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Analyzing night time wind speed reduction effects from densification on predicted outdoor thermal comfort in a subtropical setting

Eduardo Krüger[1] and Peter Bröde[2]

1 Technological University of Parana, Brazil, ekruger@utfpr.edu.br
2 IfADo - Leibniz Research Centre for Working Environment and Human Factors, Dortmund, Germany broede@ifado.de

Abstract

The relationship between urban growth and the formation of urban heat islands, i.e. climatic differences between the urban area and adjacent rural areas, is discussed by several authors and is assumed to be ubiquitous for various climatic regions. Curitiba (25.5ºS), located within a region of subtropical climate in elevation, boasts a population growth rate of approximately 2% a year. The purpose of this study is to evaluate the effect of the urban agglomeration on microclimate changes. From comprehensive long-term climate data monitoring carried out during 2011-2013 with a pair of weather stations in and outside the urban area, outdoor thermal comfort conditions are assessed by means of the UTCI index, which had been calibrated to local thermal preferences in a previous study. Comparisons between urban and rural conditions are shown as traditional Urban Heat Island (UHI) results as well as in terms of predicted comfort/discomfort levels. A projection to a more densified condition is performed by significantly reducing air speed at night. We discuss obtained results in predicted thermal comfort variations against current conditions.

Keywords: Urban Heat Island, outdoor thermal comfort, wind speed, UTCI.

1 Introduction

In tropical regions, urbanization rates tend to be the highest: the average annual rate of change of the urban population for the 5-year period 2005-2010 was just over three times higher in the less developed regions than in the more developed regions of the world, following a rising trend (United Nations 2012). As a consequence of such urban growth local climate conditions can be highly affected, which can have an impact on overall energy consumption in buildings due to unintended Urban Heat Island (UHI) effects.

In tropical areas the formation of UHI associated with climate change can bring about serious consequences, thus UHI mitigation should be part of present and future urban planning strategies. Compared to other developing countries, Brazil has a significant urban population (approximately 85%), surpassing the average urban percentage in developed countries (United Nations 2012). As a consequence, major Brazilian cities like São Paulo have reported UHI intensities in some instances reaching 10°C in the most polluted and densified areas of the megalopolis (Lombardo 1985).

Curitiba, where the present study was carried out, has a long tradition in urban planning since the 1940's. However, urban planning strategies proved to be quite limited to cope with numerous socio-environmental problems arising from uncontrolled urban growth: irregular occupations near water sources, increasingly frequent floods, pollution, among other effects. Curitiba's spatial configuration is characterized today mainly by massive vertical axes along the so called 'structural sectors', with an impact on the urban landscape and aspects related to environmental comfort; buildings in such urban canyons are affected thermally (Krüger et al. 2011), by the lack of daylight (Krüger and Suga 2009), by changes in ventilation patterns with effects on air quality (Krüger et al. 2011).

The purpose of this paper is thus to evaluate inadvertent effects from urbanization on predicted outdoor thermal comfort levels and those resulting from reduced wind speeds during night time.

2 Method

Curitiba (25°25'50" S, 49°16'15" W, 917 m elevation) is located in southern Brazil, with a present population reaching 2 Million inhabitants. It has a long tradition in urban planning, being famous mostly for its innovative mass transportation system (tube stations). With regard to local climate, average temperatures in summer range 17-20ºC and in winter 12-14ºC. Annual average temperature is about 16ºC. Daily amplitudes may vary between 0.5 and 25.7 ºC, and the average swing is 10.5 ºC. Absolute humidity ranges between about 4 to 18 $g \cdot kg^{-1}$, with an average of about 11 $g \cdot kg^{-1}$. Annual precipitation is around 1600 mm.

