J12.4A ANNUAL SPATIO-TEMPORAL VARIABILITY OF TOULOUSE URBAN HEAT ISLAND

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1 INTRODUCTION

The urban heat island (UHI) has already been observed in a wide range of cities over the world (see a review in Arnfield, 2003). The general characteristics of the UHI are its daily cycle with higher intensities during the night, its dependence with the wind speed and cloud cover. Since Oke (1982) has described the physics of the UHI formation, a large consensus has been established on the key function of the heat storage in the building material in the development of the UHI. However, most of the studies have generally focused on the UHI, in temperature climate cities, during the summertime when the anthropogenic heat flux is at its lowest values. More recently, Oke (2006) has proposed an interesting classification of Urban Climate Zone (UCZ) for which temperature characteristics have not been described.

This paper focuses on the UHI for the city of Toulouse. From February 2004 to February 2005, the CAPITOUL field project (Masson et al., 2008) has been conducted in this city. A network of temperature and moisture stations has been deployed to assess the UHI. In this study, these measurements will be analyzed, first, to describe the temperature behavior of some UCZs proposed by Oke (2006) and, second, to evaluate the relation between the UHI development and the anthropogenic heat releases.

2 METHODS

2.1 TOULOUSE AGGLOMERATION

The agglomeration of Toulouse is located in the south-west of France, 80 km to the north of the Pyrénées, 140 km from the Mediterranean sea and 230 km from the Atlantic ocean. The agglomeration has a circular pattern of a 20 km diameter (Figure 1). The population is 871 000 inhabitants. The prevailing winds in Toulouse are from west to north-west and from south-east (Figure 2).

2.2 MEASUREMENTS

During the CAPITOUL field campaign, a network of 27 temperature and moisture stations has been deployed over the agglomeration (Figure 1) during a one year period from February 2004 to February 2005. The chosen sites covered a wide range of urban climate zones (UCZ) described in Oke (2006). In the center of the city, the sites MIC and MNP fit in UCZ 2, then UCZ 3 is sampled by sites like BON or MIN, UCZ 4 by sites like THI or LAB, UCZ 5 by sites like UNI or VIL, UCZ 6 by sites like BL2 or FRA and UCZ 7 by MON. The network was composed of 2 permanent stations of the French national network (BL2 and FRA) equipped with 100Ω platinum thermistor (PT100) inside a Stevenson radiation shield (see photos corresponding to BL2 on Figure 3). For these stations, the sampling rate was 6 minutes. Then, 24 stations were set up for the field campaign: 3 of them (MET, AUZ and MON) were equipped with HMP233 probes from Vaisala in a light radiation shield at 2 m from the ground and were also sampled at a 6 minutes rate. Finally, the 21 other sites were instrumented with thermo-hygrometers from Rotronic (PT100 for temperature also) set in a radiation shield at 6 m above the ground on electrical pylons like in Pigeon et al. (2006) and sampled with a 12 minutes rate. For sites in UCZ 2 or 3, it was considered from results of Nakamura and Oke (1988) and Eliasson (1996) that the measurements of temperature at 6 m were representative of the temperature at 2 m from the ground. Then, for UCZs 4 and 5, a site was instrumented at 2 levels, one at 2 m and the other at 6 m. A Student statistical test on the temperature difference between the two levels was applied and the conclusion was that neither during the day nor during the night, the difference was significant. Consequently, the measurements at 6 m in these UCZs were considered to be representative of the temperature at 2 m. In sites classified as UCZ 6 and 7, the measurements were made at 2 m.

In this paper, a focus is set on three sites BON, BL2 and MON which are compared to the site MIC which is taken as the reference site (Figure 3). Site MIC is located in the old core of Toulouse and classifies as UCZ 2. From the aerial photography on Figure 3, a high built ratio can be inferred. The building are typically 3-5 storey and the aspect ratio about 2. Site BON corresponds to UCZ 3 with medium density and typical buildings of 1-2 storey. The site BL2 is the typical station taken as a reference in many UHI studies since it is an airport site. Finally, site MON, is located in a agricultural area about 10 km from the center of Toulouse and fits in UCZ 7.

