2.1 ANALYSIS OF THE URBAN THERMAL FINGERPRINT OF A SMALL CITY IN AN ALPINE VALLEY

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1. INTRODUCTION

The effect known as Urban Heat Island (UHI) is among the subjects that have been best investigated in urban meteorology. However most of the research aiming at evaluating UHI characteristics has so far concentrated on relatively big cities, typically located in flat areas. Actually the climate of large cities lying in widely open plains is relatively simple to characterize, as it mainly depends on synoptic scale factors and on boundary layer processes over flat terrain, which are very well known (Landsberg 1981; Oke 1987). The picture becomes more complicated for cities lying in areas displaying geographic inhomogeneities, such as coastal regions, as well as areas with strongly heterogeneous land use or located in complex terrain. In these cases the investigation of the UHI must take into account the interactions between the built-up area and the peculiar phenomena typical of these contexts. In fact, while in flat areas weather conditions are mainly determined by synoptic scale situations, in complex terrain the influence of local-scale phenomena may be as much important (Rotach and Zardi 2007; Zardi and Whiteman 2010). For various cases of coastal cities several works have analyzed the interactions between local phenomena, as the sea breeze circulation, and the built up area (e.g. Cenedese and Monti 2003; Gedzelman et al. 2003; Lin et al 2008). On the contrary the urban climate properties of cities located in valleys have received less attention, and only few works are available in the literature (e.g. Wanner and Hertig 1984; Kuttler et al. 1996; Piringer and Baumann 1999). However such a situation is frequently met in various cases of midsized cities that have grown in mountain areas.

Valleys are characterized by the occurrence of thermally driven local circulations systems (Whiteman 1990), and by a higher diurnal temperature range than over plains. In particular cooling rates found in valleys are usually higher than over flat terrain, due to cold air flowing down from the slopes to the valley floor, starting after sunset. As a result nocturnal thermal inversions are generally stronger in valleys than over the adjacent plains (De Wekker and Whiteman 2006).

Wanner and Hertig (1984), working on small and midsized Swiss cities, emphasized the importance of considering these local phenomena when evaluating the urban climate properties of cities located in complex terrain. Kuttler et al (1996) highlighted, for the case of the valley city of Stolberg (Germany), that the intensity of the nocturnal UHI was strongly influenced by the penetration of the cold drainage flow inside the urban area. In fact the obstruction of the built-up urban area and the narrowness of the valley hindered the penetration of cold air into the urban canopy in the first part of the night, thus leading to a strong UHI in these hours. Piringer and Baumann (1999), analyzing the urban climate of Graz (Austria), pointed out that both the complex topography of the valley and the presence of the urban area contributed to the development of heterogeneous temperature and wind fields. Furthermore the analyses presented in that work showed the development of a strong ground based thermal inversion, which is another important aspect to consider when analyzing the climate of a valley city, especially if the urban area spreads on the sidewalls, and interactions between topographic and urbanization effects arise (Goldreich 1984).

In the present paper the intensity of the UHI in the city of Trento (Italy), in the Alpine Adige Valley, has been studied evaluating the differences ΔT_{u-r} between an urban automated weather station placed over the mean roof level (T_u) and five suburban/rural weather stations (T_r), located few kilometers outside the boundaries of the city (Fig. 1). In particular the analysis focused on the time evolution of the UHI, both on the diurnal and on the yearly cycles. Moreover the dependence on wind speed and cloud amount was evaluated.

2. STUDY AREA AND MEASUREMENT SITES

The city of Trento (46°4' N, 11°7' E) lies at 200 m MSL in the Adige Valley. The latter is the southern stretch of a geographic corridor connecting the Po Plain to the Brenner Pass (roughly along a south-north direction), in the Italian side of the Alps (Fig. 1).

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The population living in the inner city of Trento amounts to about 56 000 citizens, whereas including all the surrounding suburbs the number of inhabitants raises a value around 114 000 (Municipality of Trento 2009). Nowadays the city and its suburbs can be viewed as a whole continuously built-up area, spreading out about 10 km along the valley. The built-up area fills all the valley width (about 2 km wide), including the lower part of the eastern sidewall, displaying a gentle inclination. The mountains flanking the Adige Valley reach an average altitude of 2000 m MSL, both on the western and on the eastern sidewalls.

