in cities deals with aspects of urban climate and its relation to human comfort/discomfort and health. Urban effects on components of climate such as temperature, humidity, radiation and wind have been documented throughout the world (for reviews on the subject see refs 5, 24, 25, 30–33).
Human biometeorology is a relevant area of study in the assessment of heat stress under outdoor and indoor conditions in the various microclimates that are characteristic of the urban environment. Studies on this subject are also of particular importance for urban planning and building design. Several reviews of human biometeorology have appeared in the literature (see refs 8, 23, 48).
Geographical analyses of human biometeorology have been made in the past on the global, continental/regional and local (city) scales, including tropical environments. Various approaches have been used. A large number of 'bioclimatic indices' have been developed since the 1920s in an attempt to measure the thermal sensation. The most notable example is the subjective judgement of comfort or discomfort, expressed by the effective temperature index (E.T.)[12]. (For a thorough discussion of the various indices see Taesler[42].) In this paper we shall briefly review work done in the field of human biometeorology in the tropical/subtropical environment, which covers most of the developing countries. The state of the art in this field will be discussed, and the possibilities for application of more objective approaches, such as human heat balance modelling, will be considered.

Geographical analysis of human bioclimatology in the tropical world

The characteristics of the atmospheric environment in urban areas which directly affect human beings are mainly temperature, humidity, radiation and wind on the one hand, and air quality on the other. Since most developing countries are in the first stages of industrialization, during the last decades air pollution has attained more importance as the single component of the bioclimate that is bound to affect the environmental comfort and health of the urban population most directly. As a consequence, at present air pollution studies are receiving more attention from urban climatologists and atmospheric chemists than are urban effects on the thermal bioclimate of tropical cities.
The table shows a list of papers on human bioclimatology in the tropics since the 1950s. Although the list is not intended to be exhaustive, it shows that attempts to exercise geographical analysis of human biometeorology in the tropics on the regional/local scale seem to be rather few. This situation has been noted for the entire world[42].

Bioclimatic maps of the globe

Bioclimatic maps of mean monthly E.T. or enthalpy on the global scale have a very general information value. If they are planned to be more specific and embody valuable information they should contain E.T. data for interesting hours of the day (i.e. at 0600 and 1400 hrs) or isolines of percentage frequency of classes of the given bioclimatological index, as suggested by Hentschel[11]. This author concludes that among the various indices presently available, the E.T. concept is the most suitable for use in global/regional bioclimate classifications. In his review of bioclimatological literature, Landsberg[23] concludes that in spite of its drawbacks the E.T. index is simple to use as compared with other hygrothermal indices.
While reviewing the problem of bioclimate classification Taesler[42] also notes that simple thermal indices have limitations in terms of validity and area of applicability. As has been noted by the above mentioned author, a more promising method of bioclimatic classification lies perhaps in the application of mathematical models based on human heat balance. A glance at the table provides ample evidence that the most frequently ap-

Human bioclimatological assessments comprising the tropical world at various scales

Author	Area	Bioclimatic index
Brooks[4]	world	Wet-bulb temperature
Landsberg[22]	world	Water vapor pressure
Gregorczuk and Cena[9]	world	E.T.
Gregorczuk[10]	world	Enthalpy
Terjung[46]	world	Comfort index
	Continent	
Terjung[45]	Africa	RS, SAT, E.T.
Auliciems and Kalma[2]	Australia	– human thermal stress
	Country	
Kondratiev[20]	U.S.S.R.	E.T.
Terjung[22]	Sudan	– physioclimates – cumulative stress
Jauregui and Soto[14]	Mexico	– D.I. wet-bulb temp.
Terjung[44]	U.S.A.	comfort index, wind effect index, physiological climates
Rubinstein et al.[37]	Israel	D.I., E.T.
Lakhsmanan[21]	India	E.T.
Chowdhuri and Ganesan[6]	India	E.T.
	City	
Hounam[13]	Alice Springs Darwin	E.T.
Sham Sani[38]	Kuala Lumpur	E.T.
Niewolt[29]	Singapore Dar es Salam	E.T.
Jauregui[15]	Mexico	E.T. climogram
Olaniran[34]	Ilorin	E.T.
Chowdhuri and Ganesan[6]	New Delhi Calcutta	E.T.
Padmanabhamurti[35]	Delhi	E.T. climogram

E.T. – Effective Temperature; RS – Relative Strain; SAT – Still Air Temperature; D.I. – Discomfort Index.

plied bioclimatic index has been the effective temperature concept. Advantages and limitations of this index have been pointed out by Terjung[44] and Landsberg[23].