Comprehensive long-term climate monitoring was carried out during 2011-2013 with a pair of weather stations in and outside the urban area. Climatic data were collected at two different locations: at the official meteorological station 'SIMEPAR', at the Polytechnic Center (assumed to be an 'urban' station) and at the Campus Ecoville of the Federal Technological University of Paraná (assumed as "rural"). The approximate distance between the two stations is 12 km. Variables monitored comprise air temperature and humidity, global solar radiation and wind speed. "Ecoville Weather Station" is located on the outskirts of the urban area and on the roof top of a three-storey campus building with no noticeable obstructions to wind and solar radiation. Adjustments were made only to measured wind speed so that the same height is considered for both stations (10 m) when applying the UTCI index. The monitoring period extends from December 2011 to February 2013. Only data for 2012 were used in this paper, as shown in Table 1, with the various seasons. From this set of data, a standard Urban Heat Island (UHI) analysis was initially performed, which was based on the assessment of air temperature differences between sites (urban-rural) during night time.

Table 1: Monitoring periods, divided in seasons

Period	YD	N (days)
Entire Period	1-365	326
Summer	1-79,355-365	87
Fall	80-171	66
Winter	172-263	82
Spring	264-354	91
Missing data	24,25,51,146-181	39

2.1 Thermal comfort assessment with UTCI

The Universal Thermal Climate Index (UTCI) was used for assessing the predicted thermal sensation under different conditions. UTCI aims at the assessment of the outdoor thermal conditions in the major fields of human biometeorology by a one-dimensional quantity summarizing the interaction of the basic thermal variables (air temperature, wind speed, humidity, radiant fluxes) on an equivalent temperature scale (°C). This assessment is based on an advanced multi-node model of human thermoregulation (Fiala et al. 2010, Fiala et al. 2012) coupled with a state-of-the-art clothing model (Havenith et al. 2012).

Input parameters for assessing UTCI at both sites were: measured air temperature; deviation of the mean radiant temperature to ambient temperature (ΔT_{mrt}); relative humidity or water vapour pressure; and wind speed at 10 m above the ground, which was adjusted, when needed, from onsite measurements at x m using a logarithmic scale factor log(10/0.01)/log(x/0.01) as in Bröde et al. (2012).

In a previous paper (Rossi et al. 2012) we calibrated UTCI comfort/discomfort ranges for Curitiba, from surveys conducted with local population. In structured interviews, passers-by on a pedestrian street in Curitiba provided information on their weight, height, age and gender, on their clothing as well as on their thermal sensation, affective evaluation, thermal preference and thermal tolerance using standardized scales (ISO 1995). Concurrent measurements of air temperature and humidity, globe temperature and wind speed were performed in parallel to the interviews and were used to calculate actual UTCI values. Thermal sensation responses were grouped into three categories: (1) 'cold discomfort' (thermal sensation votes -3 and -2), (2) 'neutral / comfortable' (votes -1, 0 and +1), (3) 'heat discomfort' (thermal sensation votes +2 and +3). By means of regression analysis and comparisons of actual thermal responses against UTCI estimates, it was found that the comfort range for the sample was 15-27°C (UTCI); UTCI values lower than that range were assumed to be in cold stress and higher than 27°C (UTCI) in heat stress.

Hourly values of the UTCI equivalent temperature were obtained for the monitored climatic conditions by the table-lookup approach utilizing interpolation of pre-calculated UTCI values as described in Bröde et al. (2012). Measured variables at both sites were used directly except for the wind speed at the "Ecoville Weather Station", which was scaled to the height of 10 m for UTCI calculations as described above. The mean radiant temperature, for both locations, was obtained by the estimation of that parameter with RayMan (Matzarakis et al. 2010) using local global horizontal radiation.

2.2 Assessing outdoor comfort effects with reduced wind speed

In more constrained conditions (even though the 'urban' location was central, it is a meteorological site thus presenting no noticeable wind-blocking obstacles in the surroundings), the effect of roughness on wind speed patterns will play a role in overall comfort conditions; moreover the existence of buildings will also have an impact on radiant heat loads within urban canyons (Matzarakis and Endler 2010). The convective and radiant effects from an increased densification will thus significantly alter thermal comfort/discomfort differences between such location and the rural site. To account for such effects during night time periods, a simple exercise was carried out consisting of modifying wind speed according to an increased roughness at the urban site. This exercise doesn't take into account any consequences from shading/heat gains in urban canyons, which would have altered the mean radiant temperature during the day, or any heat trapping effects from increased thermal mass by buildings during night time.

