URBAN CLIMATE STUDY OF SALVADOR: THERMAL COMFORT PATTERN

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ABSTRACT

In the city of Salvador, situated in the Northeast Brazilian coast, an urban climate investigation, with meteorological measurements, was carried out. These data could be used to calculate thermal comfort based on heat equation balance of man expressed through the Physiological Equivalent Temperature (PET) and Standard Effective Temperature (SET). It shows that for Salvador a very inhomogeneous condition is derived depending on topography and city structures. For tropical cities it is important to consider its ventilation pattern as being the dominant factor for thermal comfort. The paper correlates human sensations to the urban climate pattern using both indices: PET index was developed for urban climate situations. Any thermal comfort discussion related to planning should be based on urban climate pattern as basic information.

1 URBAN CLIMATE AND GEOGRAPHICAL SITUATION OF SALVADOR

Dense and high building areas lead to a strong heat island effect with high percentage of discomfort. Ventilation worsens and air pollution increases as new building developments are created, bringing serious health and environmental comfort problems for people. An urban climate investigation, including meteorological measurements, was carried out for Salvador. These data were used to calculate thermal comfort on the base of heat equation balance of man expressed through the Physiological Equivalent Temperature (PET) and Standard Effective Temperature (SET). It shows that a very inhomogeneous structure is derived depending on topography and city structures. The tropical climate of Salvador also shows that special attention should be given to ventilation and income radiation parameters, as these are the dominant factor for thermal comfort.

A first attempt to describe the urban climate of Salvador on a meso scale was already made (Nery *et. al*, 1997). This was the base for an approach towards describing the climatological situation in respect to urban climate influencing thermal comfort. In Salvador the annual variation of air temperature, humidity and wind velocity are rather low. Wind direction, with its characteristic daily and annual variation has na important effect.

Goulart *et. al* (1997), using a 10 year period meteorological data from the airport outside Salvador calculated the daily and annual variation for: air temperature maximum with an annual amplitude of 3,9 ^oC and air temperature minimum of 2,7 ° C; wind speed ranged from 2.5 to 3.6 m/s. The annual humidity was around 80 %, with very low variation. Thus, for planning purposes the variation of these parameters can be taken as reasonably stable.

Wind directions place more difficulty for being described. First, it presents a very characteristic annual variation ranging from SE and E (40%) in Summer and the third component of NE (15%). In Winter, S (> 50%) and SE (35 – 25%) winds occur (Goulart *et. al*, 1997). Second, there is a regional wind circulation in Summer with a Northern component in the morning, which changes to Southeast in the afternoon (Valente, 1977). This may be caused by a land sea breeze mechanism in a meso scale level.

As a first approach, regional winds in Salvador behaves differently in the shore, highlands (Upper City) and foothills (Lower City) (Figures 1 and 2). The topographical situation leads to morning winds along the bay and only afternoon winds from the ocean penetrate and overflow the city. Turbulence is combined with these effects. In the morning, the lower areas are better ventilated with winds from the land than in the afternoon where the topographically highest points are well ventilated due to the sea breeze SE.

The special situation of Salvador, between the shore of Atlantic Ocean and the All Saint's Bay buffers considerably the thermal situation. Trade Winds guarantee a positive air mass exchange. Salvador urban climate structure builds up the typical Urban Canopy Layer (UCL). Due to the topographical situation the UCL of Salvador is more complicated than in other cities. *Per* definition this should be the layer between surface and roof level. This is only partly true for Salvador, as the stronger Trade Winds reduce this typical layer. At higher points a complete different vertical structure around the 4th floor of buildings is observed. This is still subject to be confirmed by more detailed measurements.

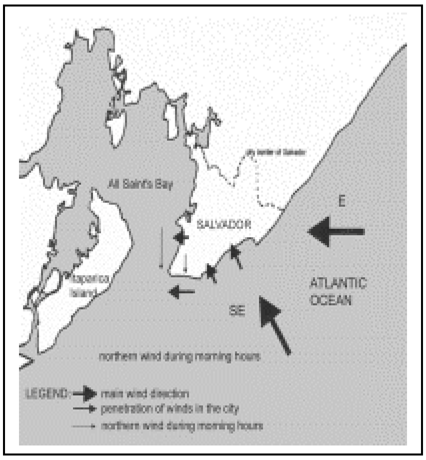

Figure 1: Regional winds in Salvador

The structure with the three main layers for Salvador is shown in Figure 2. The difference of the Urban Mixing Layer (UML) and the Urban Canopy Layer (UCL) is clearly observed.

