Assessing meteorology measure uncertainty in urban environments

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Abstract: Measurement uncertainty in meteorology has been addressed in a number of recent projects. In urban environments, uncertainty is affected also by local effects, which are more difficult to deal with than for synoptic stations. In Italy, to support energy applications, since 2010 an urban meteorological network (Climate Network®) was designed, set up and managed at national level according to high metrological standards and homogeneity criteria. Availability of this high quality operative Automatic Weather Station (AWS) network represents an opportunity to investigate station siting and sensor exposure effects and to estimate the related measurement uncertainty. An extended metadata set was established for the stations in Milano, including siting and exposure details. Statistical analysis on an almost 3-year long operational period assessed network homogeneity, quality and reliability. Deviations from reference mean values have then been evaluated in selected low gradient local weather situations in order to investigate siting and exposure effects. In this paper the methodology is depicted and preliminary results of its application to air temperature discussed, which allowed setting an upper limit of 1°C for the added measurement uncertainty at top of Urban Canopy Layer.

1. Introduction

Urban meteorology and climatology are relevant research areas and have been considered more and more important because of worldwide growing urbanization. Several social and economical needs (e.g. energy, insurance, health, urban planning issues) have to be addressed and require denser and more accurate measurements [1, 2]. Considering complexity of urbanized environments, they are more difficult to deal with in comparison with synoptic ones. Urban geometry and texture, density of buildings, road asphalt, different cover material, heating and cooling of buildings, radiation reflection by walls and windows, wind shielding and many other phenomena cause highly inhomogeneous meteorological field, both at ground and in altitude. This is especially true in European towns: it is a challenge to identify a weather station siting that can be considered as a standard site and be spatially representative. A first consequence is the historical shortage of urban weather stations working with continuity over time.

The World Meteorological Organization (WMO) classification scheme of weather stations [3] puts urban observational sites in the last two classes (classes 4 and 5 of 5), assigning very large uncertainties to them (up to 5°C for temperature). Measurement uncertainty evaluation is only seldom discussed in scientific papers related to meteorological measurements, especially for difficult environment as the urban one. It has been subject matter of specific recent WMO publications [4] and has found a stimulating reference frame in MeteoMet Projects [5].

The availability of almost 5 years dataset by Climate Network® (shortly CN) in Milano [6] allows a quantitative investigation of how station siting and sensor exposure [7] affect measurements in cities and a methodology to estimate additional uncertainties, if some pre-requisites are satisfied. CN is a private professional network of Automatic Weather Stations (AWS) in Italy, currently accounting for almost 50 stations located in the main cities centres. It has been designed, set up and maintained according to rigorous quality and metrological criteria in order to correctly represent the Urban Canopy Layer (UCL) at the mean building top level. The network can be considered the technological evolution of the city historical meteorological observers, whose weather stations had been located on top of buildings, and it contributes to the continuity of urban historical climatological series. CN also

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[(1)] Present address: UNSW Sydney Faculty of Built Environment - Kensington, NSW, Australia supports business users, such as energy industries requiring continuous supply of comparable and high quality weather/climatic data in main Italian towns to bill energy consumption and evaluate thermal plants performances.

Measuring at top building level (rooftop terraces) is the result of fulfilling requirements of strict siting homogeneity at national level, local scale representativeness for all weather parameters, continuity with past weather observations and easy maintenance in the urban context. Comparison with other urban networks measuring at different heights and sites in Milan are envisaged, but still not performed and could probably lead to a sub classification of urban stations.

This work aims to provide a contribution to a deeper understanding of the very local effects on urban meteorological measurements and to better define upper limits to the related uncertainties for a suitable station set up.A first methodological approach to evaluate siting and exposure related uncertainty, tested on 8 CN stations in Milano, is described in the following sections and preliminary results are presented.

2. Methodology

In first approximation, an urban meteorological measurement M may be broken up as sum of several and independent contributions:

$$M = M_0 + M_m + M_e + M_i$$

where:

- M_0 is the synoptic value, the greatest one, uniquely determined by the large scale meteorological situation and equal for all stations inside town;

while for the 3 correction terms, generally of a lower order:

- M_m is due to meso/local scale meteorological phenomena, varying at urban scale;
- M_e is related to specific siting of each station and to sensor exposure;
- M_i is the instrumental and calibration uncertainty.

The last one is known from the sensor calibration procedure and is the same for all CN weather stations, being already kept to a minimum through accurate calibration (performed yearly to limit drift effect) and traceability to national standards [9]. In order to investigate the uncertainty uniquely related to siting and exposure (M_e) on the basis of data itself, it is necessary to minimize M_m, selecting meteorological situations where meso/local scale patterns do not cause sensible horizontal gradients of meteorological variables at urban scale. Moreover, in relation to the very high percentage of stability conditions characterizing Milano and Po Valley, it is mandatory to single out major Urban Heat Island (UHI) episodes that can result in horizontal temperature difference of several degrees between city centre and suburban area, as well as induced secondary circulations. All these phenomena could overwhelm measure differences only due to different sitings and exposures, and must be eliminated or at least minimized. In this case, skipping M_i and reducing M_m to 0 as much as possible, above equation becomes::

$$M \approx M_0 + M_e$$

Furthermore, it is convenient to analyze only measure differences. If not otherwise available, a reference value M_{ref} can be defined as the average over N suitable network stations to minimize random errors:

$$M_{ref} \equiv \Sigma M_n / N = \Sigma (M_{0,n} + M_{e,n}) / N$$

The difference ΔM_n between measure M_n at the n-th station and M_{ref} is then:

$$\Delta M_n \equiv (M_{0,n} + M_{e,n}) - M_{ref} = M_{0,n} + M_{e,n} - \Sigma M_{0,n} / N - \Sigma M_{e,n} / N$$

Supposing $M_{0,n} \approx M_0$, having filtered out meso/synoptic and other local gradients, and considering siting and exposure effects casually distributed for the network stations around a mean so that:

$$\Sigma M_{e,n} / N \approx 0$$

and equation further simplify as:

$$\Delta M_n \approx M_{0,n} + M_{e,n} - M_{0,n} = M_{e,n}$$

The difference of each station value from reference depends only on its specific siting and exposure.

This statistical approach highlights the uncertainty added by siting and exposure effects and it allows an estimate starting from field measurements themselves in the inhomogeneous and difficult urban environment.

3. Test bed and data set

As explained in the introduction, target area of this study is Milano, where the availability of 8 CN downtown stations (figure 1) allows analysis on a relatively wide data set. Each station is representative of different built-up conditions. Dedicated mainly to urban energetic applications, CN project and set-up have been based on strict homogeneity criteria and best metrological practices with direct and full documented reference to national standards at least for temperature and humidity, and also with:

- uniform positioning rules for measuring at top of Urban Canopy Layer (UCL);
- same last generation sensors in each station (Vaisala WXT520), without moving parts (sonic anemometer) and with a redundant temperature sensor (PT100) as a check of the WXT520 thermometer (being temperature the most relevant variable for the network commercial applications);
- solar-powered installations above roof level on enough tall masts (about 2 m);
- management and maintenance according to UNI EN ISO 9001 and Quality Assurance and Quality Control (QA/QC) procedures;
- daily remote sensor control and data validation performed by both automatic procedures and experienced meteorologists.