During the field campaign, the MNP site was also equipped with a complete surface energy balance measurements system (Masson et al., 2008) where the incoming radiation (solar and infrared) was measured. The anthropogenic heat flux (Q_F) has also been diagnosed for this site from the surface energy balance measurements and from an inventory of energy consumption for the whole agglomeration

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(Pigeon2007). In this study, Q_F values are taken from the inventory of energy consumption.

2.3 POST-PROCESSING OF MEASUREMENTS

The data set collected during the campaign was first homogenized in term of sampling rate by re sampling the data at 12 minutes. Then, the data were hourly averaged. In this study, the choice has been made to evaluate the UHI with the differences of daily extremes between the stations rather than on the synchronous temperature difference since it is more representative of the climate felt at one site. For example, in case of heat stress situations, it seems more interesting to know what are the differences of maximum and minimum temperatures rather than the synchronous difference between two sites. Consequently, for each stations, the daily maximum occurring during daytime (T_X) and the daily minimum occurring during the night or early morning (T_N) temperatures have been extracted. Then, the difference with the reference station MIC has been computed. When there were very large differences of the timing of T_X and T_N between the sites (corresponding to a changing synoptic situation), the data have been excluded from the analysis.

For an analysis of the relation between the differences in minimum temperature (ΔT_N) and the incoming solar radiation or Q_F, only the events with wind speed lower than 3 m s^{-1} and no rain during the day and the night have been selected since they are necessary conditions for the development of strong UHI. Then, for the nighttime, cloudy and clear events have been separated by comparing the measured infrared incoming radiation at the MNP site with $0.7\times\sigma\times T_a^4$ where σ is the Stefan-Boltzmann constant, T_a is the air temperature measured at the top of the tower. The factor 0.7 is a good approximation for the emissivity of a clear sky. If the sky is cloudy, its emissivity will be closer to 1 (depending on the cloud type) and the infrared incoming radiation higher than $0.7\times\sigma\times T_a^4$. A threshold of 40 W m^{-2} has been taken to separate the clear and cloudy events.

3 RESULTS

3.1 DAILY VARIABILITY

The differences in T_X (ΔT_X) and T_N (ΔT_N) between the 3 sites and the MIC site have been plotted for summer (months of June, July and August) and winter (months of December, January and February) season on Figure 4. For each case, a density histogram is presented with a step of temperature difference of 0.25 K. The daily variability of the temperature difference is inferred by comparing ΔT_X and ΔT_N.

At first sight for BON, there is not a significant difference between the distribution of T_X and ΔT_N, both generally range between -1 and 1 K. A closer look enables to see that during summer, the difference during daytime (ΔT_X) tends to be negative (BON warmer than MIC) whereas it is the opposite during the night (ΔT_N). In winter, there is a wider distribution of nighttime difference than the daytime difference.

For BL2, it can be observed for both seasons, that there are higher frequencies of the highest temperature differences during nighttime (ΔT_N) than during daytime. During nighttime, the highest event are between 2 and 3 K depending on the season whereas there is almost none event higher than 2K during daytime and the frequencies of events between 1.5 and 2 K are quite low. The same behavior concerning the daytime and nighttime differences is observed for the site MON.

3.2 SPATIAL VARIABILITY

The spatial variability is inferred by comparing the 3 sites. For both seasons and both T_X and T_N, MON presents higher differences with MIC than BL2 which records higher differences than BON. This result is quite consistent with the urbanization around the sites. The highest differences for MON are about 2 K for T_X and up to 5 K for the T_N.

3.3 SEASONAL VARIABILITY

Concerning ΔT_X, the BON site has an particular behavior, during summer, the difference is regularly negative, between -1 and 0 K (BON warmer than MIC), whereas it is more generally positive, between 0 and 1 K during winter (BON cooler than MIC). This seasonal variation is not very high in amplitude, lower than 1 K, but it is quite noticeable on the histograms. For the two other stations BL2 and MON, ΔT_X is lowest during the winter of around 0.5 K but both sites record generally cooler T_X than MIC.