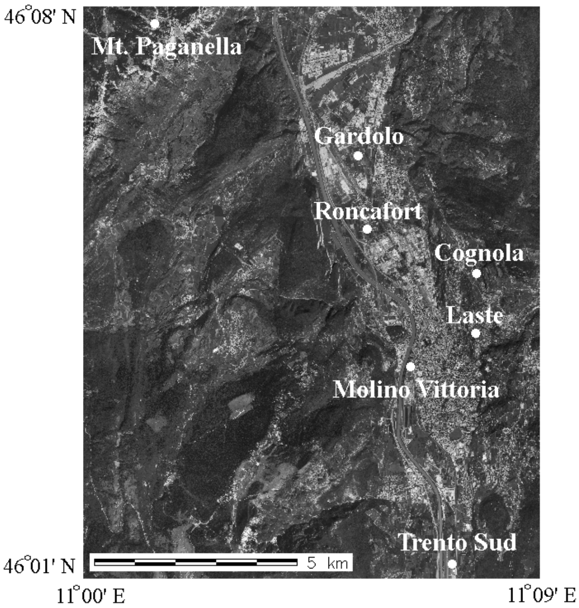

Figure 1: Aerial photo of the city of Trento in the Adige Valley. White bullets indicates the weather stations analyzed in this study.

The evaluation of the UHI intensity of the city was carried out analyzing a dataset of surface air temperature measurements composed from data collected at six automated weather stations permanently operated at different sites within or around the urban area (Fig. 1).

The first station, named Molino Vittoria after the building where it is installed, is close to the city center and therefore representative of the inner urban area. This station was installed in October 2002 and has continuously been operated thereafter by the Atmospheric Physics Group of the University of Trento (de Franceschi and Zardi 2007). Instruments are placed on the roof of a tower at 33 m AGL, which is roughly twice the average height of the surrounding buildings.

The other five weather stations are located in suburban or rural areas around the city. Three of the extra-urban weather stations are located, as the urban site, on the valley floor, while two of them are on the east sidewall. The three extra-urban weather stations located on the valley floor are placed in the countryside, two north of the city (Gardolo and Roncafort) and one south of Trento (Trento South). One of the extra-urban weather stations on the sidewall is placed in a suburban area at 312 m MSL (Laste), whereas the other is located in the countryside at 344 m MSL (Cognola).

The station at Molino Vittoria is the most recently installed (October 2002), therefore the whole dataset used for the following analyses covers the time period October 2002- December 2008.

3. DATA ANALYSIS

3.1 Average values of the UHI

As a first step, the analysis has focused on the evaluation of the average UHI intensity, by comparing all the hourly-mean temperature values from Molino Vittoria (city center) with the corresponding values of the five extra-urban weather stations. As can be seen in Table 1, on the valley floor the average urban-rural temperature differences range between 0.6°C and 1.1°C, which are quite small values compared to typical UHI intensities found in larger cities. However this average temperature difference with the urban site takes into account every weather condition and every hour of the day, whereas UHI intensity is highly variable depending on these factors, as can be argued from the high values of the standard deviations in Table 1.

NAME OF THE STATION	ALL THE DAY			DAYTIME			NIGHTTIME		
	N	ΔT_{u-r}	σ	N	ΔT_{u-r}	σ	N	ΔT_{u-r}	σ
GARDOLO	53359	0.76	1.61	29415	0.03	1.30	23944	1.67	1.49
TRENTO SOUTH	53304	0.58	1.35	29427	-0.06	1.03	23877	1.37	1.27
RONCAFORT	42704	1.07	1.50	23391	0.49	1.24	19313	1.79	1.47
LASTE	50288	0.65	1.07	27827	0.54	1.20	22461	0.79	0.88
COGNOLA	52849	1.48	1.56	29153	0.74	1.47	23696	2.39	1.13

Table 1: UHI average intensity in °C (calculated as the difference between Molino Vittoria and the five extra-urban stations) during all the day length and separating daytime and nighttime subsets. N indicates the number of hourly temperature data couples T_u and T_r used to evaluate the mean difference $\Delta T_{u-r} = T_u - T_r$, σ indicates the standard deviation.

At Laste and Cognola, on the valley slopes, the temperature contrasts with the urban site are 0.7°C and 1.5°C respectively. These differences are caused by a combination of urbanization and topographic effects. It is interesting to notice that the average temperature difference between the two stations on the slopes, one suburban and one rural, is comparable to those found between the urban and the rural weather stations located on the valley floor, thus suggesting a considerable influence of urbanization at Laste.

