Climate and Thermal Stress in Outdoor Spaces

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ABSTRACT: The outdoor conditioning is becoming an important research field not only in temperate climate areas, but also, and specially, in tropical climate ones. Nevertheless there is no consensual comfort index to evaluate such areas. In Brazil, although significantly part of its territory have tropical climate characteristics, the amount of field research, that could develop a specific methodology to outdoor spaces, is still insignificant. Aiming the implementation of such research field, this article discusses a procedure to correlate the climate conditions of most important Brazilian cities and the human thermal stress in their outdoor areas. A biophysical model describing the mechanisms of heat exchange between the body and the environment was adopted from which metabolic and environmental thermal stress on the body can be computed. In this model, a person is a vertical cylinder within a sphere of influence that is the landscape. The upper hemisphere is dominated by the sky and the lower one is dominated by the ground surface. The procedure assumes hourly data of solar radiation, air temperature, relative humidity and wind speed, for each given city. Two types of most usually found pavement are considered: asphalt and grass. At first, no sky or ground objects were taken into account, considering the hypothesis of a possible completely open area. Afterwards, the simulation is done considering the person in shaded configuration. The results are treated generating, for each city, monthly graphic charts showing, throughout a typical day period of time, hourly acceptance in terms of thermal stress, for different types of human activities and clothing. It also considers the two given pavement types in shaded and not shaded configurations, allowing establishing minimum parameters to future interventions in outdoor areas of the studied cities.

Conference Topic: 3 Comfort and well-being in urban spaces
Keywords: human thermal stress, urban climate, outdoors, pavement, Brazilian cities

1. INTRODUCTION

Outdoors, specially in hot humid tropical climates, a person is exposed to high thermal load due solar radiation (direct, diffuse and reflected) and radiation emitted by surrounding surfaces. In such situation, the human thermal-physiological equilibrium is made possible by the latent heat loss (respiration and water skin evaporation), which is the most significant and, as well, the most difficult to achieve due the high relative air humidity, leading to thermal stress and/or physiological strain. This strain can be estimated by indexes, as HL (Heating Load) and SP (Sensible Perspiration) [5], or by limit values of SWreq (required sweat rate for thermal equilibrium) and Smax (maximum heat storage in the body) stated by the standard ISO 7933 [4].

Considering four Brazilian cities (Manaus, Brasília, Rio de Janeiro and São Paulo) and their typical annual climate conditions, it is possible to verify that outdoor spaces, not shaded or inadequately paved, contribute significantly to human thermal stress. This work identifies, for the given cities, the human stress (and/or physiological strain), throughout a typical day period of time, for each month, in three different configurations: sun exposed asphalt, sun exposed grass and complete shade.

2. METHODOLOGY

2.1 Thermal-physiological balance in outdoors

The human thermal budget in outdoors is the following:

\[ S = M + Q + C + K + E + \text{Res} \quad [W/m^2] \quad (E1) \]

Where:
- \( S \): heat storage in the body [W/m²]
- \( M \): metabolic power [W/m²]
- \( Q \): heat exchange on the skin by radiation [W/m²]
- \( C \): heat exchange on the skin by convection [W/m²]
- \( K \): heat exchange on the skin by conduction [W/m²]
- \( E \): heat loss by evaporation at skin surface [W/m²]
- \( \text{Res} \): respiration heat loss [W/m²]
Q = L + R [W/m²] (E2)

Where:
L: heat exchange by long wave radiation [W/m²]
R: heat gain by short wave radiation [W/m²]

Figure 1: Thermal-physiological balance

The budget in Figure 1 illustrates the following considerations: individual characteristics (activity, position, type and color of clothing, environmental characteristics (albedo and emissivity of surfaces and shaded configurations) and local climate characteristics (direct, diffuse and reflected solar radiation, air temperature, humidity, vapour pressure, atmospheric pressure and air speed).