Concerning ΔT_N, when the UHI occurs to be at its maximum, there is no significant change in the distribution of the values for BON. The difference is more frequently positive (BON cooler than MIC) but hardly greater than 1 K. For BL2, the distribution of ΔT_N is more spread during winter than during summer. For MON, there are higher frequencies of low difference events (between 0 and 0.5 K) during winter.

3.4 RELATION WITH INCOMING RADIATION AND ANTHROPOGENIC HEAT FLUX

The relation of ΔT_N with the measured incoming radiation and anthropogenic heat flux are presented in Figure 5 for the three sites BON, BL2 and MON.

For the summer period (first line of graphics), only the relation between ΔT_N and the incoming solar radiation is presented since Q_F is rather low and constant in Toulouse during this period (Pigeon et al., 2007). It can be seen that for BL2 and MON, the higher the solar incoming radiation, the higher the difference of the minimum temperature. This relation is more pronounced for clear conditions for which ΔT_N is generally higher.

During the winter period, the relations between ΔT_N and the incoming solar radiation (second line of graphics of Figure 5) and ΔT_N and Q_F (third line of graphics of Figure 5) are studied. Again, for BL2 and MON, the higher the incoming solar radiation, the higher the difference of the minimum temperature. The same dependency is observed between ΔT_N and Q_F for both sites and it is more pronounced for MON. Looking more carefully at the nighttime cloudy conditions (black points), 3 events of ΔT_N higher than 2 K are observed for BL2 and 4 for MON. For those events, there is a wide range of incoming solar radiation during the day but on the other hand, Q_F values are among the highest. Another interesting point can be noticed when looking closer at the relation between ΔT_N and the solar incoming radiation for BL2. For incoming radiation lower than 100 W m^{-2}, there is a very good linear relationship between the 2 parameters which is not followed for the 4 highest values of incoming solar radiation. Indeed, these 4 events correspond to wind coming from south-east to south for which BL2 site is downwind of the city. For MON site, the linear relationship between ΔT_N and the incoming solar radiation is observed for the whole range of conditions since this site, to the north-east of Toulouse, is never downwind of the city.

4 DISCUSSION

In Toulouse, like in most of cities, the temperature difference between the urbanized sites and the less urbanized ones is higher when the temperature is at its minimum nighttime value than when the temperature is at its maximum daytime value. When the temperature is at its minimum, the temperature differences between a downtown dense, UCZ 2, site and an agricultural, UCZ 7, site, 10 km far away, are frequently higher than 3 K and can reach up to 5 K whereas they hardy exceed 1.5 K when the temperature is at its maximum.

The difference in minimum temperature does not present significant seasonal signal in Toulouse independently of the UCZ of the site. However, the difference of the maximum temperature, between the reference UCZ 2 site (dense urban) and the other ones, is higher during the summer than during the winter for the UCZ 6 and UCZ 7 sites. The most probable assumption to explain this phenomenon is a decrease of the Bowen ratio at the UCZ 7 and 6 sites during the summer in response to a higher activity of the vegetation in comparison with the winter period. Concerning the behavior of the maximum temperature for the UCZ 3 site (BON) during summer, warmer than at the UCZ 2 reference site, it could be explained by the higher solar admittance of the UCZ 3 site than the UCZ 2 site. Indeed, for an UCZ 3 site, the aspect ratio is generally lower than for an UCZ 2 site and a larger fraction of the streets and the wall is sunlit.

The comparison of the relationships between the difference of the minimum temperatures and the solar incoming radiation for the BL2 and the MON sites during winter shows the possible influence of the advection of the urban plume even in case of low wind speed. When BL2 is downwind of the city, the difference of the minimum temperatures is attenuated in comparison with what would be expected. This result demonstrates the care that must be taken in choosing a “rural” site. Apart from the environment around the site (airport, natural or agricultural area), its location respective to the city and the prevailing winds are determining factors.

Finally, the relations observed, for wintertime, between the difference of the minimum temperatures and the anthropogenic heat flux are quite interesting. It is demonstrated, first, that the difference of the minimum temperatures between an UCZ 6 or 7 site and an UCZ 2 site tends to increase with the anthropogenic heat flux. Second, it is demonstrated that, for cloudy conditions some medium to high minimum temperature differences can occur in relation to strong anthropogenic heat releases. Many studies dedicated to UHI in temperate climate cities generally focus to the summertime UHI for which the influence of Q_F is negligible.

