Intra-Urban Air Temperature Distribution, Urban Heat Island and Thermal Comfort Implications in A Subtropical City

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Abstract: Unlike most of the Brazilian hot-humid cities, subtropical Curitiba experiences thermal discomfort due to cold during most of the year, with the coldest air temperature occurring in winter. Due to rapid urbanization, the Metropolitan Area has been faced with critical environmental problems. Urban microclimate patterns exhibit considerable variability; particular areas of the city alternate between cool islands and heat islands, resulting in different outdoor thermal comfort levels. The objective of this work is twofold: 1) to characterize intra-urban air temperature differences and their impact on outdoor thermal comfort in Curitiba; 2) to assess the yearlong Urban Heat Island (UHI) effect and its effect on indoor thermal comfort levels. For that, a series of independent measurements and field monitoring campaigns, both outdoors and indoors, were analyzed. Results point to a great variability in intra-urban temperature differences and derived outdoor comfort levels. With regard to predicted UHI effects in low-cost dwellings, indoor comfort due to heat was found to prevail over the year; the 'net effect' between heat stress in summer and cold stress in winter point towards a prevalence of heat stress indoors.

Keywords: Urban Heat Island, intra-urban air temperature variations, outdoor thermal comfort, indoor thermal comfort.

1. INTRODUCTION

Curitiba (25.5ºS, 49ºW, 910 a.m.s.l.) is located in a tropical climate zone in a relatively high-altitude region of Brazil (Cfb/Koeppen). It often experiences unstable meteorological conditions with large daily and annual air temperature fluctuations. Average air temperature in summer is approximately 20ºC, though average air temperature in winter is quite low for tropical standards, reaching 13ºC in June/July [1].

Urban climate is influenced by the interaction of synoptic weather systems and physical characteristics of the city. Differences in urban morphology, vegetation and anthropogenic heat may lead to variations in intra-urban microclimate patterns, which in turn will affect outdoor thermal comfort levels across the urban area. In addition, such effects can have an impact on indoor thermal comfort and/or on energy needs for cooling/heating.

Urbanization alters the natural environment and has thus an impact on life quality of urbanites. Such environmental changes and inadvertent impacts on life quality result from the suppression of native vegetation, addition of man-made structures (pavement, buildings), anthropogenic heat sources (transportation, industry) accompanied by increases in urban population density, among other causes. These changes affect local meteorological conditions and create what is commonly termed 'urban microclimate'. The thermal properties of urban materials and structures are the main causes for the heat island effect in cities, although additional factors (anthropogenic sources of heat, air pollution and reduced evaporation) also play an important role [2]. Eliasson [3] states that cities often consist of not only one urban heat island (UHI) but of a mosaic of areas with higher and lower air temperature, which are highly influenced by changes in land use.

By comparing meteorological data with satellite images for the Curitiba Metropolitan Region (CMR), Mendonça and Dubreuil [4] concluded that the thermal field of the urban area forms a mosaic of heat islands and cool islands (UCIs) when compared to the surrounding rural areas. Effects of urbanization, industrialization, vegetation density and topography were found to correlate well to the diversified urban thermal fields. Moreover, intra-urban temperature variations can reach as much as 8K, closely correlating to the various types of land use and urban planning measures implemented in each particular sector.

An exception among Brazilian cities, Curitiba has relied on continuous urban planning since 1943. The mechanization of agricultural activities in the state of

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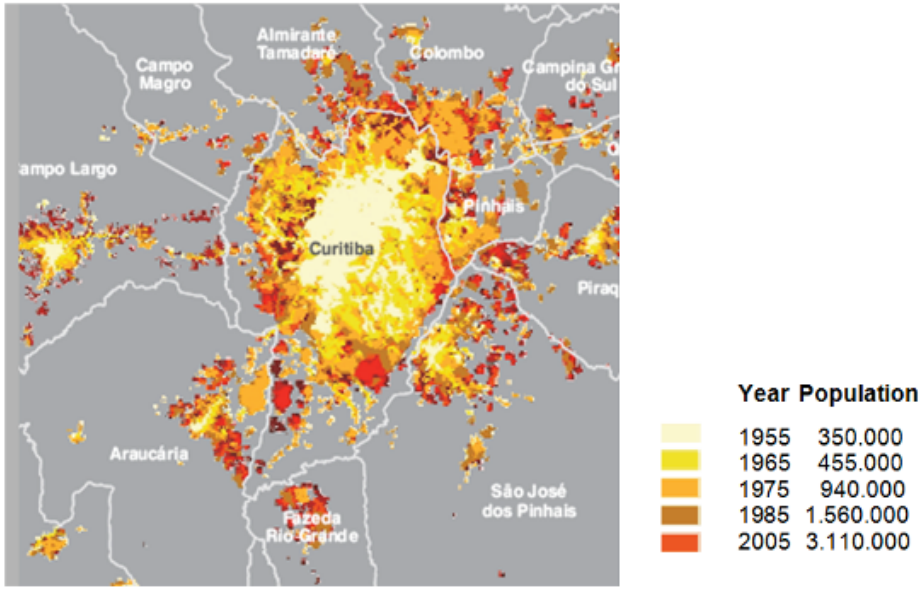

Figure 1: Regional population growth in the Metropolitan Area of Curitiba from 1955 to 2005 [6].