Wet-bulb temperature (*WBT*). The first maps of the world drawn with human bioclimatic classification in mind date from the 1950s. In 1950 Brooks[4] published two maps (January and July) showing the distribution of mean monthly wet-bulb temperatures. In figures 1 and 2, adapted from Brooks[4], the location of areas may be seen where mean monthly wet-bulb temperature exceeds 24 °C. This level, according to this author, marks the upper limit of comfort for mid-latitude individuals. These areas include (in July) the Indian subcontinent, southeast Asia, the United States and the Gulf of Mexico states, the Arabian region, the Caribbean and small portions of South America and Africa (fig. 1). In January (fig. 2) the sultry areas, according to Brooks' definition, move southward. This author suggests that the most comfortable conditions are found when wet-bulb temperatures are between 10 °C and 15 °C. These conditions are not usually found anywhere in the tropics except in subtropical deserts (due to the dryness of the air) and tropical highlands. Clearly, on this scale it is not possible to locate those tropical areas where the bioclimate is tempered by topography and so is the wet-bulb temperature.

In order to estimate the wet-bulb temperature (WBT) during the hottest hours of the day from these monthly maps, Brooks proposes to add 1.5 °C to the mean monthly WBT since, he notes, the diurnal variation of this parameter is much smaller than that of temperature. The weakness in the application of this index lies in the small diurnal variation observed, especially in the

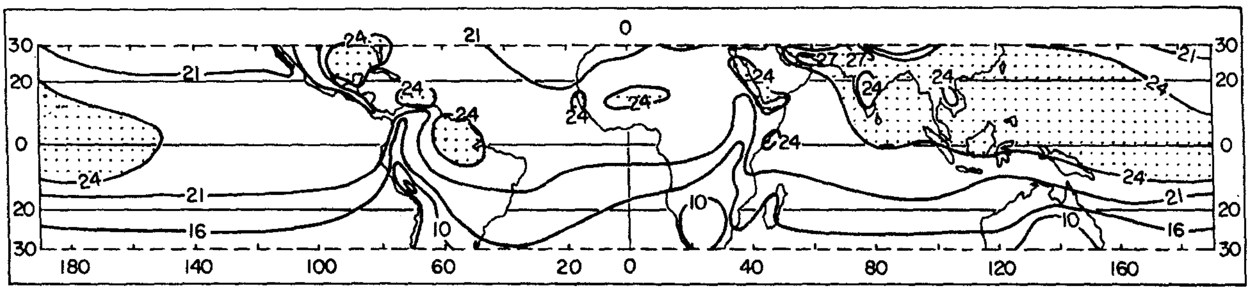

Figure 1. Mean wet-bulb temperaure (°C) in July for the tropics (adapted from Brooks[4]).