5 CONCLUSION

This study is based on the measurements collected during the CAPITOUL field program conducted in Toulouse over a year period between 2004 and 2005. The observations included temperature measurements inside the streets of the city and around the agglomeration but also surface energy balance measurements in a dense urban area.

The Urban Heat Island has been assessed by comparing the maximum and minimum daily temperature between 3 sites corresponding respectively to Urban Climate Zone (UCZ) 3, 6 and 7 (Oke, 2006) with an UCZ 2 reference site. The UCZ 2 is generally warmer than the other sites, and the maximum difference can reach 5 K with the UCZ 7 site for minimum temperature. But, it was noticed for the maximum temperature that the UCZ 3 could be warmer during summertime when there is a large insolation. Whereas, there is no significant seasonal variation of the minimum temperatures difference, UCZ 6 and 7 sites are cooler than the UCZ 2 during summertime than during wintertime. Finally, during wintertime, the minimum temperatures difference linearly increases with the anthropogenic heat flux for UCZ 6 and UCZ 7 and events of significant temperature difference can be observed with cloudy conditions when the anthropogenic heat flux is high.

These interesting cases of wintertime UHI associated with high values of anthropogenic heat flux could now be analyzed with numerical modeling. Sensitivity studies could be conducted to demonstrate the relative influence of anthropogenic heat flux and heat storage during wintertime.

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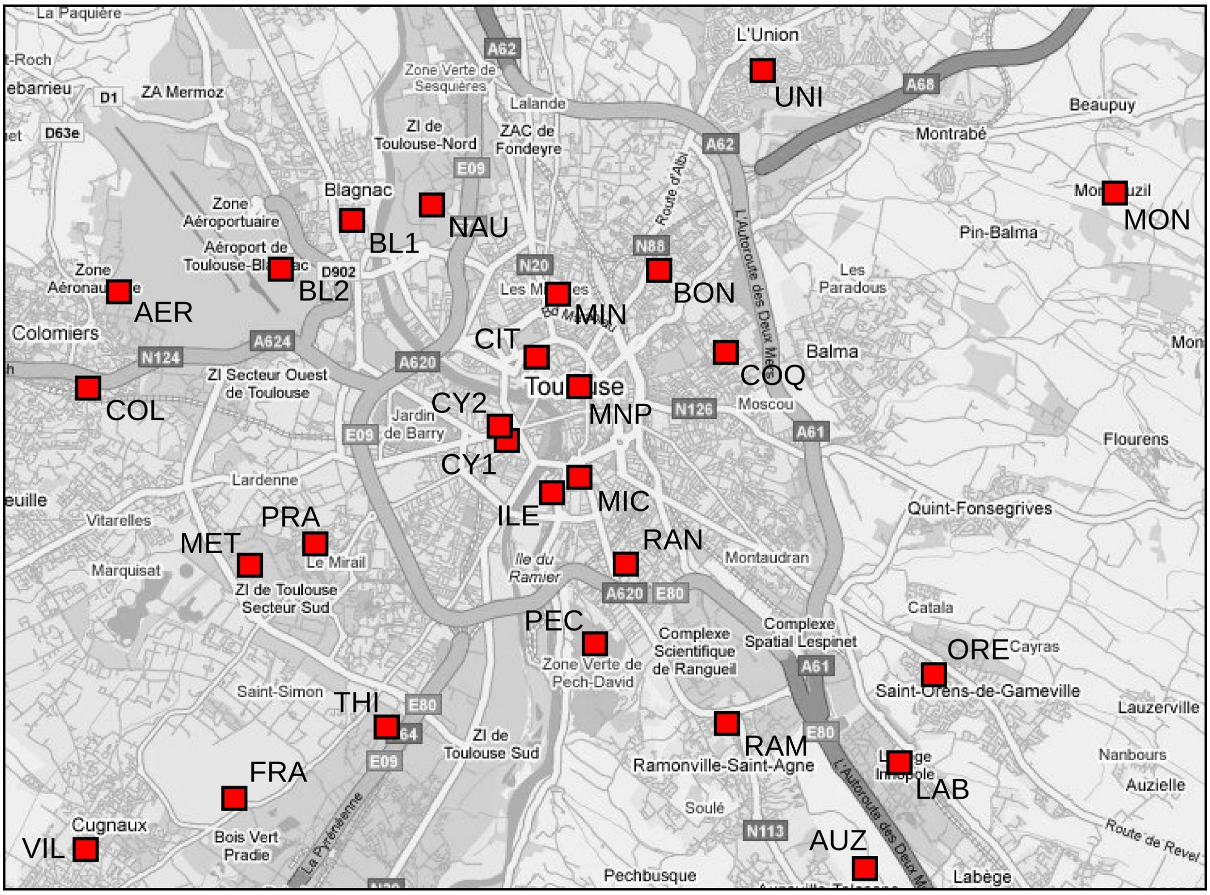