3.2 Diurnal-cycle variations of the UHI

Data were split into a daytime and a nighttime subset (simply identified on the basis of the incoming solar radiation measured at Molino Vittoria), in order to evaluate separately the average intensity of the UHI during these two parts of the day (Table 1). Based on the analysis of these subsets, three aspects can be outlined.

First, UHI intensity appears to be stronger during nighttime, especially at the rural stations, confirming the well-established concept that urban-rural temperature differences are higher at nighttime (Oke 1987). On the valley floor the average nocturnal UHI intensity is of order 1.5°C, whereas at Cognola it is higher (2.4°C). However part of this contrast has to be attributed to topographic effects.

Second, looking at the daytime UHI intensity, on average urbanization effects do not significantly affect temperatures. In fact the average daytime temperature differences with the urban site are negligible or low at all the extra-urban weather stations.

Third, concentrating on Laste, it can be seen that the temperature contrasts with Molino Vittoria are very similar during daytime and nighttime. Indeed the diurnal cycle of temperature at this station is similar to that registered at the urban site, confirming the strong influence of urbanization on the surrounding area. This conclusion can also be drawn by observing that both during daytime and nighttime the average temperature differences with Cognola are similar to urban-rural contrasts found on the valley floor.

In order to outline the characteristics of the diurnal cycle of the UHI, its intensity has been analyzed also on a hourly basis. Figure 2 shows the diurnal cycles at Gardolo (a), which is also representative of the other two extra-urban weather stations on the valley floor, at Cognola (b) and at Laste (c). The diurnal cycles of the UHI show similar features at all the extra-urban weather stations, with higher and roughly constant UHI intensities during the night and an "urban cool island" effect in the central hours of the day. However at Laste, as expected, the diurnal cycle of the UHI is flatter in comparison with those found at the rural locations. Furthermore some minor differences between these diurnal cycles can be observed. On the valley floor the maximum UHI intensity is reached during the night, when strong temperature contrasts with the urban site can be found (at Gardolo ΔT_{u-r} can exceed 6°C). On the other hand on the sidewall the maximum intensity of the UHI is reached in the late afternoon at Laste and in the evening at Cognola, i.e some hours before than at Gardolo: this is probably associated with the earlier onset of the drainage flow on the sidewall than on the valley floor.