Paraná, whose state capital is Curitiba, was carried out in the 1970s, along with the creation of the 'Industrial City of Curitiba', i.e. the industrial district in the metropolitan area. Both factors were responsible for a strong migratory movement towards Curitiba, intensified in the 1990s and further promoted by the city marketing. The creation of automotive and vehicle assembly clusters in the same decade lead to an increase in inland migration. As a result, Curitiba experienced a gradual population growth which rapidly expanded over the years, both vertically and horizontally; with urban sprawl and conurbation processes taking place (Figure **1**). With high population density and intense industrial activity, Greater Curitiba boasts today approximately 3,094,000 inhabitants (2010), and this Figure is expected to increase to 3,566,000 by 2020 [5].

Environmental concerns have intensified over the years with the increasing urbanization process. Urban zoning practices along the structural axes, designed to direct the growth of the city and allow mass transportation, have resulted in urban canyons with inadvertent effects on thermal comfort, daylight access, ventilation and air quality conditions.

Understanding which relevant morphology and land use aspects are responsible for local meteorological conditions could be an important contribution for improving human biometeorology with effects outside and inside buildings. In tropical regions, where non-insulated, free-running dwellings with no HVAC systems are common, improvements in micrometeorological conditions are particularly relevant.

An additional problem posed by present trends concerns climate change. Global mean air temperature has increased by about 0.8ºC since the beginning of the 20th century, with a likely rising trend [7]. Projected climate change scenarios for South America using Representative Concentration Pathways (RCPs) models show a less intense warming trend, when compared to the Northern Hemisphere: annual air temperature in such region is expected to be 4-5ºC higher by the end of the century and this will certainly bring about inadvertent overheating in existing households.

The relevance of the present study is that UHI effects (magnitude and seasonal changes) for IHI for Curitiba's climatic conditions can be extended to locations with similar climatic features or within a similar latitude range and elevation. The current subdivision of the Brazilian territory into climatic regions with similar bioclimatic design strategies [8] yields a substantial surface area equal to 0.8% of the Brazilian territory or roughly 680,000,000ha. Understanding local UHI and intra-urban air temperature variations as a result from urban planning measures and quantifying such effects can serve as useful information to a climate-responsive urban planning. In this sense, the study can be of particular interest to planners.

The objective of this study is twofold: 1) to characterize intra-urban air temperature differences and their impact on outdoor thermal comfort in Curitiba; 2) to assess the yearlong Urban Heat Island (UHI) effect and its impacts on indoor thermal comfort levels.

For that, a series of independent measurements and field monitoring campaigns, carried out both outdoors and indoors, have been analyzed.

2. MATERIALS AND METHODS

In this paper we show and discuss different data sets: a) satellite data interpreted for a given hour (Surface Infrared Thermography), b) spot measurements at diverse points with air temperature and relative humidity for four days in winter, and c) long-term data collected at two surface observation stations. No attempt is made to compare those measurements and each serves a different purpose: a) to give a broader view of surface temperature variations across the urban area, b) to show intra-urban temperature differences and thermal comfort variability in the same area and c) to analyze the behavior of the nocturnal UHI throughout different seasons. In addition to the third data set, implications of the UHI on indoor thermal conditions in low-cost houses are also evaluated.

2.1. Outdoor Climatic Observations and Thermal Comfort/Discomfort Levels

In order to understand the spatial and temporal interactions of the factors that determine thermal comfort levels in urban areas, the methodology proposed by Mendonça [9] was applied, which consists of two analyses:

1) A spatial analysis based on the mapping of elements within the urban site (hypsometry, slopes, orientation aspects of slopes and surface wind direction and speed), land use and occupation patterns of the urban area. The combination of these elements results in a sectorization of urban areas with a relatively homogeneous distribution across the urban area.

2) The temporal analysis uses a dynamic approach to weather observations, based on the rhythmic analysis of weather types. The simultaneous and synchronous nature of the resulting temporal graphs enables an integrated comparison of the daily and hourly variations of meteorological parameters in a given location.

To identify the types of climatic observations in Greater Curitiba, we monitored the atmospheric dynamics *via* satellite images and meteorological weather reports on a zonal/regional and sub-regional scale. Additional surface air temperature and humidity measurements were also performed.

We combined surface infrared thermography data with Landsat 5 thematic mapping images obtained on August 20th 2006, to make a spatial comparison to the simultaneously recorded air temperature at each weather station at a height of 1.5 m.

Local air temperature and humidity field monitoring was conducted at 16 selected points according to the spatial analysis. The selection of monitoring days was based on the likelihood of having overall thermal discomfort conditions from the past history of cold front episodes characteristic of the winter period. For each monitoring day (August 12th, 18th, 21st and 29th of 2006), an analysis of the synoptic situation and weather observations was performed from the daily rhythms described above. Air temperature [°C] and relative humidity [%] data were measured *in situ* at WMO standardized time intervals (6am, 9am, 3pm and 9pm) and compared to data obtained from surface infrared thermography and at meteorological stations.