Figure 1: Map of the temperature stations network.

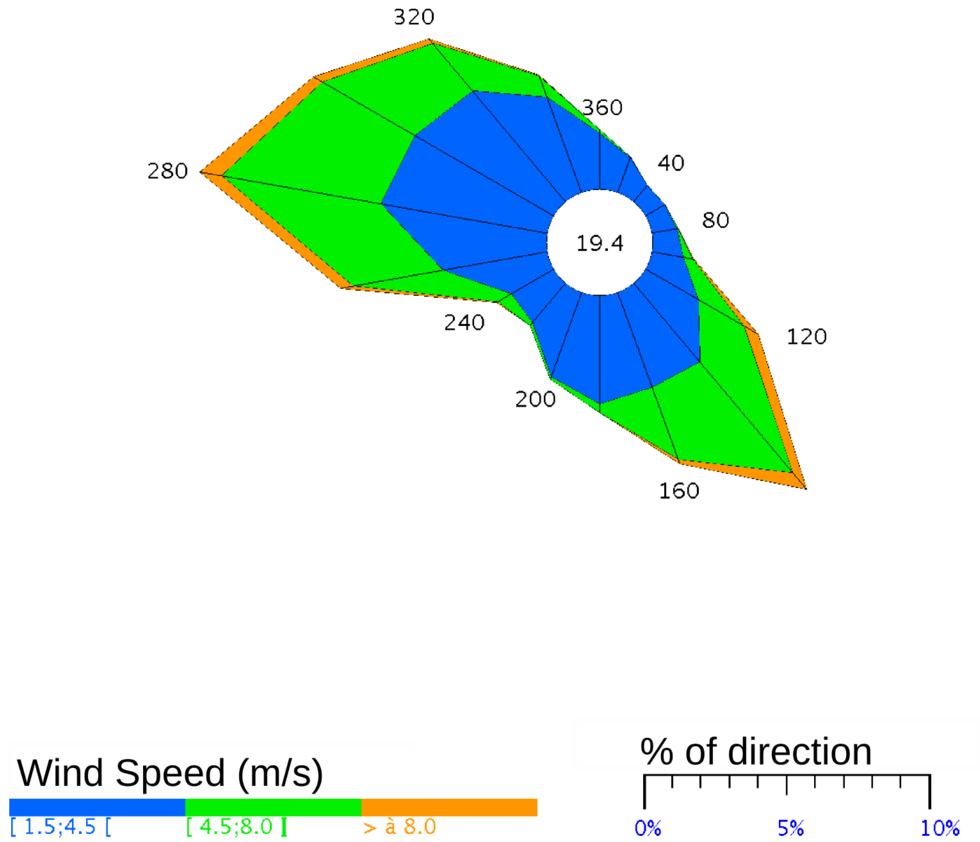

Figure 2: Diagram of wind observations at Toulouse Airport site (BL2) from 1981 to 2001