The Figure 2 shows thermal balance, in Manaus, in January, at 3 pm. The person is exposed to sun, on asphalted pavement. It illustrates that latent heat loss plays a significant role in thermal balance.

For sun altitude (h) > 5°:

\[ R = \frac{R_{\text{dir}}(26.34/h-0.329 \pm R_{\text{dir}}+R_{\text{rfl}})(0.0018+0.0462 \cdot \ln(h))}{(1-0.01a) \cdot I_{\text{rc}}} \] [W/m²] (E4)

Where:
Rdir: direct solar radiation
Rdif: diffuse solar radiation
Rrfl: reflected solar radiation
a: cloth albedo
Irc: related to cloth and convection exchanges

Heat exchange by long wave radiation (L) considers the human body (Ls), the pavement (Lp) and the sky (Lc):

\[ L = (0.5 \cdot Lp + 0.5 \cdot Lc - Ls) \cdot I_{\text{rc}} \] [W/m²] (E5)

Heat exchange by convection (C) considers the mean skin temperature (Tp) and the air temperature (t):

\[ C = h_{\text{c}} \cdot (t - Tp) \cdot I_{\text{rc}} \] [W/m²] (E6)

Where:
hc: heat exchange by convection coefficient (function of air and person speed)

Heat loss by evaporation (E) considers the diffuse evaporative rate (Edif) and the maximum evaporative rate that can be achieved with the skin completely wet (Emax). "E" depends on the metabolism, the vapour pressure, the skin saturation vapour pressure, the air and person speed.
The numerical formulation can be found in [1], [2] and [7].

Respiration heat loss (sensible and latent) considers the metabolism (M) in W/m², air temperature (t) in °C and partial vapour pressure (Pa) in kPa:

\[ \text{Res} = 0.0014 \cdot M \cdot (t-35) + 0.0173 \cdot M \cdot (Pa-5.624) \] [W/m²] (E7)

In this particular work, the following individual parameters were adopted:
Cloth: 0.5 clo; albedo 0.5
Activity: walking - 0.9 m/s (116 W/m²)

The climate data for the given cities were obtained from Climaticus [8]. Air speed data were corrected to person height, considering the surrounding as “built area”. This correction was made as following:

\[ V_h = V(10) \cdot K \cdot 1.6^n \] (m/s) (E8)

Where:
V(10): air speed (m/s) measured at meteorological station (10m height)
K e n: correction coefficient. In the particular case of “built area”: K=0.4 e n=0.25
2.2 Thermal Stress and Physiological Strain Indexes

In most cases, the indexes used to identify the human thermal stress refer to the heat storage in the body, \( S \) (equation 1). This can be seen in the standard ISO7933 [3], where the mentioned equation is solved making \( S = 0 \). Supposing this, it calculates the necessary heat loss by evaporation at skin surface to achieve the thermal equilibrium.

When the required evaporative rate (SWreq) is bigger than the maximum evaporative rate that can be achieved with the skin completely wet (Emax), there will be heat storage in the core of the body. The limits established by the standard are:

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Warning limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (maximum heat storage)</td>
<td>≤ 50 (Wh/m²)</td>
</tr>
<tr>
<td>SWreq (required evaporative rate)</td>
<td>≤300 [W/m²]</td>
</tr>
</tbody>
</table>

Other outdoor human thermal indexes also consider (S), but it is used to classify levels of thermal stress or physiological strain, considering the heat exchange on the skin by radiation (R). This is the case of Heating Load (HL), adopted in software Bioklima [1], as follows:

<table>
<thead>
<tr>
<th>HL</th>
<th>Stress by</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤0.25</td>
<td>Extreme stress (cold)</td>
</tr>
<tr>
<td>0.26 a 0.82</td>
<td>Stress (cold)</td>
</tr>
<tr>
<td>0.83 a 0.97</td>
<td>Few stress (cold)</td>
</tr>
<tr>
<td>0.98 a 1.025</td>
<td>No stress</td>
</tr>
<tr>
<td>1.026 a 1.180</td>
<td>Few stress (hot)</td>
</tr>
<tr>
<td>1.181 a 1.750</td>
<td>Stress (hot)</td>
</tr>
<tr>
<td>≥1.751</td>
<td>Extreme stress (hot)</td>
</tr>
</tbody>
</table>