Data were analyzed according to the thermal comfort assessment method proposed by Sorre (1984) [10]. This index was adopted as it consists of the two variables measured in the field monitoring. The comfort range is expressed as a combination of air temperature and humidity readings as effective temperature (ET), according to Equation 1:

$$ET=0.4\times(T_S+T_U)+4.8 \quad (1)$$

where T_S and T_U are the ambient dry-bulb and wet-bulb temperature, respectively (in ºC). The comfort range is 16-23ºC (ET in ºC).

2.2. Long-Term Monitoring Series and Predicted Indoor Thermal Comfort Due to UHI Effects in Low-Cost Houses

2.2.1. Procedure Adopted for the UHI Analysis

Data collected in two different areas of the city are used for a long-term assessment of the UHI effect in Curitiba: data from the a meteorological station 'SIMEPAR', located at the Polytechnic Center (assumed to be an 'urban' station) and data registered in the Ecoville region, at the 'UTFPR' station, located on the Ecoville Campus of the Federal Technological University of Paraná (assumed as peripheral or "rural") (Figure **2**). The approximate distance between the two stations is 12 km.

The "Ecoville Weather Station" was implemented in December 2011 (HOBO weather station model H21 – 00), it is equipped with a temperature and humidity

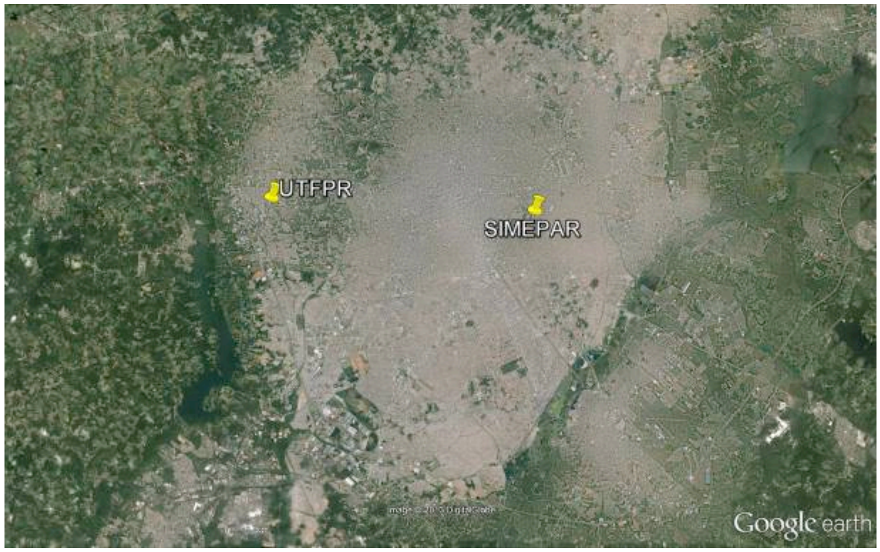

Figure 2: Location of the two weather stations - Google Earth image of July 2009.

sensor (S-THB-M002), a silicon pyranometer (S-LIB-M003) and cup anemometer with wind vane (S-WCA-M003). The "SIMEPAR Weather Station" was implemented in 1997, registering hourly data continuously. The equipment adopted by the SIMEPAR network in automatic weather stations consists of: barometer (Sutrom Accubar, Model 5600-0120), pyranometer (LI-COR), thermohygrometer with relative humidity and air temperature probes (Sutron, Model 5600-0313-1) and anemometer (Young Meteorological Instruments, Model 05103).

In terms of geographic location and characteristics of the surroundings, “UTFPR Weather Station" is located on the outskirts of the urban area and on the rooftop of a campus building with no noticeable obstructions to wind and solar radiation. There are no significant anthropogenic heat sources in the surrounding area. “SIMEPAR Weather Station" in turn is located in an urbanized area, on a grassy surface at the entrance of the Polytechnic Center. The few obstructions to direct and diffuse solar radiation are low-rise buildings nearby, and a few scattered trees located mostly on the south side of the station. A nearby freeway, approximately 50 m from the station, is an important source of anthropogenic heat.

The analysis was performed for different conditions/time periods: a) the whole monitoring period; b) by season; c) for night time and daytime periods. The transitional two-hour period around sunrise and sunset hours, which was determined for each day according to Szokolay [11], was left out of the analysis when defining night time and daytime hours.

Urban heat island effects were expressed as differences between air temperature values measured at the urban and those at the rural site ($\Delta T_{u\text{-}r}$).

2.2.2. Procedure Adopted for Predicting Indoor Thermal Comfort Effects in Low-Cost Houses

The Technological Village of Curitiba was inaugurated in May 1994 and consists of 120 houses, 100 of them inhabited by low-income families. In a previous study, 18 occupied houses made with different wall and roof materials were monitored by the authors [12] in respect of indoor air temperature (Table **1**).