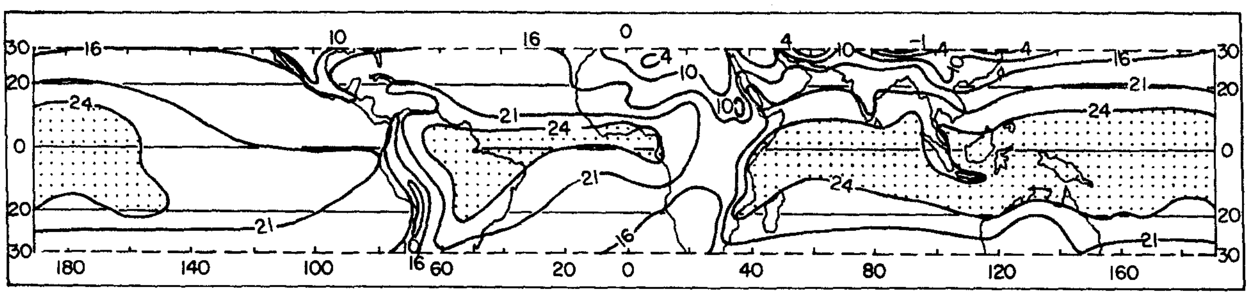

Figure 2. Mean wet-bulb temperature (°C) in January for the tropics (adapted from Brooks[4]).

humid tropics. However it is useful as an indicator of humidity conditions when comparing bioclimatic conditions in coastal versus inland/highland areas in the tropics.

Water vapor pressure. Maps of distribution of water vapor pressure on the global scale have been prepared by Tunnel[49] and Landsberg[22]. Like WBT, the vapor pressure is an expression for the humidity content in the air and therefore a potential indicator for use in human bioclimatic evaluations. Again, few researchers have attempted to suggest a scale of hygrothermal sensations based on physiological reactions related to this simple index, which obviously leaves out the effects of the other bioclimatic factors mentioned above. Scharlau[39] has proposed a sultriness (or heat stress) limit value of $e = 18.9$ hPa, in order to delineate the regions of the world where 'sultry' (or heat stress) conditions are dominant. As it would be expected on this scale, there is general agreement between the sultry (or high heat stress) regions encompassed by the application of this index with those defined by use of other bioclimatic parameters. 'Sultry' conditions are referred to in the literature as the combination of high temperature and humidity with low ventilation, producing heat stress in humans.

Effective temperature. As already mentioned, this has been the most frequently used bioclimatic index on the various scales.

On the global scale, Gregorczuk and Cena[9] have delimited the regions of the world displaying well-defined heat stress conditions (E.T. > 24 °C). These include most of the developing countries, at least in some seasons. As already mentioned, the E.T. is based on temperature/humidity values empirically related to a table of comfort/discomfort sensations experienced indoors by groups of persons in the United States. Landsberg[23] has commented that despite its comprehensive nature the E.T. scheme is not based on meaningful relationships between simultaneous data.

Enthalpy. In contrast with the E.T. index, enthalpy (or total heat) has rarely been used for bioclimatic charting. This parameter is linearly related to the wet-bulb temperature, and consequently shares some of its limitations as a bioclimatic index. Gregorczuk[10] published mean global distributions of this index, which involves the sum of sensible and latent heat present in the air. He uses a subjective table of equivalent thermal sensations proposed by Brazol[3] which, in the opinion of this writer, is not adjusted for use in a tropical environment. Again, it seems to be of little use to try to adapt Brazol's subjective scheme of thermal sensations to humans living in the tropics, given the inherent limitations of such an indicator.

Bioclimatic maps on the regional (country) scale

The first bioclimatic maps on the scale of a region or a country, to our knowledge, are those of Kondratiev[21], who used the E.T. concept to delimit comfort regions of the former U.S.S.R.. Brazol[3] has described the bioclimates of Argentina using the enthalpy of air and then associating these numbers with a comfort scale of thermal sensations. Terjung[45] has delimited the physioclimatic regions of Africa using several indices (E.T., Still Air Temperature (SAT) and Relative Strain (RS)). Jauregui and Soto[14] have used the wet-bulb temperature and the discomfort index concept as proposed by Tannenbaum and Sohar[43] to describe bioclimatic conditions in Mexico.

The Indian subcontinent has been by far the most-studied tropical country from the human climate point of view. Many local climatologists have published studies. The first bioclimatic classification was attempted by Subhramanyan and Sivaramakrishnaiah in 1964[41].

Applying Terjung's method (1967), Chowdhury and Ganesan[6], using monthly norms of maximum and minimum temperature and their corresponding relative humidity, presented distributions of Annual Cumulative Stress (CS), Proportional Cumulative Stress (PCS) and Annual Physioclimatic Regimes (APR) over India. For a detailed account on the subject of human bioclimate in tropical cities the reader is referred to a recently-published paper by the author[16].