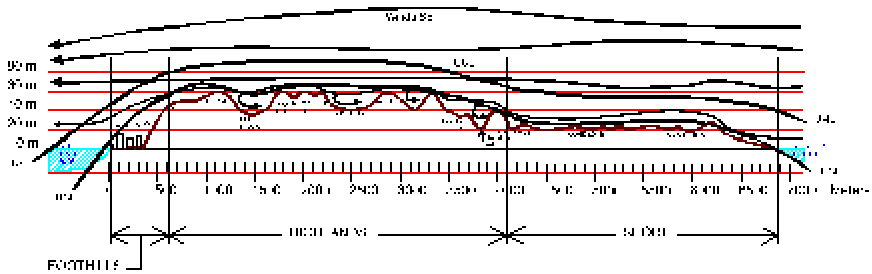

Figure 2: Boundary layers in Salvador: UCL and UML

2 METHODOLOGY

It was developed a methodology for the urban area of Salvador City, as it is very complex. (Katzschner, 1997). Based on it, specific criteria were drawn to derive an urban climate classification (Table 1). The first investigation considered topography, land use categories, city structures and vegetation. This classification is based on a qualitative description of urban structures and the wind distribution mentioned above.

Table 1: Criteria for urban climate classifications for Salvador

***G.C. = Geographical classification: 1 shore; 2 highlands; 3 foothills**

Criteria	Classification	GC*	Surface	Roughness length z_o	Sealing degree (%)	City structure
Heat Island Max	HMW	1	Concrete	> 1.5	>60	Mainly high buildings
Heat island	HM	2	Concrete some trees	1 -1.5	50	High buildings, streets with trees, ventilated
Heat island Min	HR	2	Concrete	0.5 -1	40	Small buildings
Heat island with thermal discomfort	HD	2	Asphalt and bare soil	0.5-1	40	Small houses without green areas in between
Dune climate	D	1	Sand	< 0.5	10	Some houses, vegetation
Industrial climate	I	2	Asphalt, concrete	1	60	Halls for production
Air paths (SE)	VSE	-	Asphalt or pure vegetation	< 0.5	< 20	Streets, free spaces, vegetation
Air paths (NE)	VNE	-	Asphalt or pure vegetation	< 0.5	< 20	Streets, free spaces, vegetation
Areas of local circulation	VCL	1 + 3	All surfaces	0.5 -1.5	10 -60	Independent from city structures
Cool areas	C	-	Vegetation	0.5 -1	< 10	Parks, green areas
Cool areas	CD	1	Vegetation and sand	0.5	< 10	Dunes and parks

3 THERMAL COMFORT PATTERN OF SALVADOR

The heat island phenonmenum should consider: first, the topographical situation and the heat island reduction by the wind; second, the climatic effects of open spaces, due to their various surface conditions. Mainly the trees combined with the higher wind speeds in hilly situations in the highlands reduce the heat island effect. Therefore, high building situation is divided in two categories: HM, which stands for the Maximum Heat Island without ventilation and HMW, Heat Island with ventilation (Table 1).

Small building structures mainly occur in the highlands. Topography makes the difference. Heat island with HR index means warm areas with some shading. Heat Island with HD index means warm areas, but with a high variety of microclimates with thermal discomfort. Housing areas are often without vegetation and shade, but there are places with cold stress in Winter, due to higher wind speeds and slightly lower air temperatures.

Warm areas with I index are related to industrial or industrial influenced situation. Penetration of wind occurs, as the distances between the buildings are wide. The warming effect is due to the high sealing degree with very warm surface temperatures. A singular situation occurs in the dune area, D index. They belong to the warm areas too, as they have a high radiation income and the surface temperatures are immediately increasing after sunrise.

Parks and green areas, C index, play a very important role for Salvador. They are considerable cooler than the other spaces, and produce fresh air, which is transported into the city, inducing local thermal circulation. Thus, the cooling is not only restricted to the area itself, but influences the neighborhood. Not listed in that level because of their size are urban places like Campo Grande Square and others, but from which is known they have a considerable different microclimate. The CD index areas are cool regions but through housing and the topographical situation with some thermal discomfort.