Besides air temperature, all CN stations measure relative humidity, atmospheric pressure, wind speed and direction, gusts, rain and hail. One station measures also global solar radiation (MI-Città Studi). CN database contains 10 minutes mean data for each meteorological variable, then aggregated into hourly and daily values in the Data Base. Extended metadata for each station have been established since set up alike to Birmingham network [10, 11], with mapping and photographic documentation of siting at different scales and detailed exposure parameters measurements (figure 2).

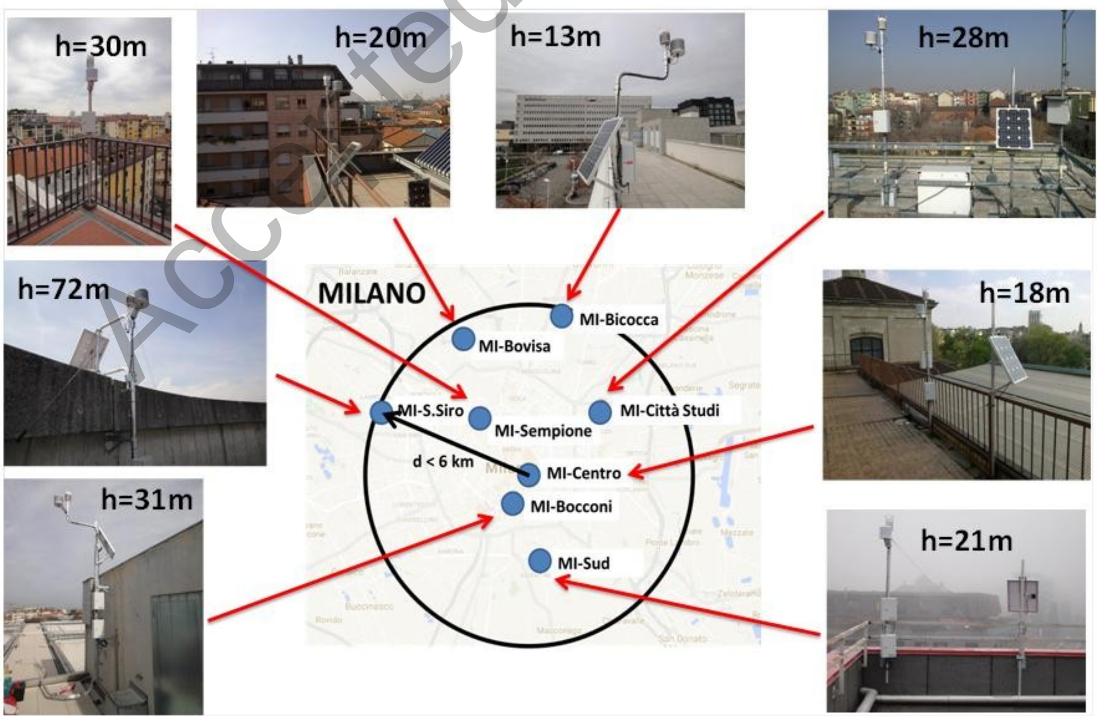


Figure 1: Siting of the 8 Climate Network® weather stations in Milano downtown, located at a distance of less than 6 km from city centre. Pictures show details of the different sensor exposures. Height over local ground (h) of each WXT520 is also indicated.

Recently, metadata have been completed with albedo measurements of the surfaces above which stations are located. The albedo was measured at the height of instruments, with a secondary standard albedometer (Kipp&Zonen CMA11). In Milano, albedo values show differences not exceeding 7% from each other, with a minimum of 0.14 at MI-Sud station and a maximum of 0.21 at MI-Bicocca. These figures are mostly due to terrace materials, mainly light gray concrete tiles, as their signal prevails in the albedometer field of view over that of background.
Not considering MI-S.Siro station, located on the top of S. Siro Stadium tower, the mean altitude of weather stations is 143 m above m.s.l., and the maximum difference in height among stations is 23 m. Instead, MI-S.Siro height is 55 m above the mean altitude.
Mean hourly values were used of each measured meteorological variable. For control purposes only, also daily synoptic weather types based on 850 hPa pressure analysis chart (UTC 12) have been considered. Data refer to period since 1st December 2012, date of the last installed MI-Bicocca station, until 21st September 2015 when MI-Sempione station was relocated in a different site. This fully homogenous database consists of 24600 averaged hourly values (missing data less than 0.3 %, confirming CN reliability).
As explained above, for this work it is necessary to select meteorological situations where synoptic and mesoscale patterns (circulation disturbances, frontal systems, föhn episodes, fog) do not cause considerable horizontal gradient of meteorological parameters inside town. Moreover, in relation to very high percentage of stability conditions characterizing Milano and Po Valley, it is mandatory also to single out UHI episodes. Specific objective criteria have been implemented to remove from the initial database measurements corresponding to relevant synoptic and meso/local scale episodes. The resulting dataset consists of hourly data that satisfy the following requirements:

- mean wind speed (i.e. average of the 8 stations values) not larger than 3 m/s;
- differences between wind speed maximum and minimum among all stations not larger than 2.5 m/s;
- differences between temperature maximum and minimum among all stations not larger than to 2°C;
- differences between maximum and minimum of mean hourly relative humidity among all stations not larger than 10 %.

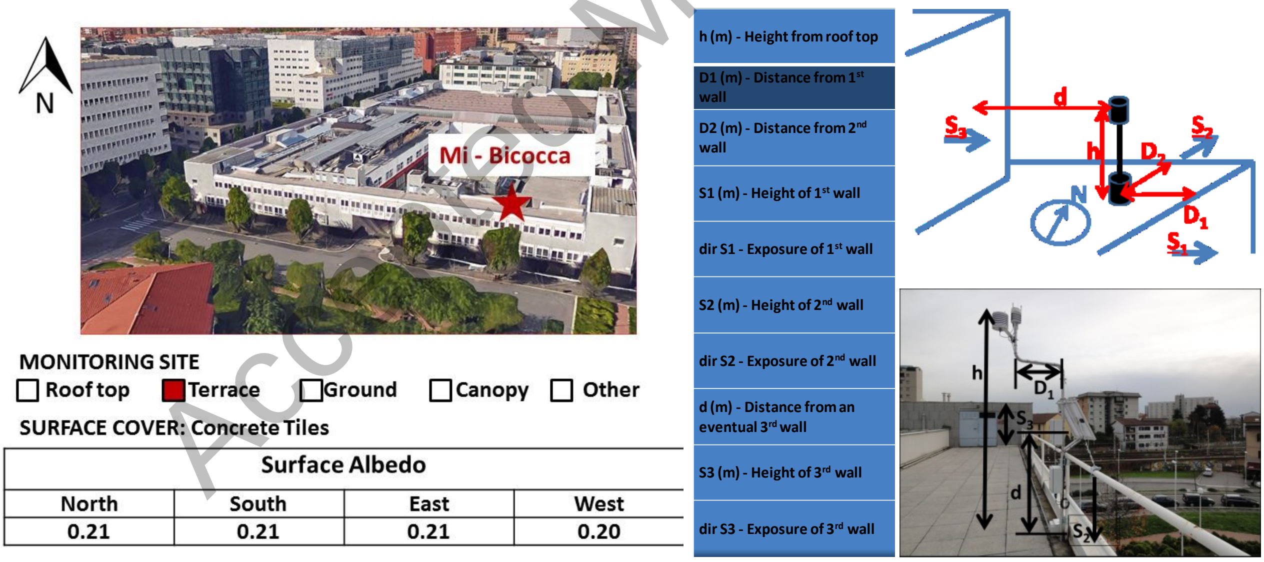


Figure 2: MI-Bicocca simplified metadata as example, with albedo measurements of the underlying surface.