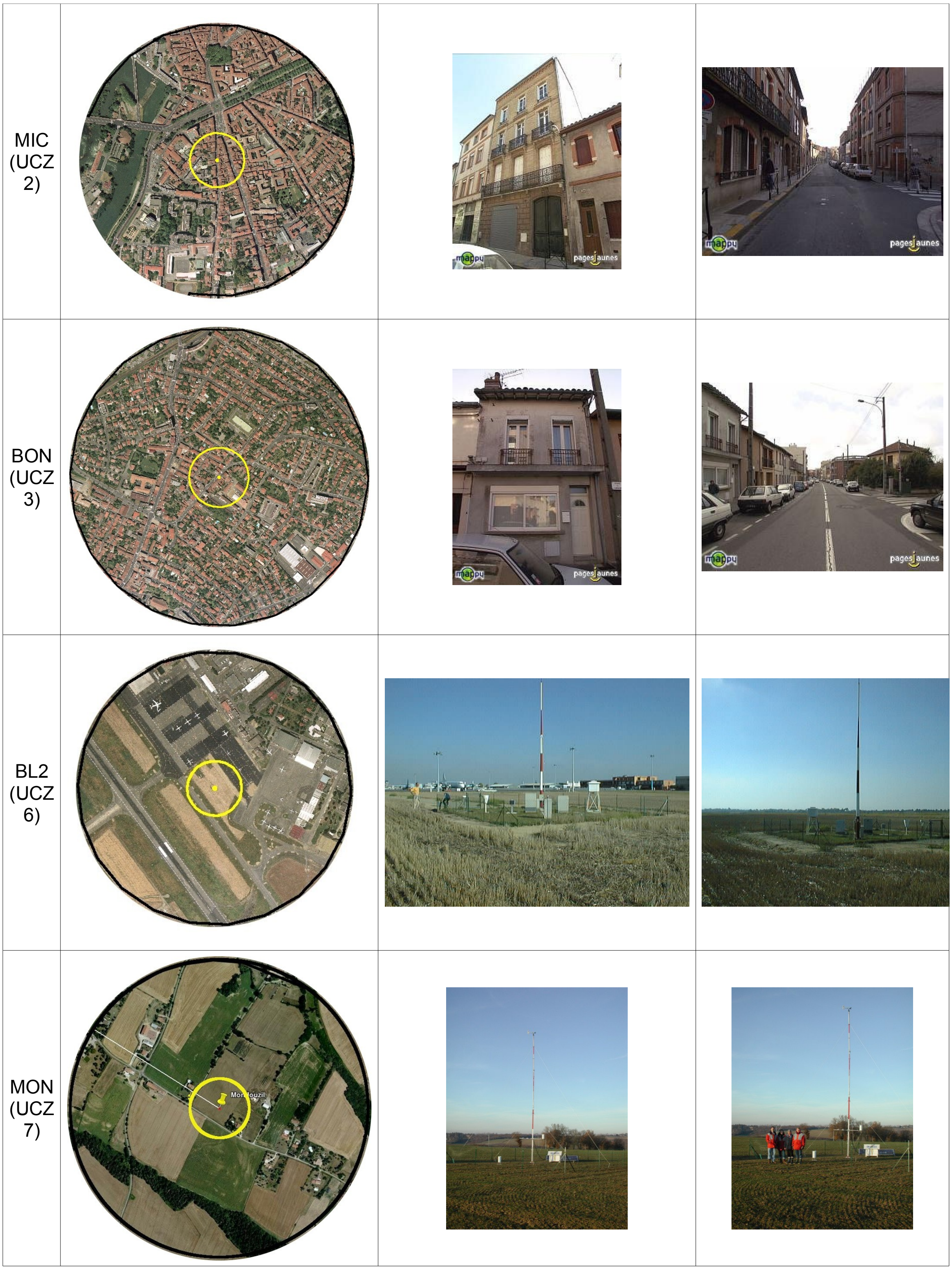

Figure 3: Aerial photography and street views of the sites MIC, BON, BL2 and MON. The yellow ring indicates the 100 m radius circle around the site whereas the black one indicates the 500 m radius circle.