Table 1: Building Systems Monitored in Respect of Indoor Temperatures

Building System	Description
1.	Concrete panels
2.	Wood panels
3.	Wood panels
4.	Mineralized wood boards
5.	Polystyrene plastered boards
6.	Earth cement bricks
7.	Hardwood boards
8.	Masonry, insulated
9.	Lightweight concrete panels
10.	Fiber cement panels
11.	Concrete panels with inner air layer
12.	Concrete boards
13.	Concrete panels with inner air layer
14.	Concrete panels with polystyrene inner layer
15.	Ceramic hollow blocks
16.	Concrete hollow blocks
17.	Concrete boards
18.	Concrete panels

The thermal evaluation was conducted with air temperature measurements taken at the middle point of each dwelling with HOBO Temp data-loggers in two different periods: in winter, from July 9th to August 3rd 2000 and in summer, from December 12th 2000 to January 12th 2001. From such thermal evaluations, mean departures from the outdoor air temperature (collected with a logger placed outside the houses within a naturally ventilated radiation shield) were calculated for each dwelling, for both periods and for daytime and night time (Figure **3**).

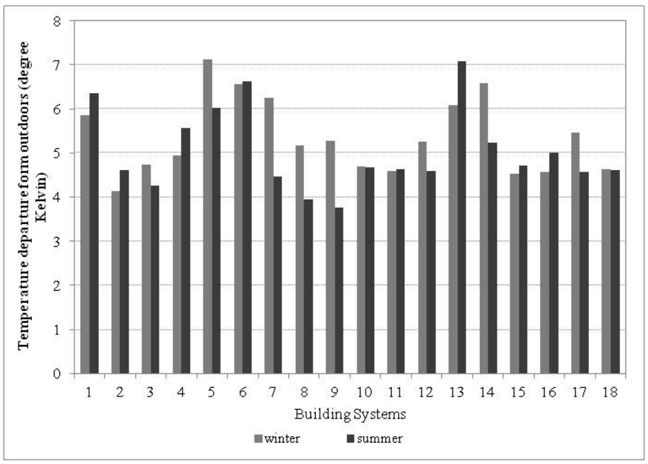

Figure 3: Mean indoor departures from outdoor air temperature during night time in the 18 monitored houses – winter and summer periods.

The majority of the dwellings had a night time occupation (about 100% of mean occupation during night time against 50%-60% for daytime, from 8am to 6pm), thus only night time conditions are analyzed, allowing direct comparisons to nocturnal UHI results. Assuming that thermal comfort conditions would primarily impact sleep quality in dormitories, the temperature of thermal neutrality (Tn) in the bedroom area is estimated as a function of outdoor air temperature (Te), as follows [13]:

$$Tn = 16\ ºC \qquad \text{for } Te < 0\ ºC \qquad (2)$$

$$Tn = 0{,}23Te + 16 \qquad \text{for } 0\ ºC \le Te < 12{,}6\ ºC \qquad (3)$$

$$Tn = 0{,}77Te + 9.18 \qquad \text{for } 12.6 \le Te < 21.8\ ºC \qquad (4)$$

$$Tn = 26\ ºC \qquad \text{for } Te \ge 21.8\ ºC \qquad (5)$$

A comfort range can then be defined around the obtained neutral temperature for 90% thermal acceptability by applying a ±2.5°C deviation to results from equations 1-4 [14]. Therefore, assuming a more pronounced night time occupation in the houses and that the bedroom area does not differ significantly in respect of thermal behavior from the original location of the loggers (typically placed in the corridor area), the mean night time departures for both summer and winter seasons can be added to monitored air temperatures at SIMEPAR and UTFPR allowing a simplified comfort assessment in the bedroom area. The percentage of night time hours above and below that range is defined as 'heat stress' and 'cold stress', respectively.

3. RESULTS

3.1. Observed Synoptic Conditions – Intra-Urban Air Temperature Measurements

Figures **4** and **5** show synoptic conditions of South America and southern Brazil, respectively, on August 20th 2006. These images allow a visualization of atmospheric dynamics on zonal and regional scales. The intense cold air mass between 20th to 22nd August lead to an abrupt air temperature drop in the entire region.

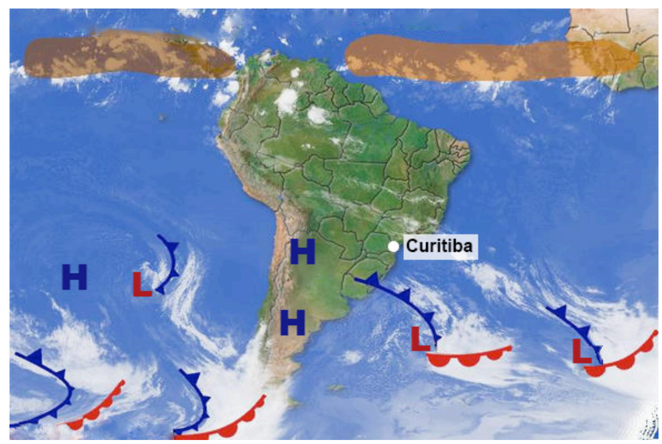

Figure 4: Synoptic image of South America on August 20th 2006 at 12:00 z with direction of high (H) and low (L) pressure zones and location of Curitiba at 25.5º S (Source: www.cptec.inpe.br).