Indexes as Sensible Perspiration (SP) [5] evaluate the evaporation rate in the body-cloth ensemble. It is calculated as follows:

\[ SP = -0.35(E_{req}/E_{max}) \]  

Where:
- \( E_{req} \): required evaporative rate
- \( E_{max} \): maximum evaporative rate

A similar formulation is proposed by Belding and Hatch [5]. The Heat Stress Index (HSI) also considers \( E_{req} \) and \( E_{max} \), which numerical values taken by the bigger between:

\[ HSI = (E_{req}/E_{max}) \times 100 \]  
\[ HSI = (E_{req}/2400) \times 100 \]

Note: 2400 (in BTU) is the value of evaporative heat loss of one litre of sweat.

The numerical values, which are possible to be found, are between 0 and 200, where 0 is no stress by heat (something near comfort zone) and 100 is the upper limit of thermal equilibrium.

There are also other indexes that don't consider the thermal stress, but the physiological strain. For example, the PhS (Physiological Strain) [1] is set considering the heat exchange by convection (C) and the heat loss by evaporation (E), as follows:

\[ PhS = C/E \]  

PhS adopts the following scale:

<table>
<thead>
<tr>
<th>PhS</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.25</td>
<td>Extremal hot strain</td>
</tr>
<tr>
<td>0.25 a 0.75</td>
<td>Great hot strain</td>
</tr>
<tr>
<td>0.75 a 1.5</td>
<td>Slight hot strain</td>
</tr>
<tr>
<td>1.5 a 4.0</td>
<td>Slight cold strain</td>
</tr>
<tr>
<td>&gt;4.0</td>
<td>Great cold strain</td>
</tr>
</tbody>
</table>
In the present work, it was adopted the limits established by the standard ISO 7933 for the S (maximum heat storage) and SWreq (required evaporative rate), as seen in table 1. The indexes HL, PhS and SP (Tables 2, 3 e 4) were also taken into account, once the influence of pavement and shade is highlighted by them.

3. CLIMATE AND STRESS IN OUTDOORS

3.1 Chosen Cities

Four Brazilian cities (Manaus, Brasília, Rio de Janeiro and São Paulo) were chosen to apply the proposed methodology, considering their particular characteristics of air temperature and relative humidity. The climate data for the given cities were obtained from Climaticus [8].

In this paper, as methodology apply illustration, only the most significant results are presented.

The given cities can be located in the map of the following figure:

![Figure 3: Localization of the studied Brazilian cities](image)

The two following figures illustrate the hourly variation of the air temperature and relative humidity for the city of Rio de Janeiro and Manaus (main city in the Amazon Forest):

![Figure 4: hourly variation of the air temperature in the hottest month (Manaus and Rio de Janeiro).](image)

3.2 Built environment characteristics

Aiming the human thermal stress evaluation outdoors, three configuration types were considered:

- a. asphalted pavement
- b. grass (0,10 m)
- c. shaded configuration

In the former two alternatives, the person is under open sky and without built area in the near surroundings. In the third alternative, (shaded configuration) it is not considered any specific cover type, assuming that its inferior surface temperature, as well as superficial pavement temperature and air temperature are in equilibrium. In this particular case, the person is not exposed to direct, diffuse or reflected solar radiation.

To the case of asphalted pavement, it was adopted a emissivity of 0,95 and an albedo of 0,1. To the case of grass, 0,9 and 0,23, respectively.

Superficial asphalted pavement temperature was calculated using the air-sun temperature model. To the case of grass, it was adopted the model proposed by Roriz [6].