Measured wind speed at the urban site (U) was modified according to a power law equation (Allard 1997):

$$\frac{U}{U_{10}} = K z_1^a \qquad \text{(Eq.1)}$$

where the coefficient *K* and the exponent *a* are given as a function of roughness characteristics of the site (for 'City' conditions, *K*=0.21 and *a*=0.33); z_1 is the measurement height (10 m) and U_{10} is the wind speed measured at the met site.

UTCI predictions were made using modified wind speed for the urban measurement site, which were subsequently compared to the original UCI predictions (with wind speed as measured at the urban site).

3. Results

3.1 Urban heat island effects

The urban heat island is a nocturnal phenomenon which usually takes place after sunset on clear days with low wind speed. Its maximum intensity, expressed as temperature difference between a rural, reference site and an urban counterpart, occurs a few hours after sunset. Table 2 shows results in terms of maximum heat island intensity during night time ($\Delta T_{u-r(max)}$) and average intensity, averaged for each period of analysis. The mean UHI intensity is highest during summer. Although it is very similar to fall and spring periods, it almost doubles the winter intensity. However the mean maximum intensity is stronger in winter, as during this season the frequency of clear sky days is somewhat higher in Curitiba.

Table 2: Maximum heat island intensity (ΔTu-r(max)) and average UHI intensity (for night time hours, in ºC)

Period	Mean heat island intensity (ΔTu-r(avg))	Maximum heat island intensity (ΔTu-r(max)) – averaged over the period
Entire Period	0.53	1.54
Summer	0.61	1.39
Fall	0.58	1.59
Winter	0.34	1.71
Spring	0.60	1.49

3.2 Effect on predicted thermal comfort percentages

Table 3 shows average differences in UTCI units for urban against rural conditions ($\Delta UTCI_{u-r}$), for night time and for all periods.

Although differences are small, slightly highest UTCI variations are found for the summer night time hours. Considering UTCI comfort ranges during night time, virtually no night time in 'heat' category are found; UTCI averages, even for summer, lie within the calibrated comfort range (15-27ºC UTCI) or lower than that. Mean percentage distributions of night time hours in cold stress are shown in columns 2 to 4 of Table 4.

As expected, percent rates in cold stress are the lowest for summer and higher for fall and winter. It can be noticed that percent changes in predicted cold stress due to urbanization are higher in summer and lower for the other seasons, which could suggest that the rural site and areas on the outskirts may benefit from "cooler" nights in summer. In terms of outdoor comfort this is accompanied by a reduction of comfort hours; however, within buildings, living outside the urban area could mean less heat stress during night time, therefore improving sleep quality. On the other hand, urbanization effects in winter are less evident (4% decrease in cold stress).

Table 3: Variations in terms of UTCI and average differences between urban and rural conditions (ΔUTCIu-r) (for night time hours, in ºC)

Period	UTCI_rural (avg)	UTCI_urban (avg)	ΔUTCIu-r – averaged over the period
Entire Period	12.9	13.9	1.0
Summer	16.2	17.3	1.1
Fall	12.1	13.1	1.0
Winter	10.0	10.7	0.7
Spring	12.9	13.9	1.0