4. Dataset definition and analysis.

This "*reduced dataset*" can be considered not only homogeneous, but also consistent from a meteorological point of view in relation to the aim of the study. It consists of 17059 hourly records that correspond to 69 % of starting CN database, sufficiently well distributed among hours and months.
To study siting and exposure effects, only temperature differences (ΔT_h) have been analysed so far. Temperature has been considered not only the most important parameter because of network tasks, but

also the better one to identify and test the methodology: it has a well documented traceability chain, proposed and tested within MeteoMet Project, with a periodical calibration to national standards. The resulting calibration uncertainty at coverage factor k = 2 (95% confidence level) has been determined at 0.2 °C [12].
Two further steps were performed: a suitable definition of the urban reference temperature (T_{ref}), and the statistical analysis of hourly temperature differences with respect to T_{ref} for each station as depicted in paragraph 2, where the measure M is now temperature T.
At first, the urban reference temperature was estimated as the hourly mean of all the 8 available urban weather stations. Comparing hourly temperature differences between each station and such reference (figure 3), similar behaviours were observed with small biases and reduced amplitudes for three weather stations: MI-Centro, MI-Bocconi and MI-Sempione. The last one is not fully compliant with CN siting criteria: this station was not placed on an open building top, but on a rooftop terrace with large nearby walls (it has been used mainly for technical experiments and later dismissed). Therefore, only MI-Centro and MI-Bocconi have been hourly averaged to define T_{ref}. This choice is supported by metadata similarity, especially about sensor exposure and environmental characteristics. It is only functional to highlight behavioural differences due to different siting and exposure.

5. First evaluations

The daily trends of hourly differences ΔT_h with respect to T_{ref} appear to be modulated with different amplitudes, periodicities and times of maxima/minima for each station (figure 4, figure 5). In all cases trends are evidently influenced by solar radiation. Considering only nocturnal hours, ΔT_h are almost constant and lower than T_{ref}, a clear evidence that diurnal ΔT_h depend mainly on solar radiation due to sensor exposure.
Indeed, we suppose that biases measured during nighttime are strictly connected to siting aspects, the most important of which is the distance from city center (figure 6): a relative good correlation (R^2 = 0.8) occurs between the averaged ΔT_h in time interval 00 ÷ 04 a.m. and the distance from MI-Centro station.

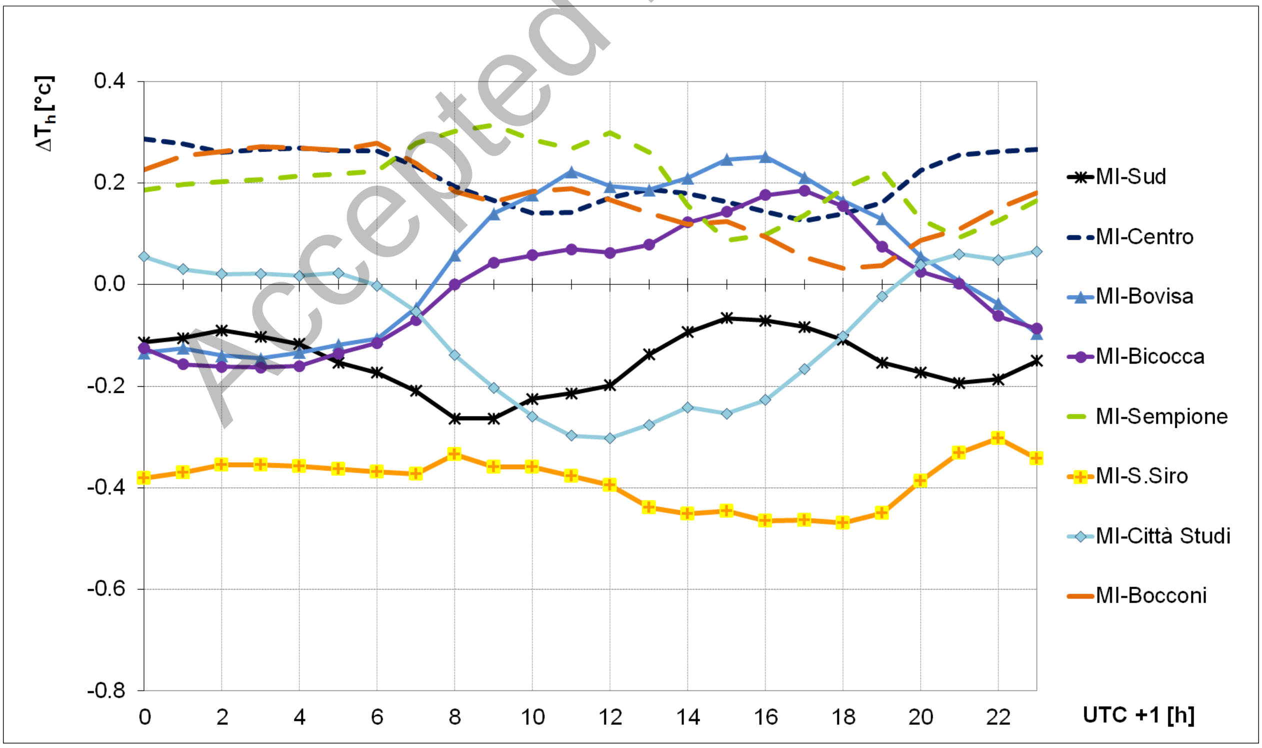


Figure 3: Daily trend of ΔT_h, with T_{ref} defined as average of all stations: similar trends are in dashed lines.