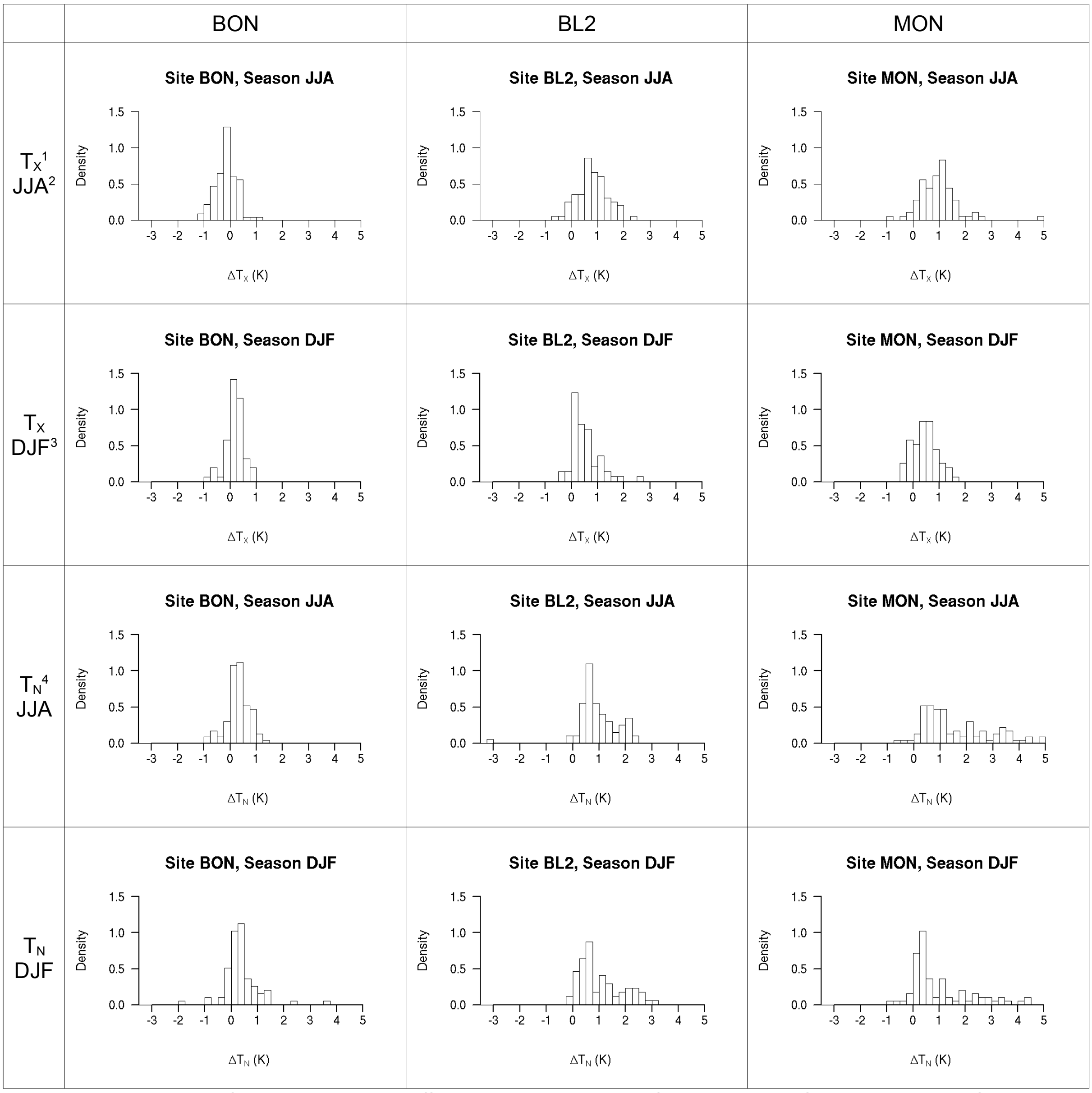

Figure 4: Histograms of the temperature difference between the reference site MIC and the sites BON (column 2), BL2 (column 3) and MON (column 4). The differences are computed with the daytime maximum temperature for the summer season (line 2) and the winter season (line 3) and with the nighttime minimum temperature for the summer season (line 4) and the winter season (line 5).

[1] T_X is the daytime maximum temperature; [2] JJA stands the months of June, July and August; [3] DJF stands for the months of December, January and February, [4] T_N is the nighttime minimum temperature.