The following figure illustrates the hourly variation of asphalted pavement and grass superficial temperatures, in the hottest month, for the case of the city of Rio de Janeiro:

![Figure 6: Hourly variation of the superficial temperature of given pavements (Rio de Janeiro, January).](image)
3.3 Thermal Stress in Brazilian Cities

Considering the heat loss by evaporation at skin surface (E) as thermal index parameter, it is possible to verify the importance of specific air relative humidity of each given city. High values of air relative humidity are restrictive for the evaporative heat loss, as can be seen in the following formulation [4]:

\[ E_{\text{max}} = \frac{(P_p - P_a)}{R_p} \text{ [W/m}^2\text{]} \]  \hfill (E13)

Where:
- \( E_{\text{max}} \): maximum evaporative rate
- \( P_p \): saturated vapour pressure at skin temp. (kPa)
- \( P_a \): partial vapour pressure (kPa)
- \( R_p \): total evaporative resistance of limiting layer of air and clothing (m²kPa/W)

The following two figures show, for the hottest month in Manaus and Brasília, the maximum evaporative rate that can be achieved with the skin completely wet (\( E_{\text{max}} \)) and the required evaporative rate (\( S_{\text{Wreq}} \)).

![Figure 7: Heat loss by evaporation (Manaus, hottest month)](image)

![Figure 8: Heat loss by evaporation (Brasília, hottest month)](image)

In Figure 7 it can be observed that, from 9 am to 7 pm, it will be heat storage, once the required evaporative rate is higher than the maximum evaporative rate that can be achieved. Such situation, obviously, indicates the need of heat gain reduction or heat loss increase.

The figures 9 and 10 show the monthly hourly acceptance in terms of heat storage, which is 50 W/m², according to the limit established by the standard ISO 7933 [3].

![Figure 9: Manaus, in asphalted pavement, 44% of hours (considering the whole number of hours in the year) presents human thermal stress.](image)

![Figure 10: Rio de Janeiro, in asphalted pavement, 32% of hours (considering the whole number of hours in the year) presents human thermal stress.](image)

![Figure 11: Percentage of number of hours of human thermal stress, considering the pavement type and shade, in four Brazilian cities.](image)

In Manaus, considering grass instead of asphalted pavement, there is a reduction of 6% in the number of hours of human thermal stress. Considering a shaded configuration there is a reduction of more 11%. In Rio de Janeiro, shaded configuration reduces in 24% the number of hours in stress. Despite the great reduction, the problem is not fully solved.
Due to the local climate, and considering typical clothing and activities, as it was considered in this work, even shade configuration is not enough to eliminate the human thermal strain in cities like Rio de Janeiro (high air relative humidity), as it could be verified. However, in cities like Brasilia, grass and shaded configurations reduce 15% and 27%, respectively, the number of hours of human thermal stress.

On the other hand, in order to emphasize the relative importance of each pavement and the shaded configuration, the following figures illustrates the physiological strain, during a day period of time, through the application of the Sensible Perspiration Index (see table 3 for SP values).

Legend for figures 12, 13, 14 and 15:
- asphalt
- grass
- shade

Figure 12: Sensible Perspiration (SP) - Manaus (hottest month)

Figure 13: Sensible Perspiration (SP) - Rio de Janeiro (hottest month)

Figure 14: Sensible Perspiration (SP) - Brasilia (hottest month)

Figure 15: Sensible Perspiration (SP) - São Paulo (hottest month)

4. FINAL CONSIDERATIONS

Architects and landscape designers consensually agree that asphalted or concreted pavements are less adjusted to hot humid climate areas. Nevertheless, the quantitative impact on the human stress can not be estimated by simple intuition, but it can be by the knowledge of the human thermal-physiological balance. Considering the climate and the surroundings, the methodology presented in this work culminated in the Urbanus software, which supplies an objective evaluation of adopted solutions to treat outdoor spaces, concerning the human thermal stress.

5. REFERENCES