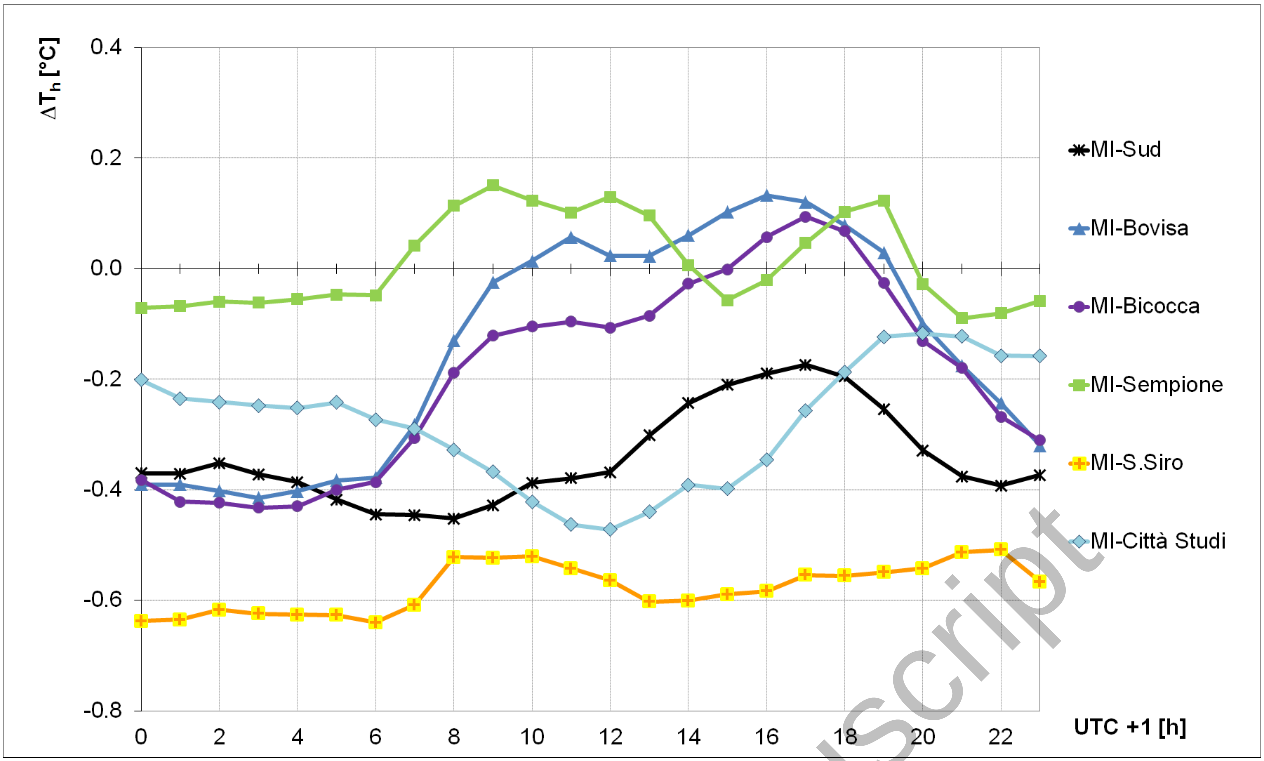


Figure 4: Daily trends of ΔT_h, referring to T_{ref} defined as average of MI-Centro and MI-Bocconi mean hourly temperatures for the *"reduced dataset"*.

We note that this correlation improves excluding MI-S.Siro and MI-Sempione. On the contrary, a significantly worse correlation is obtained averaging over 24 hours.

Seasonal daily trends of ΔT_h have also been studied. Only winter (3494 hourly values) and summer (5069 hourly values) ΔT_h are analysed in this paper.

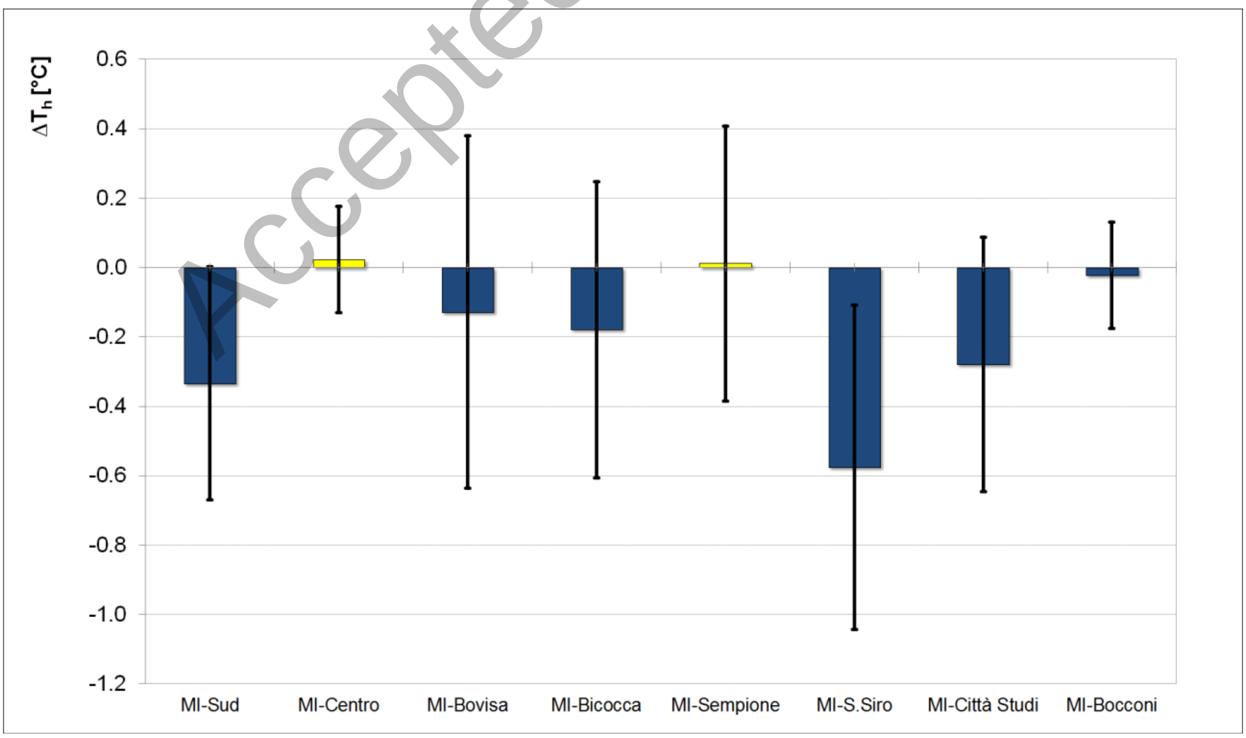


Figure 5: Biases (columns) and standard deviations (bars) of ΔT_h for all the 8 Milano CN stations.