Wind distribution pattern is characterized by SE and NE Trade Winds (Figure 1). The mean wind speed in urban areas is between 2,0 and 3,0 m/s. The criteria of roughness length (z_o) and the topographical situation lead to the dynamic analysis (Figure 2).

<u>SE Winds:</u> It is the dominating wind in Salvador. Penetration of air masses from the ocean occurs into the UCL. There are remarkable ventilated zones, mainly along rivers or valleys of former rivers. These air paths built up a system of winds, with a particular maxima and minima wind, the former with NE-SW. In the ventilation zones air masses go along the surface crossing the city within the UCL. This induces some secondary circulation. Along All Saint's Bay the SE wind direction is changed slightly creating a Southern component.<u>NE Winds</u>: It is the second important weather situation in Salvador. Ventilated zones bring fresh air into the city, especially due to the location of the Northern green areas, favoring thermal comfort conditions. <u>Local circulation</u>:Together with low wind speed, thermal effects induce local circulation. Normally the SE wind can overcome these local systems, but within some areas, local circulation occurs regularly (Figura 3). This is caused by a land sea breeze along the littoral with a maximum at the entrance of the valleys and the turbulence connected to different land use near the bay. This turbulence is caused by thermal interactions between the foothills and the bay, which interests the microclimate conditions.

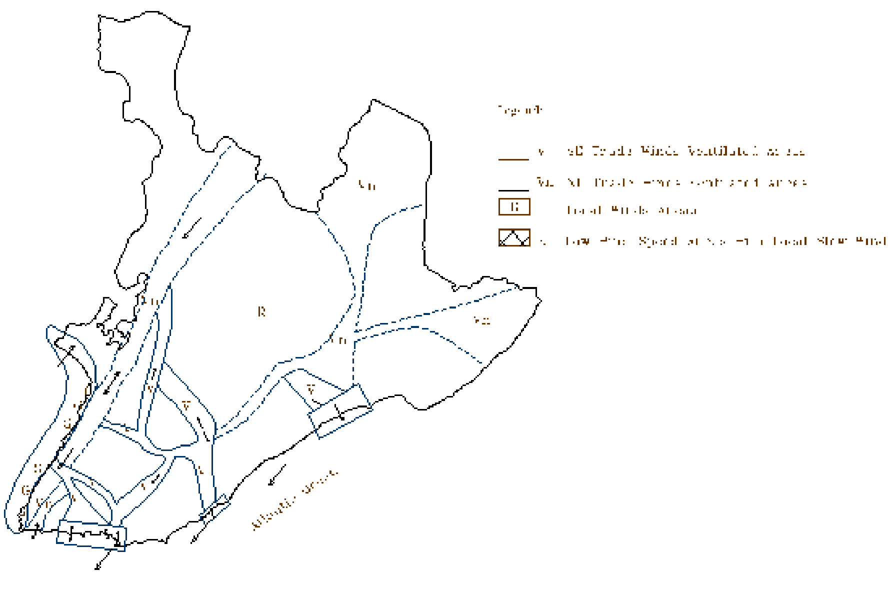

Figure 3: Dynamic Analysis

The paper does not discuss the different indices used with thermal comfort, but rather correlates human sensations in connection to the urban climate pattern with the indices of a Physiological Equivalent Temperature (PET) and a Standard Effective Temperature (SET). Any thermal comfort discussion related to planning should take the urban climate pattern into account, on which thermal comfort discussion can happen. Moreover, there are many different values for thermal comfort conditions.

The values chosen here calculate temperature, humidity, wind and radiation. They are based on the heat balance equation of a human body under steady-state conditions. Differing from the approaches used by Fanger (Fanger, 1972) PET incorporates real values for skin temperature and the evaporation of sweat, depending and calculated from the meteorological conditions in urban climates while SET takes them as separate input values.