A detailed study on India has been undertaken by Lakshmanan[21] using Thom's index (also known as temperature-humidity index)[47] to characterize the human bioclimate for different months and hours of the day. Using a bioclimatic index based on Thom's, Park and Kawamura[36] have charted the south and east of Asia (monsoon Asia) which comprises vast tropical regions. In reviewing the various bioclimatic indices (which originated from mid-latitude experience) that have been applied in India, Lahiri (1984) raises some points that should be considered when using these indices in a tropical environment. She proposes a table of bioclimatic categories that could be more realistic under Indian conditions. This table (based on experiment with students) shows in general more tolerance by locals to heat loads than that observed for mid-latitude subjects, given such environmental differences as acclimatization, dress and culture.

Finally, bioclimatic maps of Mexico (showing E.T. and enthalpy) have been prepared by the present writer[17] as part of the National Atlas of Mexico.

The bioclimate of cities

A rather large number of studies on the specific bioclimate of tropical metropolitan areas have been undertaken. Tropical cities in Africa and southeast Asia have been the objects of bioclimatic assessments[27,28,34]. The human bioclimate of the cities of Madras, Bombay, Calcutta and Delhi (in total 30 Indian cities) has been assessed by Chowdhury and Ganesan[6] (using the E.T. concept). Applying the same index, Sani[38] has evaluated the bioclimate of Kuala Lumpur located in the low tropics. The present writer has attempted the study of bioclimatic conditions prevailing in different areas of Mexico City[15,18]. Given their limitations in terms of validity and region of applicability, these rather simple thermal comfort indices are likely to give only a first approximation of the 'real' human bioclimate of a place.

Concluding remarks

The field of human bioclimatology in the tropics started to gain relevance during the 1980s. Attempts to chart human bioclimatic conditions on the regional, local scale have been undertaken in several developing countries located in the tropics (India, Malaysia, Mexico, tropical Africa). Among the various indices used in these evaluation efforts, the effective temperature scheme (with all its restrictions) has been the most frequently applied, given the relative accessibility of the required data (temperature and relative humidity). While easy to apply, however, the E.T. method only gives a first approximation of the physical environment of man and a related (subjective) scale of physiological reactions of selected groups of individuals. It is clear from the above that application of mid-latitude empirical indices that relate thermal sensations to a subjective rating of comfort/discomfort or to physiological reactions need to be adapted to the tropics. Therefore, more work needs to be done with experimental groups of people acclimatized to the tropical environment in order to adjust the related scales of thermal sensations postulated by studies in the United States. The results of applying mid-latitude thermal neutrality criteria indiscriminately to tropical areas are illustrated by Auliciems and Dedear[1] for tropical Darwin in northern Australia, where they have found that the population does not actually desire air-conditioning in over-cooled buildings. An approach that apparently has not been attempted in the tropics is that of Fanger[7] who proposes a thermophysiological model starting with a comfort equation, to derive an index which makes possible a prediction of the thermal sensation experienced by a group of humans for any given combination of activity level, clothes value and four thermal environmental parameters (air temperature, (°C), mean radiant temperature (°C), relative air velocity (m/s) and air humidity (mmHg)). Since the mathematical expressions of comfort and Predicted Mean Vote (PMV) are complicated, Fanger presents the results of PMV calculations in tables and graphs which are easy to interpret.

As noted by Mayer and Höppe[26], Fanger's model assumes mean skin temperature and sweat rate to be always at comfort values, and therefore it cannot be used to model actual physiological parameters and heat fluxes. In order to overcome this difficulty, an energy-balance model in which the sweat rate is a function of mean skin and core temperature has been developed by these authors. From their model they derive the thermal components of microclimates at selected sites of an urban area.