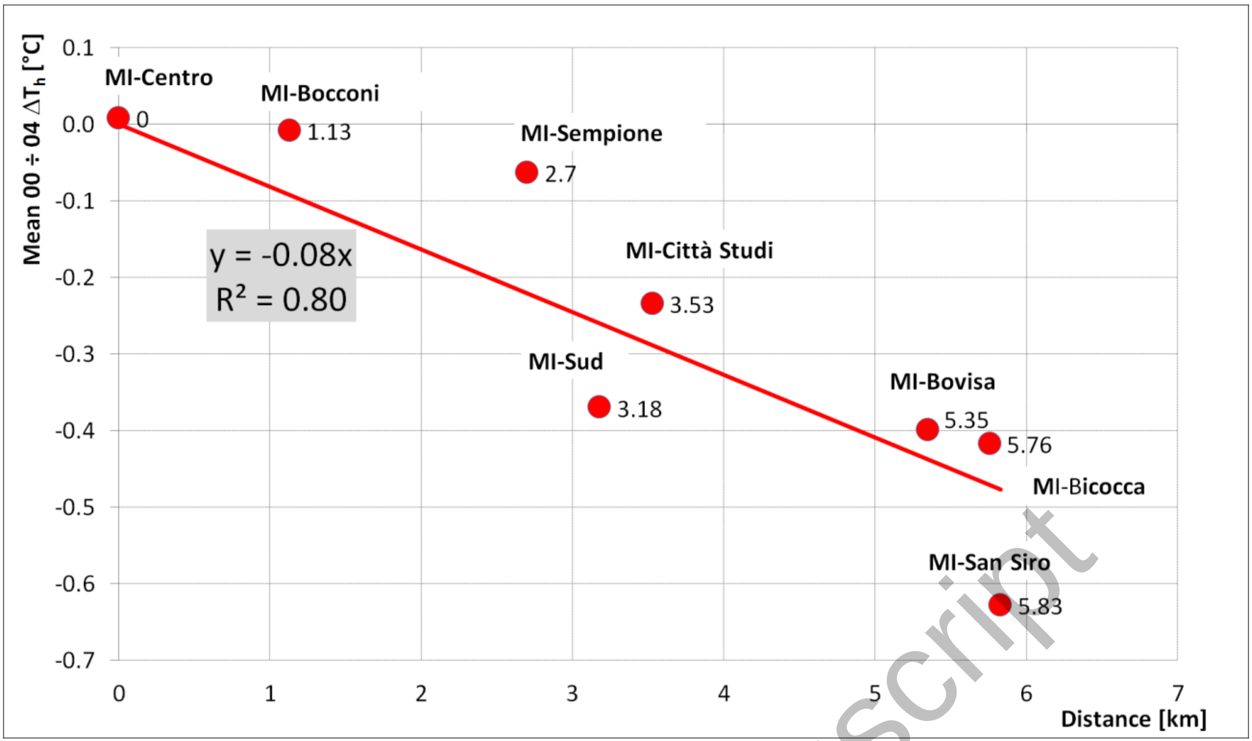


Figure 6: Mean temperature differences vs distance from city centre during nighttime (00 ÷ 04 a.m.).

Winter daily trends (figure 7a) show an increase in variability during daylight hours. Some features are worthy of attention:

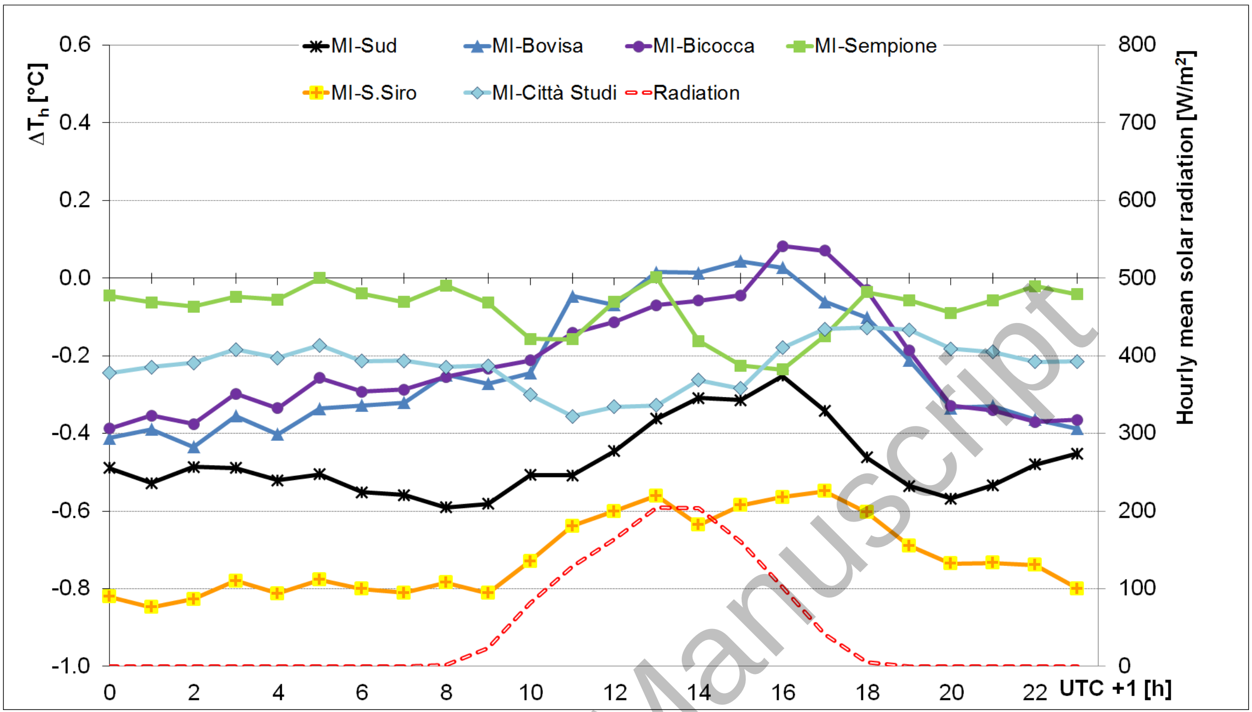
- Nighttime MI-Sempione shows ΔT_h a limited range of values close to T_{ref} and two minima recorded at 10 a.m. and 04 p.m.;
- MI-Bovisa, MI-Bicocca, MI-Sud and MI-S.Siro, although characterized by different night biases, show similar trends. In the morning ΔT_h increases starting by the nighttime bias until they reach a maximum in the afternoon at 04 ÷ 05 p.m.;
- MI-Città Studi has an opposite trend, showing a minimum around 12 a.m..

Summer daily trends show different behaviors (figure 7b), compared to winter ones. As expected, the variability of temperature differences appears around 6 a.m., at sunrise, and decreases after sunset at 9 p.m.. We can note:

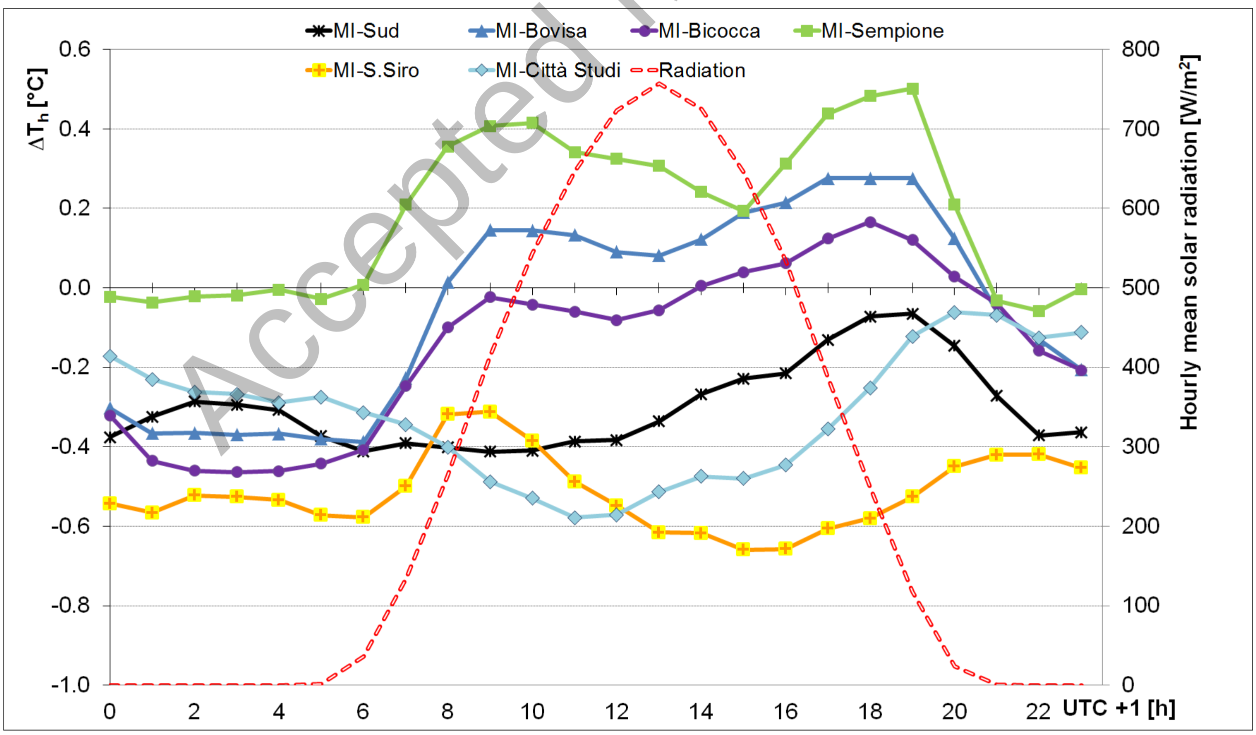
- during night MI-Sempione shows ΔT_h which are close to T_{ref} as in winter, but trend becomes bimodal during daytime with two maxima of 0.4 °C and 0.5 °C at 09 a.m. and 08 p.m. respectively;
- MI-Bovisa, MI-Bicocca and MI-Sud have very close nighttime biases; but during daylight they show different increasing trends and reach maximum in the afternoon around 06 or 07 p.m.;
- MI-Città Studi shows an opposite trend with minimum at 11-12 a.m., as in winter;
- MI-S.Siro shows an increasing trend, just after sunrise.