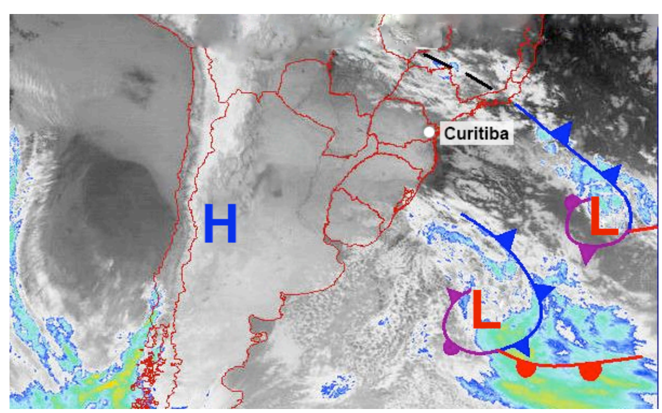

Figure 5: Synoptic image of the southern region of Brazil on August 20th 2006 at 3:45 z with direction of high (H) and low (L) pressure zones and location of Curitiba at 25.5º S (Source: www.simepar.br).

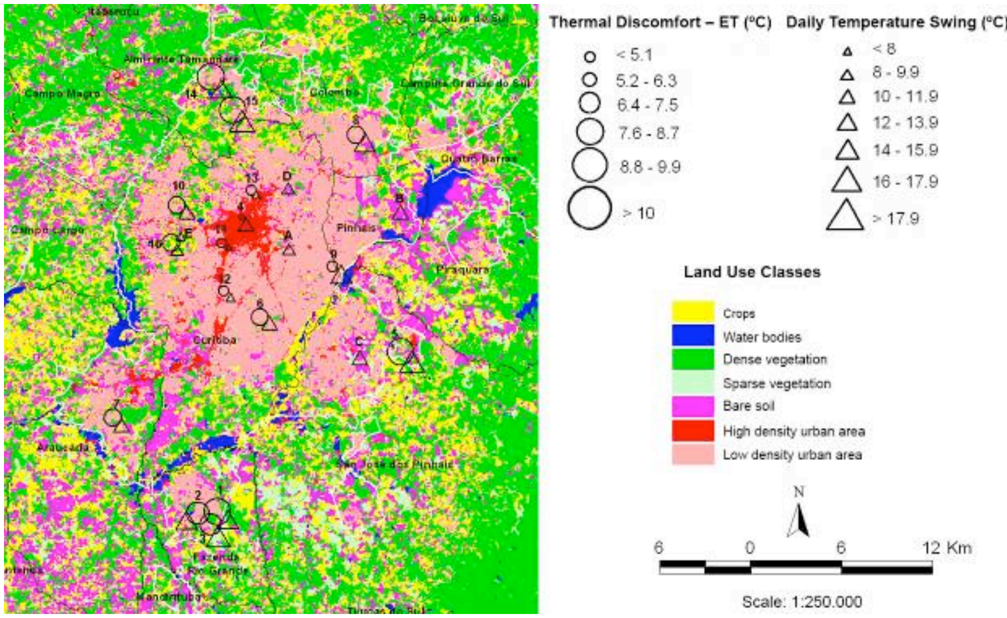

Figure 6: Thermal comfort conditions and daily air temperature swings for the monitored points overlapped on Land Use map - Source (land use classes): Multispectral satellite images from LANDSAT-7 ETM +, 220-078, September 27th 2002.

Table 2: Air Temperature Distribution (Ta), Diurnal Air Temperature Swing (∆Ta) and Effective Temperature (ET) at the Monitoring Points for August 21st (in ºC)

Monitoring Points	6 am		9 am		3 pm		9 pm		Swing (∆Ta)
	Ta	ET	Ta	ET	Ta	ET	Ta	ET	
Fazenda Rio Grande	0.7	4.8	5.7	8	15.7	14.4	3.7	7.2	15
Fazenda Rio Grande	2.0	6.3	6.0	8.7	16.0	14.3	5.0	8.3	14
Fazenda Rio Grande	2.0	6.2	5.5	6.2	18.5	16.8	6.5	9.6	16.5
Centro Histórico	7.3	9.4	8.3	10	20.3	17.4	7.8	10.4	13
São José dos Pinhais	0.5	5.1	7.5	9.2	17.0	16.5	4.0	7.5	16.5
Xaxim	3.8	7.5	8.3	10.1	16.8	15.1	5.8	9.1	13
Araucária	2.8	6.8	10.3	11.6	15.8	14.8	4.8	8.4	13
Colombo	3.3	7.4	12.3	13	17.3	15.8	4.3	7.8	14
Cajuru	5.3	8.5	9.3	10.8	20.3	17.3	6.3	9.4	15
Santa Felicidade	2.6	6.6	6.6	8.6	15.1	13.8	5.6	8.9	12.5
Batel	4.4	7.6	5.2	7.8	11.6	11.5	6.1	8.8	7.2
Novo Mundo	5.8	8.7	8.8	10.9	14.4	15.5	6.8	9.2	8.6
Ahu	5.3	8.4	*	*	14.6	14.2	6.1	9.2	9.3
Almirante Tamandaré	-0.3	4.3	7.7	9.5	13.7	13.1	4.7	8.2	14
Almirante Tamandaré/Dorcas	0.5	4.8	6.5	9.0	19.0	17.6	4.5	8.4	18.5
Campo Comprido	3.0	6.8	8.1	10.5	14.0	14.2	6.3	9.4	11
Relative difference (max-min)	*7.6*	*5.1*	*7.1*	*6.8*	*8.7*	*6.1*	*4.1*	*3.2*	*7.6*