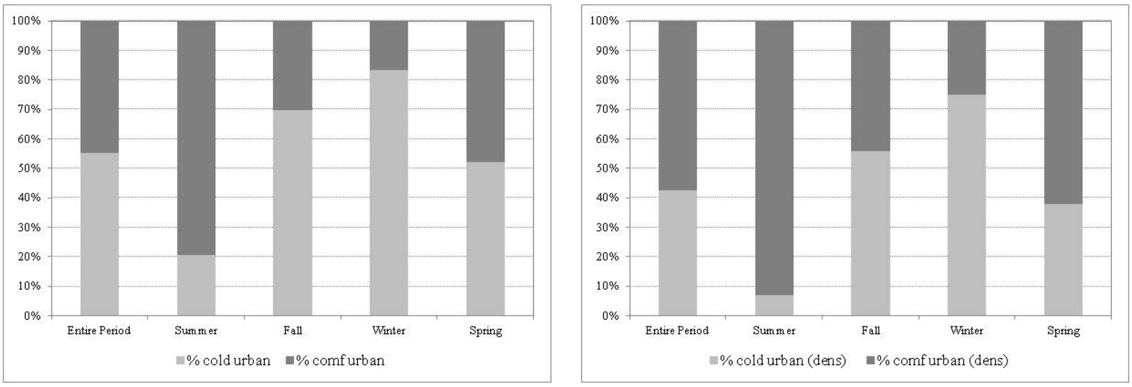
Table 4: Percent rates in cold stress for night time hours – present conditions and with reduced wind speed

Period	rural	urban	% changes	urban (low wind speed)	% changes (low wind speed)
Entire Period	63	55	-8	43	-20
Summer	34	21	-13	7	-27
Fall	77	70	-7	56	-21
Winter	88	83	-4	75	-12
Spring	59	52	-7	38	-21

3.3 Predicted effects for more densified conditions during night time

As results shown previously for the urban site refer to data collected at a meteorological station with no significant obstructions, we performed UTCI simulations for outdoor conditions with diminished wind speed as a surrogate of more constrained urban conditions. Figure 1 shows percent rates in cold stress and comfort for the urban site, allowing a first-hand comparison between actual conditions against of those resulting from a rougher urban morphology. Cold discomfort during night time, shown in terms of percent rates, suggest an exacerbated picture of the present situation, which could correspond more closely to those of nearby built-up areas. A reduction in time percent rates in cold can be as much as 27% for the more densified urban site (Table 4, columns 5 and 6). As a matter of fact, not far from the urban site (meteorological station), within a 5-km distance, lies the “Structural Sector” of the city[1], which allows verticalization and high-rise buildings resulting in reduced wind speed profiles.

[1] Those “structural axes” present no height restrictions to buildings. Through such street canyons, the most intense vehicular traffic flows towards the city center. The Structural Sector congregates three distinct and inseparable functions: to serve as important traffic routes, to support the existent mass transportation system and to function as a means of controlling land use (Krüger and Suga 2009).



a) b)

Figure 1: Percent change rates in cold/comfort for the urban site: a) from measured data; b) from modified wind speed (urban – rural)

4. Conclusions

The underlying motivation for this study was to evaluate whereas the urbanization process and the intensification of the urban heat island as one of its inadvertent impacts is beneficial to Curitiba in the colder part of the year, taking into account its status as the "coldest capital of Brazil". Local climate is characterized by cold spells in winter which are responsible for extreme cold discomfort in dwellings (Krüger and Dumke 2001), furthermore the use of heating devices is not customary. Analysis of year-long air temperature monitoring data at two sites with significant differences in urbanization levels shows a small nocturnal heat island effect with weak differentiation over the seasons. The combined effect of climatic variables measured at the two sites as a single UTCI unit yielded again negligible seasonal differences. However, percent rate changes of night time hours in thermal stress due to urbanization effects were found to be significantly higher in summer than in other parts of the year. In a similar study, Matzarakis and Endler (2010) argue that in cities changes in terms of temperature can be less significant as changes in outdoor comfort index results.

The assumption of diminished wind speeds during night time to account for a more constrained urban morphology enhanced even more discrepancies in percent rates in cold stress at the urban area relative to the rural site. The impact of the UHI in summer was found to be as much as three times larger than in winter for the present situation; for reduced wind speed this relationship drops to a factor of two. The implications of this effect are that, in households located in downtown Curitiba, heat discomfort in summer can be become more hazardous than a reduction of cold hours in winter; in addition, users' adaptation measures can be more effectively implemented in winter (by e.g. increasing internal heat loads) than in summer (as ventilation potential is generally lower during night time).

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