Finally, compared to overnight ΔT_h values (00 ÷ 04 a.m.), diurnal variability ranges are higher in summer than in winter.
Peculiarities of each station have then been investigated in relation to exposure characteristics.
MI-Sempione shows the most complex behavior, because of its siting on northern corner of a terrace. In summer (figure 8), it shows two maxima. During morning the underlying wall facing to NE is directly irradiated by the sun (figure 9a). This induces an upward flow of warm air that reaches sensors and causes an increase of ΔT_h (first maximum).
The same effect happens again in late afternoon when the NW wall is exposed to the sun (figure 9b), producing the second maximum. This does not occur in reference stations (MI-Centro, MI-Bocconi), placed

at the centre of their respective terraces. In winter, both walls below the station are always in shadow because of low elevation of sun in this season. Winter diurnal trends show two minima in daytime, corresponding to shadowing of floor below the station (figure 10a). During the day (figure 10b), when the floor is fully sunlit, difference with reference stations decreases until almost zero. Data seem to suggest an increase of ΔT_h with different floor solar illumination.



a)



b)

Figure 7: ΔT_h daily trends: a) winter, b) summer. The dashed line is the mean Global Solar Radiation as measured in MI-Città Studi.

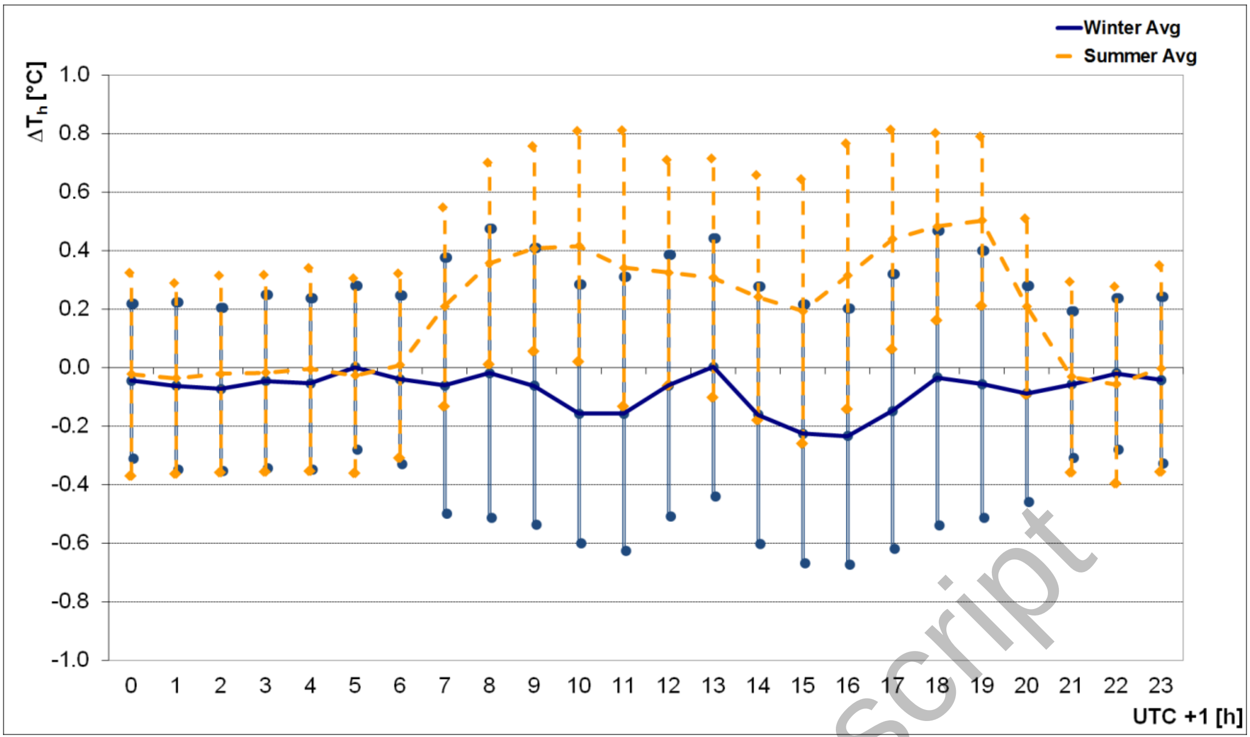


Figure 8: Seasonal ΔT_h for MI-Sempione (winter and summer only) with clear differences during daytimes). Error bars are standard deviations of each hourly mean value over the "*reduced dataset*".

a) b)

Figure 9: Summer exposures and direct solar illumination of underlying vertical walls at different day times for MI-Sempione Automatic Weather Station (AWS in pictures): a) morning, b) afternoon.

MI-Bovisa station is located at the edge of a building top floor only facing to South (figure 11). It isn't surrounded by close buildings and it is sunlit all day long. In both seasons, nighttime ΔT_h are negative and increase only after sunrise (figure 12). The south wall beneath the station is warmed during diurnal hours and produces an upward flow with consequent raise of ΔT_h. A decreasing trend is evident again after sunset. The strict connection with solar radiation is further supported by the different start/end times of increase and decrease of ΔT_h, agreeing with unlike seasonal daylight hours. Among all stations, MI-Bovisa shows the higher variability of positive diurnal ΔT_h compared to nocturnal values. We suppose this is due to the combined effects generated partly by air flow rising along the underlying wall, and partly by the large solar cells placed behind the station.

a) **b)**

Figure 10: Shadowing of terrace at different times for MI-Sempione station: a) morning, b) afternoon. Pictures were taken after station removal: the AWS was originally placed on the left corner as shown (see also figure 1).

a) **b)**

Figure 11: MI-Bovisa station: a) sensor exposure at the southern edge; b) station siting in an almost open environment. Large solar cells are clearly visible behind the station.