*Missing data

Figure **6** represents effective temperature (ET in ºC) deviations, relative to the lower ET limit of 16ºC (ET) according to Sorre [15], plotted against local land use patterns for spot measurements made at 6am on August 21st 2006. This particular data set is discussed in more detail as it entails the lowest air temperature recorded among all four monitored days. A comprehensive Table is shown below for the same date with all monitored air temperature and calculated effective temperature data (Table **2**). The highest effective temperature (ET in ºC) deviations were found in the Historic Center (point 4), and the lowest daily air temperature fluctuation (7.2°C) was found in Batel (point 11), an area characterized by a high population density. Lower air temperature values were observed to the east, on the outskirts (point 5), to the south, in Fazenda Rio Grande (points 1, 2 and 3) and to the north in Almirante Tamandaré (points 14 and 15), which also had the lowest observed air temperature (-0.3ºC) as well as the largest daily air temperature fluctuation of the sites monitored during the day (18.5°C).

The large daily air temperature fluctuation which characterizes local climate, often reported to be a contributing factor to local thermal discomfort is noticed in the monitored points of Figure **6**: locations with lower air temperature values and thus higher differences in ET (ºC) to the lower comfort range also had the largest daily air temperature ranges on August 21, 2006. The highest thermal cold stress as well as the largest ET deviations were found on the outskirts, in the municipalities of Almirante Tamandaré, São José dos Pinhais and Fazenda Rio Grande.

Interestingly, from Table **2**, strong correlations were found for measured air temperature between the first and the last monitoring hours (6 am and 9 pm), r-value=0.81, which suggests a consistent pattern of relationship among stations for the night time period, i.e. a map similar to Figure **6** could also be drawn for an hour closer to the maximum urban heat island intensity (9 pm) with comparable results. For the other two monitoring hours the similarity to the 6am-conditions weakens over the course of the day (r=0.33 for 9 am, r=0.15 for 3 pm). From the calculation of the relative differences among the stations (Ta and ET) for the two night time hours, it is noticed that the maximum occurs at 6am and not at 9pm.

In Figure **6**, land use categories for the urban area are superimposed on observed thermal comfort conditions. The first category comprises of high density areas with high rise buildings (downtown area and the so called 'structural sectors' of the city). In the Historic Center, height restriction according to local legislation provides direct daylight to buildings and streets. Areas with higher urban density and vertical growth are able to store heat and reduce wind speed in the canopy layer. Such morphology provides thus conditions for reduced thermal discomfort due to cold. Along the structural axis at Batel (point 11), sunlight does not effectively reach the lower floors or the ground due to high-rise buildings, an effect which is particularly intensified during winter when solar angle is low. However, in this area high-mass buildings store heat, which results in a smaller air temperature swing.

Low-density areas present conditions of intermediate comfort and are located in the residential sectors and in the industrial sector. Such areas are more or less homogeneous and exhibit similar air temperature and outdoor comfort levels. An exception is Cajuru (point 9) with low cold stress but with large daily air temperature swing. This area has irregular settlements and a natural preserve. It is in the Rio Iguaçu valley, prone to flooding due to its low elevation; the region presents a high socio-environmental vulnerability.

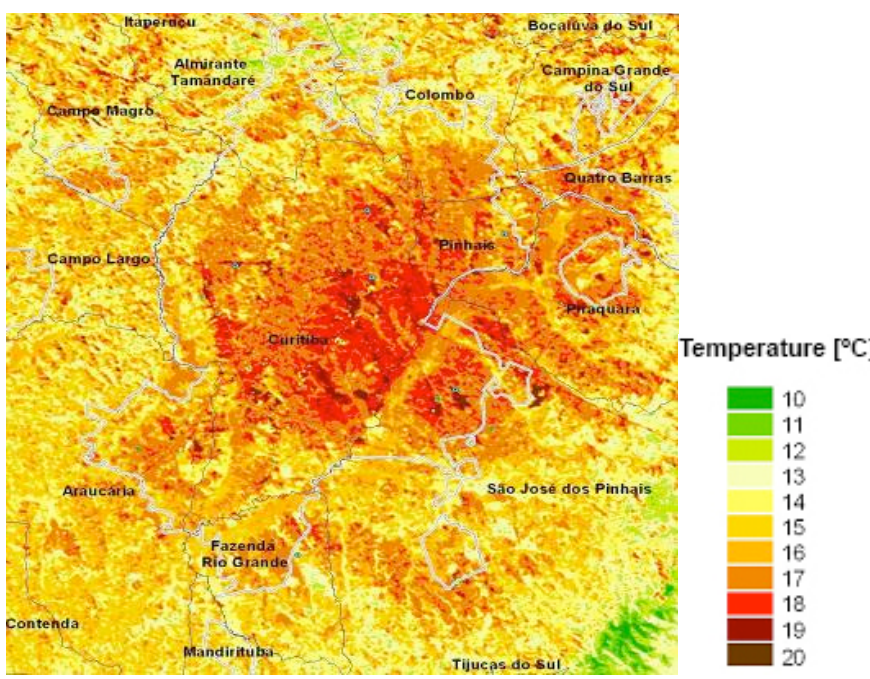

Figure 7: Surface Infrared Thermography for August 20th 2006, 10 am - Source: INPE - Instituto Nacional de Pesquisas Espaciais (National Institute of Spatial Research Image), LANDSAT-5 TM 220-078.