PET index calibrates thermal sensations with indoor conditions and suggests a temperature which can be used for the outside situation. It was developed especially for urban climate considerations. SET (Gagge, 1974 in: Markus, 1980) and PET (Höeppe, 1984) use the heat balance equation as a base and take the meteorological parameters of air temperature, mean radiant temperature, humidity and wind velocity into consideration. The urban structures can be calculated by the influence on the mean radiant temperature. Furthermore, for SET, activity and clothing are calculated separately while PET takes clothing and activity levels into account through a heat balance model of the human body considering the influence of sweat, diffusion of water vapour etc. SET establishes comfortable conditions around 25 ^{o}C and PET around 20 ^{o}C. The differences occur through the different clothing conditions, which is taken into consideration for indoor situations.

Table 2 shows a comparison of these values with the empiric feeling of people compared to different climates. The grade of physiological stress is taken from an European person. It also includes a comparison for Predicted Mean Vote (PMV) from Fanger (1972). Thus, the thermal comfort can be considered for different climates and thermal sensations.

Table 2: Bioclimatic values and human sensation (after Matzarakis/Mayer, 1996 and Freire, 1986)

PMV	SET ^{O}C	PET ^{O}C	THERMAL SENSATION European climate	THERMAL SENSATION Tropical climate	GRADE OF PHYSIOLOGICAL STRESS
			Very cold	Extremely cold	Extremely cold stress
- 3,5	10	4			
			Cold	Very cold	Strong cold stress
- 2,5	15	8			
			Cool	Cold	Moderate cold stress
- 1,5	20	12			
			Slightly cool	Cool	Slight cold stress
- 0,5		16			
	25	20	Neutral		No thermal stress
0,5		24		Neutral	

	30		Slightly warm		Moderate heat stress
1,5		28		Slightly warm	
	35		Warm		Strong heat stress
2,5		32		Warm	
	40		Very hot		
3,5		36		Hot	
		40		Very hot	

As far the thermal analysis is concerned, if the wind and temperature aspects are considered together that thermal discomfort in Salvador occurs mainly in narrow valleys with densely built up areas. High heat storage, high values of short wave radiation and weak ventilation leads to discomfort. Table 1 shows areas with HMW and HD indices which present discomfort. This does not always imply in heat stress; some areas within HD classification tend to show cold stress too (deep valleys). The reason for discomfort is different but in both areas, HMW and HD, extreme climatic conditions can be observed. Also, in the HMW area discomfort will be felt due to high wind pressure in high buildings.

Table 3 presents the results of a set of measurements for different urban conditions. PET ranging from 37 to 42 ^{o} C was found in valleys and urban structures of densely built up areas without shading, while it was reduced to 34 ^{o} C in areas with ventilation and shading.

Table 3: Bioclimatic values for Salvador on November 10th,1998 - 10.00 o'clock

Meteorological parameters	Valley without ventilation	Valley with ventilation	Street with trees	Street without trees
Global radiation (W/m^2)	1050	1050	436	1068
Mean radiant temperature (^{o} C)	60.2	60.0	45.5	69.8
Air temperature (^{o} C)	32.1	31.8	30.5	30.9
Wind velocity (m/s)	0.2	3.2	2.5	2.5
Vapor pressure (hPa)	21	20	25	22
PET (^{o}C)	48.4	40.6	34.5	47.1

The results show very inhomogeneous thermal conditions due to topography and city structure. As far as planning is concerned, it means that urban actions can be taken to improve vegetation and reduce radiation income through adequate built areas in association with vegetation.

PET values calculated for the meteorological data from Salvador's Airport were: 36.8 ° C (under solar radiation) and 31,3 ° C (under shading) for Summer. The difference is explained by the mean wind speed of 3.6 m/s (airport) and city wind speeds of 2.5 m/s (built areas of reduced ventilation) and 3.2 m/s (ventilated areas). Recalculating PET values for airport, assuming the lower wind speeds found in the city, PET was 40.9 ° C. This illustrates the dominant influence of ventilation on thermal comfort.

Thus, it does not make sense to calculate bioclimatic conditions using database from a station at the outskirts. It is very important to observe the very inhomogeneous pattern of the urban climate as a base for any bioclimatic judgement. Knowing the importance of wind in connection to thermal comfort, the ventilation systems of the city have to be investigated in a more quantitative way. With the methodology of urban climate pattern as the basic knowledge for thermal comfort and air pollution, a good tool is given to implement climatological results in planning processes.

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