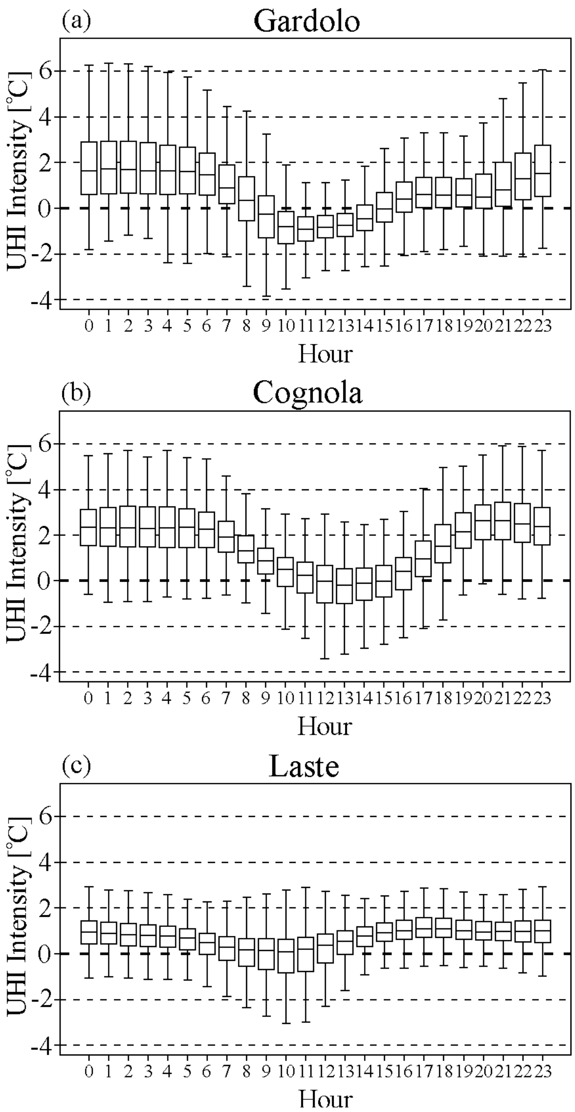

Figure 2: Box-plots of hourly temperature differences ΔT_{u-r} between Molino Vittoria and (a) Gardolo, (b) Cognola, (c) Laste. The bottom and the top of the boxes represent respectively the first and the third quartile (Q_1 and Q_3), while the line in the middle is the median (Q_2). The ends of the whiskers represent respectively the lowest datum within Q_1-1.5(Q_3-Q_1) and the highest datum within Q_3+1.5(Q_3-Q_1). This description applies to all the box-plots shown in this paper.

3.3 Seasonal variations of the UHI

After evaluating the diurnal cycle of the UHI, its behavior on a larger time scale was explored by investigating the yearly cycle on a monthly basis. Following the remarkably different features characterizing the daytime and nighttime phases of the UHI, these two subsets were analyzed separately. The yearly cycles of daytime and nighttime UHI for Gardolo and Cognola are shown in Figs 3 and 4. These are also representative of the other extra-urban weather stations on the valley floor and on the slopes respectively.

At Gardolo the seasonal variations of UHI intensity are negligible over daytime (Fig. 3a). On the other hand nighttime UHI intensity (Fig. 4a) is slightly stronger during winter and summer, i.e during "dry" months, when clear skies are more likely to occur, as in these periods weather conditions are most favorable for nocturnal radiative cooling.

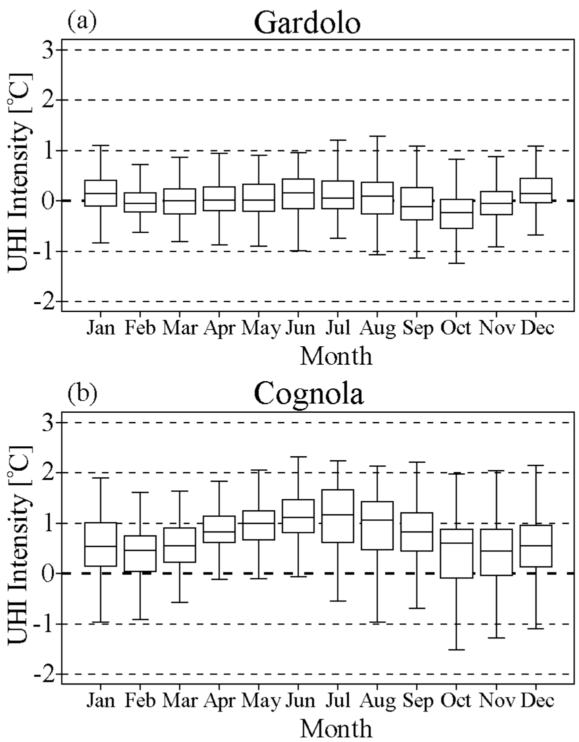

Figure 3: Box-plots of the daytime monthly temperature differences between Molino Vittoria and (a) Gardolo, (b) Cognola.

The extra-urban stations located on the sidewall show a completely different yearly cycle, both during daytime and nighttime (Figs. 3b and 4b respectively). Maximum UHI intensities are reached during summer months, while the lowest differences are recorded in the winter period. This can be explained by considering that in the Adige Valley the mean lapse rate is lower during the cold season than in summer months, partly for the occurrence of frequent ground based thermal inversions. Therefore in this period of the year temperature differences between the urban station, located on the valley floor, and those lying on the slopes of the valley are on average lower.