Table 3: Maximum Heat Island Intensity (ΔTu-r(max)) and Average Differences for Different Periods in Kelvin (Values in First Line are for Daytime, the other Lines Contain Night-Time Values)

	Urban heat island intensity ($\Delta T_{u-r(max)}$), maximum over the period	Urban heat island intensity ($\Delta T_{u-r(max)}$), averaged over the period	Mean heat island intensity ($\Delta T_{u-r(avg)}$)
Entire period (daytime)	*11.5*	*1.6*	*-0.3*
Entire period (night time)	5.3	1.2	0.5
Summer	5.3	1.2	0.6
Winter	2.7	1.2	0.3
Spring	5.1	1.3	0.6
Fall	4.6	1.2	0.5

Peripheral areas in the southern, eastern and northern limits of the urban sprawl present less favorable thermal comfort conditions due to low air temperature and large air temperature fluctuation. Climatic conditions of these areas are affected by sparse population and by the surrounding rural areas.

The surface infrared thermography (Figure **7**) obtained from Landsat 5 at 10am on August 20th 2006 shows a detailed view of the different microclimatic conditions on the intra-urban scale.

The influence of urban characteristics on surface temperature suggests strong contributions of land use patterns, urban morphology and density, and anthropogenic heat. By comparing the surface infrared thermography data to the Land Use map (Figure **6**), three major findings can be listed: 1) the urban sprawl area practically coincides with higher surface temperature with an UHI effect of average intensity 7 K (though here expressed as surface temperature differences instead of air temperature differences), relative to the immediate rural surroundings; 2) lowest air temperature values are found in the mostly rural, southeastern, northern and northwestern portions of the image, in high elevation, with a more varied topography and dense vegetation; 3) the urban areas with the highest vertical growth do not exhibit the highest air temperature values. The latter factor could be explained by overshadowing effects in urban canyons at this time of day.

Detailed analysis shows cool islands in urban parks, green areas, at the bottom of valleys and near water bodies. Highest air temperatures were observed in areas with high urbanization with asphalt surfaces, including the airports of São José dos Pinhais and Bacacheri, the industrial sectors to the west (Industrial City), south (Araucaria) and east (São José dos Pinhais) and the principal transportation routes.

3.2. Long-term UHI Monitoring and Predicted Indoor Thermal Comfort Effects

3.2.1. UHI Analysis

The long-term monitoring period at the two stations (Figure **2**) took place from Mid December 2011 through the end of February 2013. Results show the highest difference between recorded air temperature values measured at SIMEPAR and UTFPR occurring during daytime, due to differing radiant gains at both stations during the day (first results line of Table **3**). The pattern, however, does not hold for the mean differences, pointing to the existence of a small cool island effect in the urban area. As for the night-time data, during which solar gains are not present, but only the heat stored in the surrounding surfaces and mainly convective exchanges take place, there is a greater consistency in the data. The maximum intensity of the urban heat island of 5.3 K occurs in the midsummer (on 02/02/2013) and the mean UHI intensity is also higher during that season.

3.2.2. Predicted UHI Effects on Indoor Thermal Comfort Conditions

Considering that Curitiba has a subtropical climate in elevation (25.5ºS, 920 m a.m.s.l.) with cold winters, an exception for mostly warm humid Brazil, the UHI effect in Curitiba in theory could be beneficial in the colder part of the year, reducing cold stress. Even though this result is applicable to outdoors, it may not necessarily apply to the indoor environment. From thermal monitoring in low-cost houses, Dumke [16] found indoor air temperature values normally higher than outdoors and throughout the day, both in summer and in winter: deviations ranged 4.3-7.7 K for the indoor minima. Thus comfortable outdoor conditions could turn to thermal discomfort indoors, especially during the night, when occupation is highest, which could particularly affect the quality of sleep.

For both summer and winter, the consideration of a mean night time air temperature departure from outdoors allows a straightforward estimation of indoor air temperature values in each dwelling at the urban and rural locations. In addition, by applying equations 2-5, comfort levels for the night time can be obtained (Table **4**).

Virtually no thermal discomfort due to cold stress is noticed indoors in summer, while such effect is present in all houses in winter. An overall 6% increase in heat stress takes place in the urban area during summer (relative to the rural surroundings). In winter, a corresponding drop in cold stress would be expected; however this was found to be about 1% at the urban area. Interestingly, slight overheating also takes place in winter, a fact related to the characteristics of local climate, with high daily air temperature fluctuation throughout the year. Moreover, the extent of changes in heat stress hours in the dwellings in summer ranges (0-36% of the time); in winter changes in cold stress hours range from -2% to 5% (in the latter case, *warmer* conditions are found at the rural location –house 2).

In summary, cold stress in its intensity prevails; the urban heat island effect is not sufficient to offset it in the houses in winter as significantly as it increases heat stress in summer. This is linked to the adaptive behavior of the occupants as well as to the fact that the urban heat island effect is weaker for winter conditions.