MI-Bicocca station presents a behavior similar to MI-Bovisa figure 13). In both seasons, compared to nighttime, ΔT_h trends are positive and increases occur in correspondence of sunrise. As in case of MI-Bovisa, this station is mounted directly on the roof top edge and sensors are exposed to warmed ascent air from underlying wall.

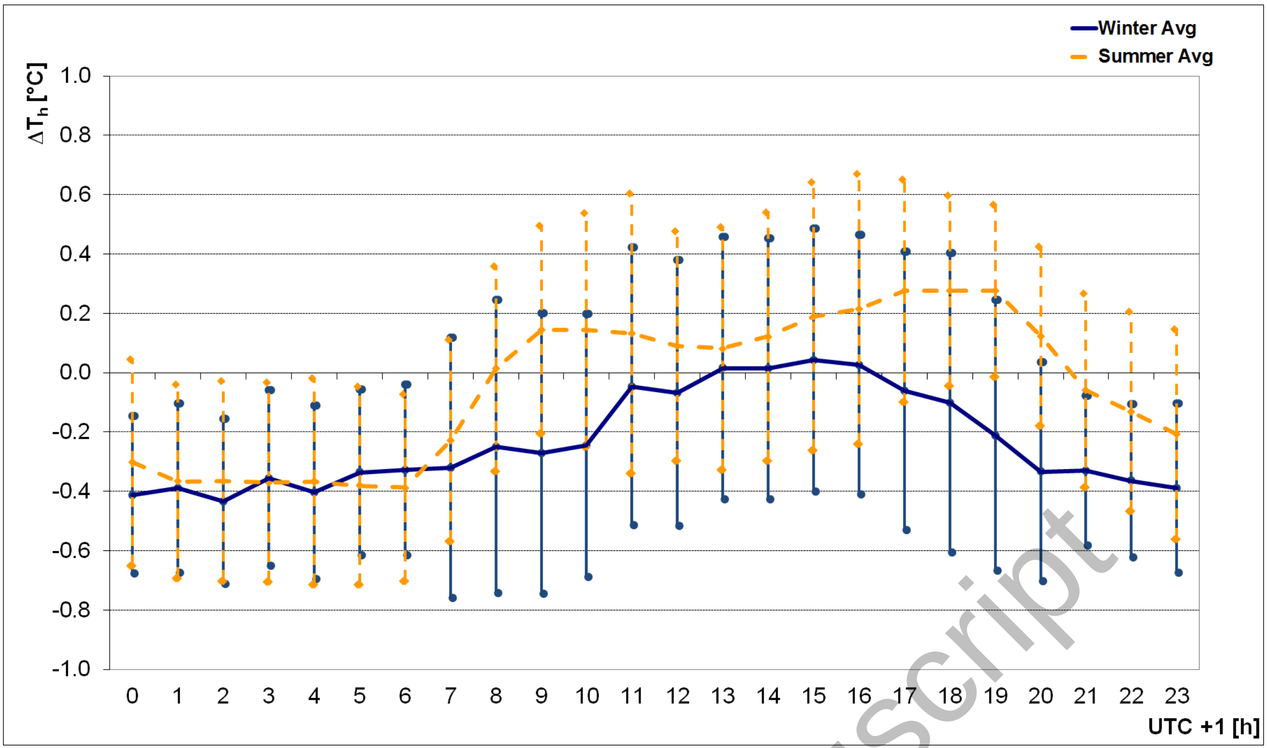


Figure 12: Seasonally daily trend of ΔT_h for MI-Bovisa station (only winter and summer shown). Error bars as in figure 8.

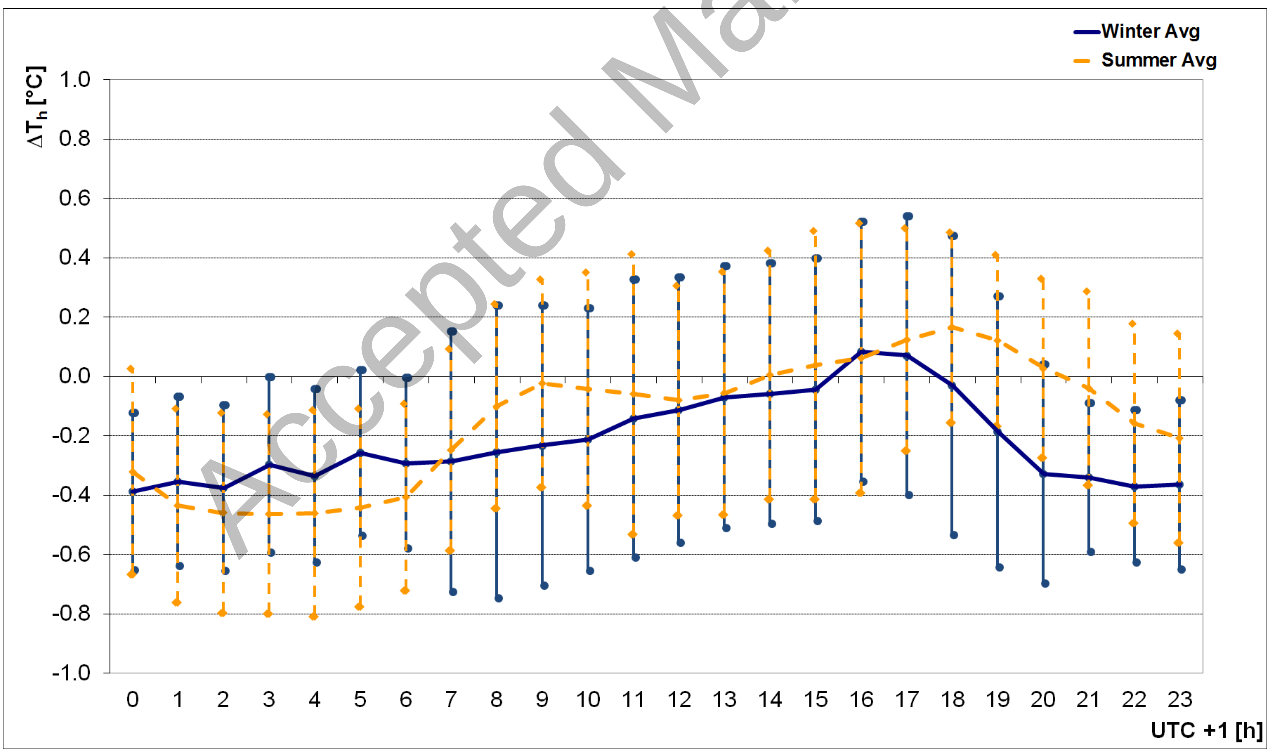


Figure 13: Seasonally daily trend of ΔT_h for MI-Bicocca station (only winter and summer shown). Error bars as above.

MI-Città Studi, MI-Sud and MI-S.Siro have different characteristics, which deserve further analysis but are likely related to siting peculiarities: MI-S.Siro being installed on a tower at 72 meters above local ground in a less urbanized environment (both characteristics may explain the colder bias), Mi-Città Studi located in a more green area and Mi-Sud lying in an industrialized suburb area. Further work is anyway needed to better understand their behaviour.