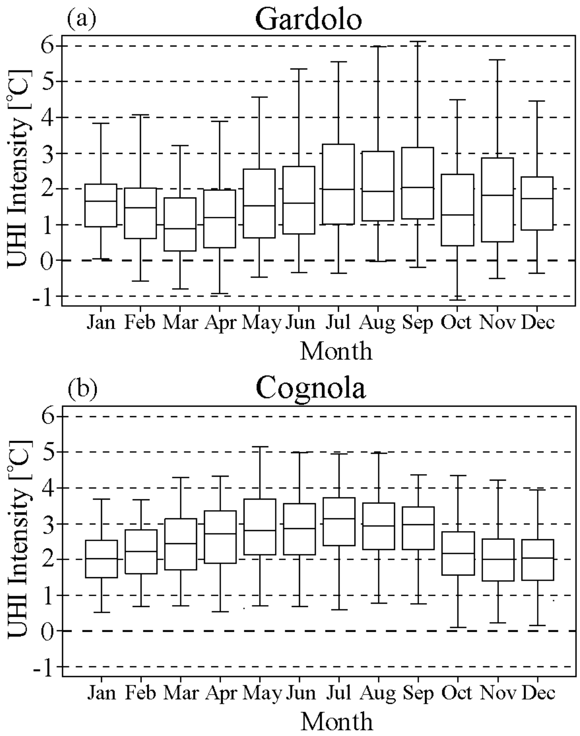

Figure 4: Box-plots of the nighttime monthly temperature differences between Molino Vittoria and (a) Gardolo, (b) Cognola.

3.4 Evaluation of cloud cover effects

The analysis of the dependence of UHI intensity on cloud cover has been carried out dividing the data into five cloud cover classes, based on measurements at Mt. Paganella weather station (2125 m MSL), located 10 km north-west of Trento.

Fig 5 shows the box-plots of Gardolo, which is again also representative of the other rural stations on the valley floor. Urban-rural temperature differences decrease progressively as cloud cover increases, both during daytime and nighttime. Under clear sky conditions urban-rural temperature differences are positive and quite strong at night, whereas in the central hours of the day the temperature at Molino Vittoria is lower than at Gardolo. On the contrary when the sky is completely cloudy, temperatures at the urban site and at Gardolo are similar for the whole day.

At Cognola and Laste the behaviors found are similar, with only some differences caused by the interactions between urbanization and topographic effects (not shown here).