With regard to the different building systems evaluated, assuming house 15 as a reference (built with ceramic bricks with no insulation and roof consisting of a wooden ceiling and ceramic tiles, a common building system employed in Brazilian social housing), the relative difference in percentages in heat (summer) against cold discomfort (winter) is halved in the latter case: an urban instead of a rural location for such dwelling would mean an increase in heat stress in 2% of the time against a drop in cold stress by 1% in winter. The most critical difference however is seen for

Table 4: Percentage of Hours in Thermal Discomfort for 90% Thermal Acceptability in Each House, Numbered as in Table 1, Expressed as Heat and Cold Stress (Above and Below Tn, Respectively) and for Summer and Winter Periods Considering an Urban Versus Rural Condition

Building System	Summer				Winter			
	Percentage of time above Tn+2.5°C (%)		Percentage of time below Tn-2.5°C (%)		Percentage of time above Tn+2.5°C (%)		Percentage of time below Tn-2.5°C (%)	
	urban	rural	urban	rural	urban	rural	urban	rural
1	21	4	0	0	4	2	10	12
2	3	1	0	0	1	1	35	30
3	2	1	0	0	2	1	24	23
4	8	3	0	0	2	1	20	21
5	13	3	0	0	15	3	5	7
6	30	5	0	0	9	2	7	9
7	3	1	0	0	7	2	8	10
8	1	1	0	0	2	1	17	19
9	1	0	0	0	3	2	16	18
10	3	1	0	0	2	1	25	23
11	3	1	0	0	2	1	26	25
12	3	1	0	0	3	2	16	18
13	54	18	0	0	6	2	9	11
14	6	2	0	0	9	2	7	9
15	3	1	0	0	2	1	27	26
16	4	2	0	0	2	1	26	25
17	3	1	0	0	3	2	14	15
18	3	1	0	0	2	1	25	24
Mean	9	3	0	0	4	1	17	18
Mean relative difference (urban versus rural) in %		6		0		3		-1

house 13 (double-paned concrete walls with air layer), where increases in summer due to heat stress are 36% while cold stress is winter is diminished by only 2% as a result from its relocation (rural to urban)!

4. CONCLUSIONS

The analysis of Curitiba's intra-urban air temperature distribution indicated that, given its size and heterogeneity, Curitiba is not simply one large UHI. Different urban structures and morphologies characterize the urban landscape, which differs from that of traditional cities, where commercial and more densified areas are typically located downtown, from which urban density gradually decreases towards the outskirts.

Intra-urban thermal variability is influenced by the characteristics of urban geometry, such as the linear axes ('structural sector') with vertical growth, varied urban density patterns and unevenly distributed green areas. Results presented here support the analysis of Curitiba's climate made by Mendonça and Dubreuil [4] as well as the findings of Eliasson [3] on thermal variability and its relation to intra-urban and rural surroundings. The dynamics observed apply to four days of measurements and under different synoptic conditions (Tropical Continental Air Mass, Atlantic Polar Front and Atlantic Polar Air Mass).

Nevertheless, a clear UHI effect is observed with lower air temperature values in the bordering regions of the urban area. In addition, on the outskirts, diurnal air temperature swings tended to be higher than downtown. Both factors contributed to enhanced cold stress in this region.

The long-term monitoring series allowed us to identify the summer period as having the highest UHI intensity. Additionally, from simultaneous data measured at two sites (urban versus rural), it was possible to predict indoor comfort implications of the UHI in two seasons of the year.

UHI results for Curitiba corroborate a generalization proposed by several authors and presented by Arnfield [17], from an extensive review of studies carried out during 1980-2000 in the field of urban climate, suggesting that the UHI intensity tends to develop more evidently in summer or in warmer periods of the year. For Curitiba, the winter period, although exhibiting a similar average UHI intensity as in summer, has about half the maximum intensity than the latter.

As observed during the intra-urban monitoring campaigns, within the UHI slightly warmer conditions are found in winter with consequently higher comfort levels in the downtown area. By assessing indoor comfort effects in summer, it is possible to obtain the 'net effect' of thermal discomfort/comfort for the two seasons. For a mostly nocturnal occupation in the houses, the bedroom area was taken into account. Peeters *et al*. [13] discuss the quality of sleep in relation to bedroom air temperature and list a number of studies that point to a drop in sleep quality with the elevation of the bedroom air temperature. The limits used for the evaluation of the dwellings' performance were 16ºC (lower limit, according to the World Health Organization) to a maximum of 26ºC (bedroom air temperature limit in the absence of an elevated air speed, according to CIBSE [18]. The 'net effect' in thermal discomfort in the houses evaluated, with regard to the two periods of analysis, suggests an overall prevalence of heat stress in terms of relative changes due to relocation rural-urban.

In summary, results suggest that the UHI intensity measured in Curitiba over different seasons, despite exhibiting a relatively low mean of about 0.5°C over the year, could translate to increased heat stress in low-cost houses located at the urban area under summer conditions. It was verified that increases in indoor air temperature values in summer are more significant than a drop in cold stress in winter in the UHI.

Since Curitiba is a benchmark for cold cities in Brazil and in similar latitude ranges, results could be applicable to a larger range of cities. Under such conditions, obtained results indicate that the existence of the UHI can be primarily detrimental to indoor thermal comfort in summer, having a smaller effect on improving indoor comfort in winter.

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