6. Uncertainties

The frequency distributions of ΔT_h (figure 14) are clearly different from each other as a result of the combined effect of station siting (which is affecting mainly the bias) and sensor exposure (affecting mostly the data distribution around the mean). As expected, two stations (MI-Centro, MI-Bocconi) have very similar and nearly Gaussian distributions, with low and comparable standard deviations. This result supports their choice as references. The other stations show a multiplicity of biases, amplitudes and in some cases deviations from Gaussian form, which can be explained at some extent by metadata itself as done in paragraph 5.

In the light of the above considerations, CN in Milano offers a variety of sitings and exposures allowing an evaluation of the related measurement uncertainties U_s: if we may assume that the distribution standard deviation is an approximate measure of the added measurement uncertainty, we can pose $U_e = M_e$. Therefore, uncertainties can be estimated as proposed in paragraph 2, if meteorological noise is sufficiently reduced as explained in paragraph 3. Table 1 shows standard deviations at coverage factor k = 2. Reference stations MI-Centro and MI-Bocconi have the minimum value (U_{exp} = 0.3°C), while MI-Bovisa gets the maximum (U_{exp} = 1.0°C). We conclude that for the CN stations in Milano the added uncertainty due to siting and exposure is not larger than 1°C, which is much less than the 5°C upper limit stated by WMO [3], but still significantly larger than the calibration uncertainty of 0.2°C.

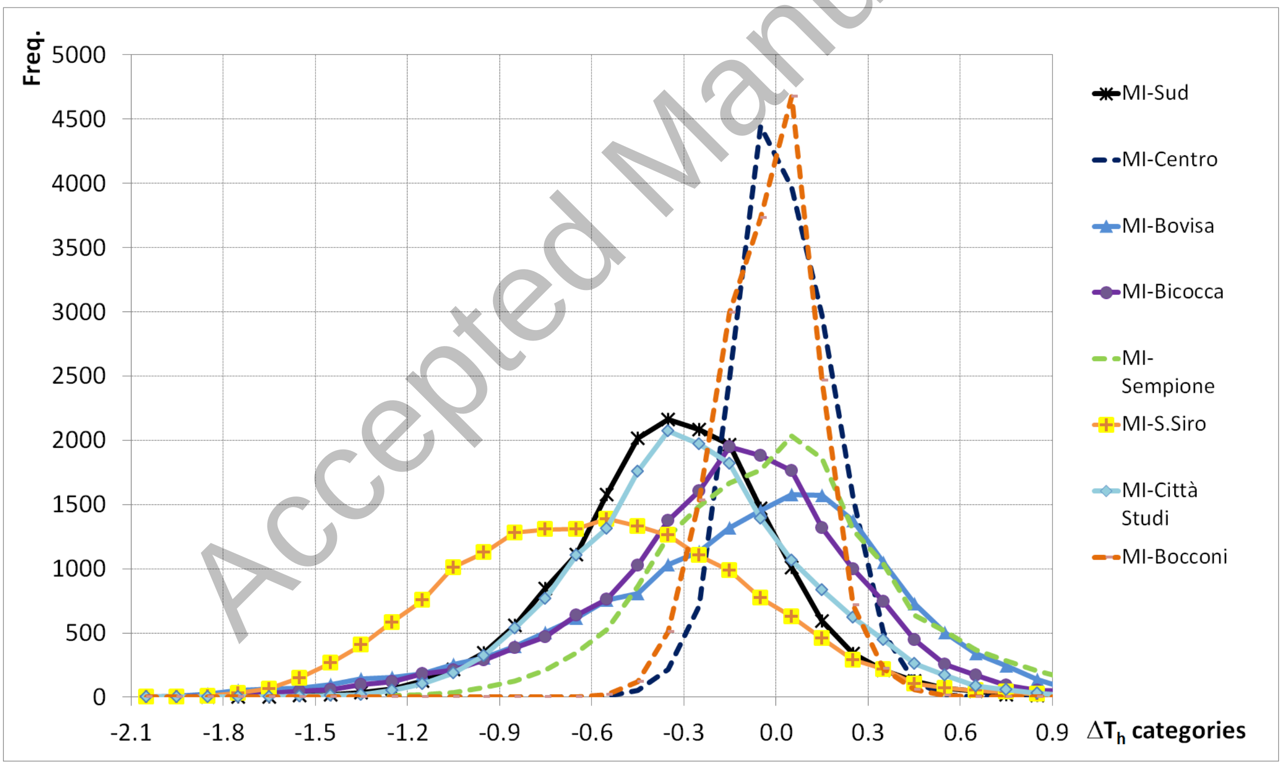


Figure 14: Frequency distribution of ΔT_h (°C) for the 8 Milano CN stations. Vertical scale is frequency computed for ΔT_h = 0.1°C.

	MI-Sud	MI-Centro	MI-Bovisa	MI-Bicocca	MI-Sempione	MI-S.Siro	MI-Città Studi	MI-Bocconi
$U_{exp\ (k=2)}$	0.7	0.3	1.0	0.9	0.8	0.9	0.7	0.3

Table 1: Added measurement uncertainties of CN weather stations in Milano due to the combined effect of station siting and sensor exposure.

7. Conclusions

The availability of an operational, homogeneous and metrological maintained set of automatic weather stations as Climate Network®, measuring the thermal field at top of UCL for urban energy applications, allowed the selection of a high quality database of urban weather data to investigate siting and exposure effects in complex urban environments and climates. The study aimed to analyse this topic referred to temperature in Milano, meteorologically characterized by very high percentage of stability conditions and remarkable UHI episodes. Statistical analysis of hourly mean temperature differences with respect to a suitable urban reference has been performed for a suitably selected subset from a homogeneous 3-year database, representative of low gradient meteorological conditions at synoptic and meso/local scale. By this approach it has been possible to highlight behavioural differences related to different station sitings and sensor exposures. Indeed it revealed for some stations a strict dependence on explicitly defined exposure parameters, especially related to distance from underlying vertical walls exposed to solar radiation or affected by shadowing. The standard deviations found, interpreted as uncertainties, at coverage factor k = 2 are all in the range 0.3 °C ÷ 1.0 °C. We conclude that, at least in case of a homogenous and well managed urban network measuring at top of UCL as the Climate Network®, the added uncertainty on long term hourly temperature averages due mainly to exposure effects may be estimated to have an upper limit of about 1°C. We note that this is much less than the estimated 5°C uncertainty indicated by WMO Guide No. 8, but still significantly larger than the thermometer calibration uncertainty of 0.2 °C. It is obviously related to the constraints of the always difficult meteorological urban measurements: anyway, it could and should be reduced by careful siting and exposure choices, or at least clearly estimated and indicated for special meteorological stations for which better siting and exposure solutions could not be found.

This first result represents a start point for specific case studies and further methodological investigations, encouraging a well based evaluation of uncertainty upper limits in specialized urban meteorological observations and suggesting the possibility of their classification in a more suitable way than as stated in WMO CIMO Guide N. 8. A similar work is in progress for humidity and such analysis will be extended to other relevant meteorological variables in the near future.

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