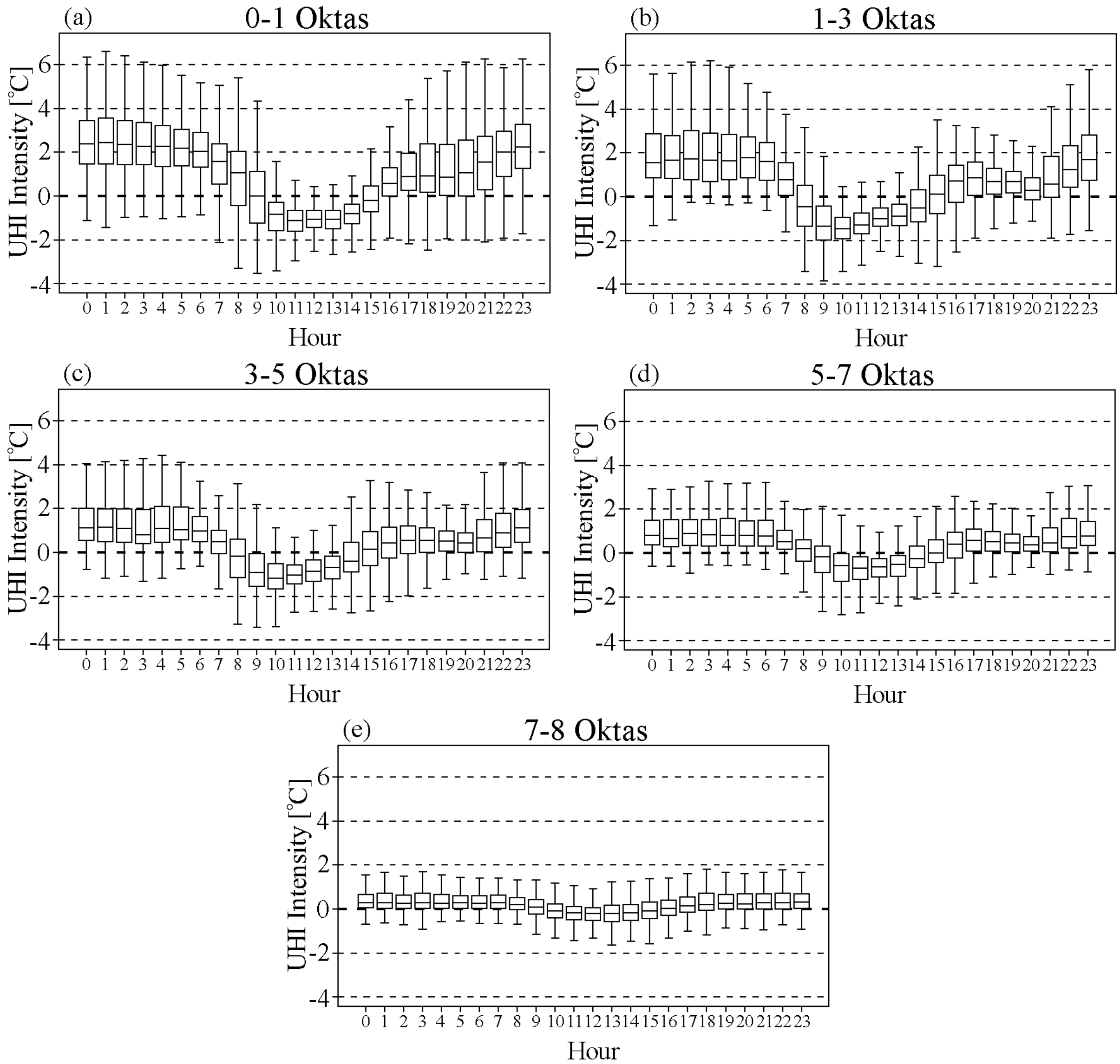

Figure 5: Box-plots of hourly temperature differences between Molino Vittoria and Gardolo classified by cloud cover classes in oktas observed at Mt. Paganella weather station.

3.5 Evaluation of wind effects

A similar analysis has been carried out to outline the effect of wind speed. Temperature differences ΔT_{u-r} were grouped into six wind speed classes, based on the values of wind intensity recorded at Molino Vittoria station. Classes were sized so as to include into every class a fairly representative number of data.

On the valley floor (in Fig. 6 are shown the box-plots of Gardolo) during nighttime UHI intensity decreases as wind speed increases, whereas during daytime urban-rural temperature differences seem not to be significantly affected by wind speed. During nighttime wind speed affects UHI intensity to a lower extent than cloud cover.

The analysis of the dependence of UHI intensity on wind speed at the extra-urban weather stations on the slopes has not been carried out, as wind speed at Molino Vittoria is not fully representative of the conditions on the slopes of the valley, especially at night, when local drainage winds are likely to occur.