Jendritzky and Nübler[19] have adapted Fanger's comfort PMV equation to outdoor conditions by parametrizing short- and long-wave radiative fluxes derived from regular meteorological data, with some assumptions on atmospheric turbidity and the physical properties of surfaces surrounding humans. These authors have applied the energy balance approach to assessing the bioclimatic conditions in a small European city. They find in this case that the PMV distribution differs markedly from the distribution of temperature, and conclude that air temperature is an inappropriate parameter by which to assess human comfort, since at noon irradiation is dominant in the suburbs as compared with the central district. This physiologically relevant approach offers, as the authors suggest, new possibilities for the assessment of human bioclimatic conditions in the urban environment. It is to be hoped that this methodology will soon be applied in the tropical environment. It will provide local architects and planners with useful information for bioclimate-conscious design.

1 Auliciems, A., and Dedear, R., Air conditioning in a tropical climate: impacts upon European residents in Darwin. Int. J. Biometeor. *30* (1986) 259–282.
2 Auliciems, A., and Kalma, J., A climatic classification of human thermal stress in Australia. J. appl. Meteor. *18* (1979) 616–626.
3 Brazol, D., The optimal biological temperature (in Spanish). Meteor. Argentina *1* (1951) 99–106.
4 Brooks, C. E. P., Climate in Every Day Life. E. Benn, London 1950.
5 Chandler, T., Urban climatology and its relevance to urban design. WMO T.N. 149. WMO, Geneva 1976.
6 Chowdhuri, A., and Ganesan, H., Meteorological requirements on air conditioning in relation to human habitat for comfort. Mausam *34* (1983) 281–286.
7 Fanger, P. O., Thermal Comfort: Analysis and Applications in Environmental Engineering. McGraw-Hill, New York 1972.
8 Flach, E., Human bioclimatology, in: World Survey of Climatology, vol. 3, pp. 1–187. Elsevier, Amsterdam 1981.
9 Gregorczuk, M., and Cena, K., Distribution of effective temperature over the globe. Int. J. Biometeor. *2* (1967) 145–149.
10 Gregorczuk, M., Bioclimates of the world related to air enthalpy. Int. J. Biometeor. *12* (1968) 35–39.
11 Hentschel, G., A human biometeorological classification of climate for large/local scales. Proceed. Symposium on Climate and Health. WCAP-No. 1 (1987) 120–138.
12 Houghten, F. C., and Yaglou, C. P., Determining lines of equal comfort. Trans. ASHVE *29* (1923) 163–176.
13 Hounam, C. E.: Meteorological factors affecting physical comfort (reference to Alice Springs). Int. J. Biometeor. *11* (1967) 151–162.
14 Jauregui, E., and Soto, C., Wet-bulb temperature and discomfort index areal distribution in Mexico. Int. J. Biometeor. *11* (1967) 21–28.
15 Jauregui, E., The urban climate of Mexico City, in: Proceed. Tech. Conf. on Urban Climate and its Applications with Special Regard to Tropical Areas. Ed. T. Oke. WMO No. 652, pp. 63–82. WMO, Geneva 1986.
16 Jauregui, E., The human climate of tropical cities: an overview. Int. J. Biometeor. *35* (1991) 151–160.
17 Jauregui, E., Bioclimatic maps for Mexico, in: Proceed. Int. Tagung f. Human-Biometeorologie, Annalen der Meteorologie, 28, pp. 90–93. Deutscher Wetterdienst, Offenbach 1992.