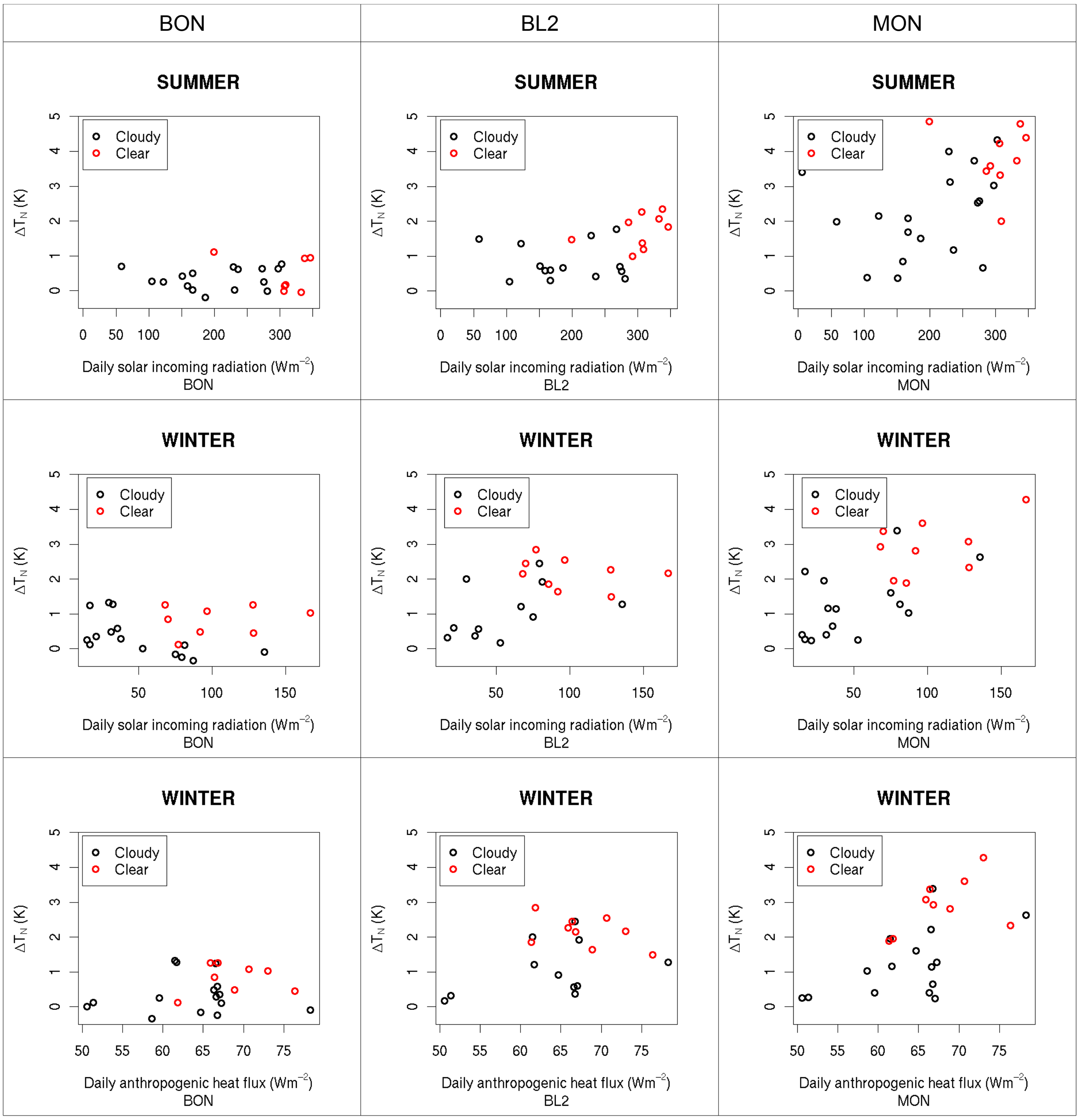

Figure 5: Scatterplots of minimum temperature difference with the reference site MIC for sites BON (column 1), BL2 (column 2) and MON (column 3) and the daily incoming solar radiation during summer (line 2), the daily incoming solar radiation during winter (line 3) and the daily anthropogenic heat flux (line 4) during winter.