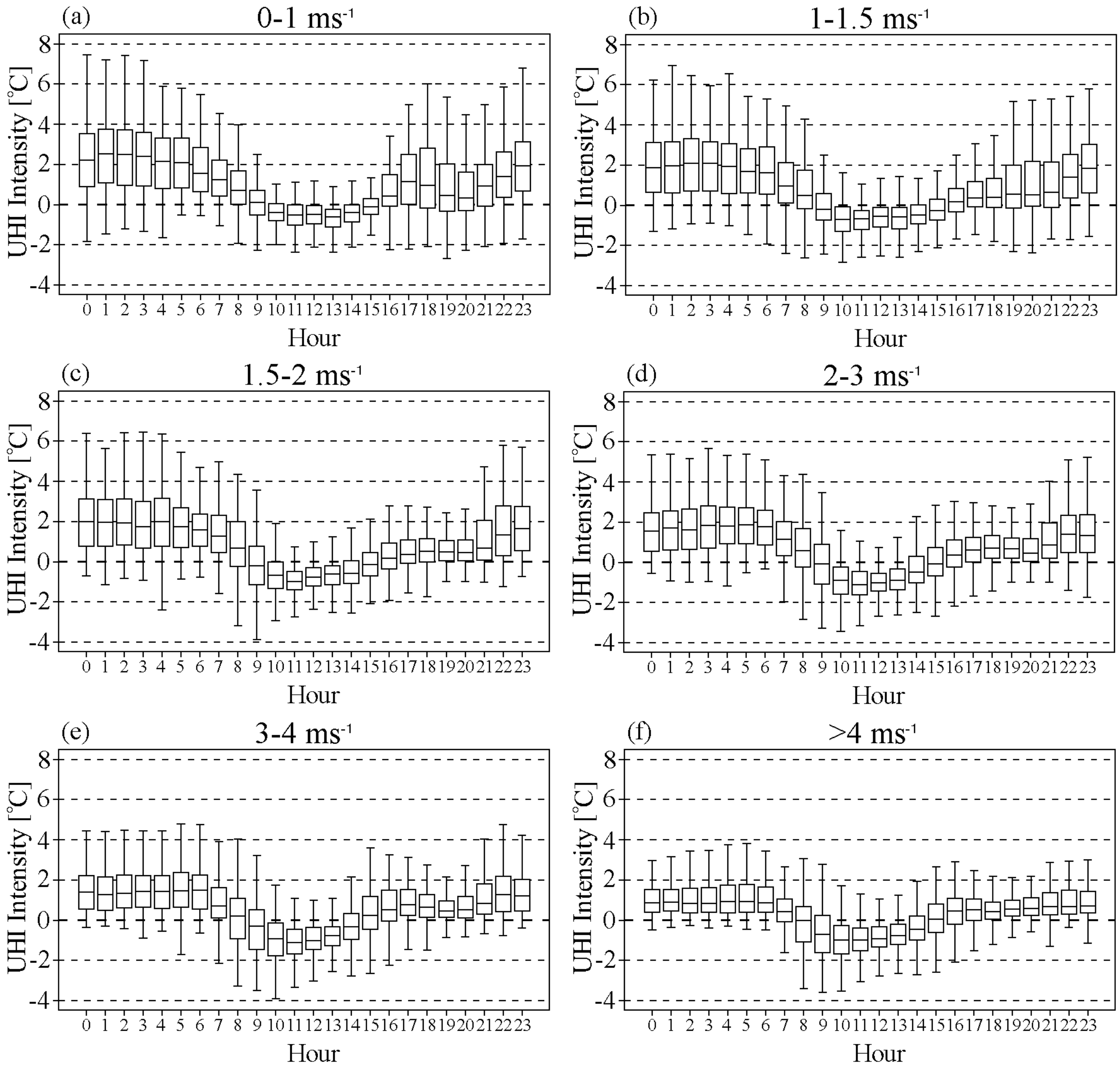

Figure 6: Box-plots of hourly temperature differences between Molino Vittoria and Gardolo classified by wind speed classes measured at Molino Vittoria.

4. CONCLUSIONS

The UHI of the city of Trento, in the Italian side of the Alps, has been evaluated by analyzing the differences between the temperature time series registered at one urban station and at five surrounding extra-urban weather stations over the period October 2002 – December 2008. After evaluating the average values of the UHI, the analysis has focused on its time evolution and on its dependence on wind speed and cloud amount.

As to the diurnal cycle, UHI intensity is stronger after sunset and during nighttime at all the five extra-urban weather stations. On the other hand in the morning UHI effects rapidly vanish and during the central hours of the day an urban cool island is likely to occur.

As to the yearly cycle, the average daytime UHI intensity is constant (and on average almost negligible) throughout the year at the extra-urban weather stations on the valley floor. On the other hand in these locations during nighttime temperature contrasts with the urban site are slightly stronger during dry months. At the extra-urban stations located on the slopes, the seasonal variations of UHI intensity seem mainly affected by the seasonal changes in the mean lapse rate rather than by urbanization effects. In fact during both daytime and nighttime UHI intensity is lower during winter months, when the mean lapse rate in the Adige Valley is lower.

The analysis of the impact of cloud cover and wind speed on the diurnal cycle of the UHI has highlighted that in the case of Trento the former is the meteorological factor which most influences UHI intensity. In fact cloud cover, being connected with incoming solar radiation during daytime and with longwave radiative cooling at night, affects directly both heating and cooling rates, as well as their differences between urban and rural areas. For this reason temperature contrasts due to urbanization effects are more remarkable in clear sky conditions, producing positive and strong UHI intensities at night and an urban cool island effect in the central hours of the day. On the contrary when the sky is completely cloudy, and thus radiative effects are negligible, urban-rural temperature differences tend to be negligible as well throughout the day. Wind speed seems to affect UHI intensity only at night, when on the valley floor urban-rural temperature contrasts tend to decrease as wind speed increases. In fact the development of the urban cool island in the central hours of the day seems to be not significantly influenced by wind intensity.

This work provides a first insight into the UHI of the city of Trento. Being based only on single surface data, it still has some inherent limits. In fact some aspects, such as the assessment of the three-dimensional temperature field in the surroundings of the city, and the interactions between local wind systems and the built up area, have not been completely clarified yet, and require further investigations. For this reason, in order to get a more detailed picture of the influence of the urban area of Trento on the meteorological phenomena typical of an Alpine valley, numerical simulations with a mesoscale model, coupled with a suitable parameterization of urban surface effects, are under way.

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