18 Jauregui, E., Bioclimatic conditions in Mexico City – an assessment, in: Preprints. Second Tohwa Univ. Int. Symp. on Urban Thermal Environment, pp. 173–174. Fukuoka, Japan, 1992.
19 Jendritzky, G., and Nübler, W., A model analysing the urban thermal environment in pysiologically significant terms. Arch. Met. Geophys. Biokl. Ser. B *29* (1981) 313–326.
20 Kondratiev, P., New tables of effective temperature and maps of distribution of E.T. for U.S.S.R. (in Russian). Naut. Arch. NIK, Moskwa 1950.
21 Lakshmanan, V., Discomfort index over India in different months of the year. Mausam *35* (1984) 487–492.
22 Landsberg, H., Die mittlere Wasserdampfverteilung auf der Erde. Meteor. Rundschau *17* (1964) 102–103.
23 Landsberg, H., The assessment of human bioclimate. T.N. 123, WMO No. 331. WMO, Geneva 1972.
24 Landsberg, H., Weather climate and human settlements. WMO No. 448. WMO, Geneva 1976.
25 Landsberg, H., The urban climate, in: International Geophysics series, vol. 28. Academic Press, New York 1981.
26 Mayer, H., and Höppe, P., Thermal comfort of man in different urban environments. Theor. appl. Climat. *38* (1987) 43–49.
27 Ngang'a, J., and Ngugi, G., Indices of comfort for towns in Kenya. Proc. Symp. Climate and Human Health II, pp. 190–199, UNEP/WMO/WHO, Leningrad/Geneva 1987.
28 Niewolt, S., Tropical Climatology. Wiley, Chichester 1977.
29 Niewolt, S., Design for climate in hot humid cities, in: Proceed. Urban Climatology in Tropical Areas, pp. 514–534. Ed. T. R. Oke. WMO No. 652. WMO, Geneva 1986.
30 Oke, T., Review of urban climatology 1968–73. T.N. 134. WMO, Geneva 1974.
31 Oke, T., Review of urban climatology 1973–76. WMO T.N. 169. WMO, Geneva 1979.
32 Oke, T., Bibliography of urban climatology 1977–80. WCP-45. WMO, Geneva 1982.
33 Oke, T., Bibliography of urban climatology 1981–88. WCAP-15. WMO, Geneva 1990.
34 Olaniran, O., The physiological climate of Ilorin, Nigeria. Arch. Geophys. Biokl. B *31* (1982) 287–299.
35 Padmanabhamurti, B., Urban climates of India, in: Proceed. WMO, Tech. Conf. on Urban Climatology in Tropical Areas, pp. 137–166. Ed. T. Oke. WMO No. 652. WMO, Geneva 1986.
36 Park, H. S., and Kawamura, T., Sensible climates in monsoon Asia. Int. J. Biometeor. *35* (1991) 39–47.
37 Rubinstein, M., Ganor, E., and Ohring, G., Areal distribution of the discomfort index in Israel. Int. J. Biometeor. *24* (1980) 315–322.
38 Sani, S., An index of comfort for Kuala Lampur, in: Urbanization and the Atmospheric Environment in the Low Tropics. Penerbit University Press, Malaysia 1987.
39 Scharlau, K., Die Schwüle als messbare Grösse. Bioklimatol. Beibl. Meteor. Z. *10* (1943) 19.
40 Scharlau, K., Die Schwülezonen der Erde. Ber. Dtsch. Wetterd. (U.S. Zone) *42* (1952) 246–249.
41 Subhramanyan, V. P., and Silvaramakrishnaiah, K., Bioclimatic classification of India and the neighbourhood with special reference to its significance for human comfort. I.J.M.R. *52* (1964) 6–9.
42 Taesler, R., Climate characteristics and human health. Proceed. Symposium on Climate and Human Health. WCAP No. 2, pp. 81–119. WMO/UNEP/WHO, Geneva 1987.
43 Tannenbaum, J., and Sohar, E., The Significance of Cumulative Discomfort Index as Measure of Daily Heat Load. Solar Lab. Technion, Israel 1960.
44 Terjung, W., Physiologic climates of conterminous U.S.: a bioclimatic classification based on man. Annls Assoc. Am. Geogr. *56* (1966) 141–179.
45 Terjung, W., The geographical application of physioclimatic indices to Africa. Int. J. Biometeor. *11* (1967) 5–19.
46 Terjung, W., World patterns of the distribution of monthly comfort index. Int. J. Biometeor. *12* (1968) 119–151.
47 Thom, E. C., A discomfort index. Weatherwise *12* (1959) 57.
48 Tromp, S. W., Biometeorology. Heyden, London 1980.
49 Tunnel, G. A., World distribution of atmospheric water vapour. Geogr. Mem. 12, No. 100. Met. Office, London 1958.