The AWS based operational urban network in Milano: achievements and open questions.

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Abstract

After almost 5 years continuous operation, Climate Network® (hereafter shortly CN), owned by Fondazione Osservatorio Meteorologico Milano Duomo (Fondazione OMD), represents a successful example of an urban meteorological network for energy application and climate services. Carefully planned with the best possible fulfilment of generally accepted siting and exposure criteria for urban weather stations, detailed and frequently updated metadata, strict requirements of sensor calibration procedures with some duplication (sensors of different type at the same site, as for temperature and precipitation), affordable management and maintenance and multilevel data validation, the network is routinely providing affordable and reliable high quality observational data in the Urban Canopy Layer at a high temporal and spatial resolution. Gradual transition from previous traditional stations in town and also related to the 250 years long Milano meteorological series allows correct measurement continuity, essential for climatological purposes. Furthermore, the already available dataset is a valuable starting point for a complete evaluation of critical aspects in station siting and sensor exposure. Based on a carefully selected data subset, an estimation of field measurement uncertainties in the complex urban environment has been obtained partially in the framework of MeteoMet Project (EURAMET). In this paper characteristics and operational procedures of Climate Network are reviewed and specific experiences discussed especially in relation to internal calibration procedures and to siting and exposure uncertainties for temperature and humidity, with some suggestions for an improved classification of urban automatic stations and an outline of further developments.

1. Introduction

Meteorological measurements in cities are much more challenging than synoptic or meso-synoptic ones because of the strongly inhomogeneous urban environment, mainly due to irregularly distributed buildings of different characteristics producing a number of relevant small-scale effects, which severely restrict their representativeness (Oke, 2007). Nevertheless, urban weather and climate monitoring is more and more important because of the rapidly growing worldwide conurbation with an estimated 55% of the world population living in urban settlements (UN, 2016), and for different applications in many sectors as, for instance, human health and wellness, energy and emergency management and urban planning. Consequently, in more or less recent times several cities developed urban meteorological networks (Muller et al., 2013), sometimes only for experimental campaigns but in other cases also for operational use.
At the same time, meteorological modelling is rapidly improving in resolution as well as in the capacity of describing complex boundary layers, and specific modules have been specifically developed to deal with built-up urban environments (Barlow, 2014). Assimilation of urban meteorological observational data becomes then an unavoidable necessity, but it requires a sound knowledge of the measured data characteristics, as spatial representativeness and measure uncertainties, which are often critical.

Continuing and expanding the experience of the city meteorological observatory, related to the historical meteorological series in Milano dating back to 1773 (Camuffo et al., 2002; Maugeri et al, 2002), Fondazione Osservatorio Meteorologico Milano Duomo manages (on strict concepts of homogeneity, traceability and integration for operational applications and easy management) a unique Italian urban meteorological network based on Automatic Weather Stations (AWS) that was planned and deployed since 2011 by Climate Consulting srl for urban energy and other applications (Borghi et al., 2014; Paganelli et al., 2013; Curci et al.: 2014). The Climate Network® has a nationwide distribution, but has in Milano the largest number of installed and operating stations: this paper aims to describe the network technical characteristics and its operational procedures and to discuss the experience gained in almost 5 years of continuous operation in Milano, especially about data quality and uncertainties due to station siting and sensor exposure (Curci et al., 2017). Final considerations are also drawn about the opportunity to introduce a sub classification for urban stations, to improve the scheme described in the CIMO Guide (WMO, 2014).

2. Climate Network®: a new Italian urban network

Climate Network® (CN) is a private professional network of Automatic Weather Stations (AWS) in Italy, currently accounting for almost 50 stations located in the main Italian cities (Figure 1). The network can be considered the technological evolution of the urban historical climate observatories, whose weather stations had been located on top of buildings, and it contributes to the continuity of urban historical climatology series. CN also 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 performances of thermal plants and air conditioning systems.
It was planned in 2010 to meet the following requirements:

a) strict siting homogeneity at national level;
b) local scale representativeness for all weather variables;
c) continuity with past weather observations;
d) no connection to power supply and internet network (e.g. constraints to siting);
e) last generation sensors;
f) easy maintenance in the urban context;
g) Quality Assurance and Quality Control (QA/QC) according to international standard procedures (to supply traceable, accurate, precise measures);
h) maintenance and management according to UNI EN ISO 9001;
i) data validation, storage, processing for derived quantities, and delivery of data reports to users in a integrated system (ad hoc designed software);
j) 10 minutes data availability and transmission daily and on request.

The AWSs are solar powered and communicate with the data centre through GSM modems (point d). In this way there are less constraints for positioning the weather stations, all of which are located at the mean building top level in order to correctly represent the top Urban Canopy Layer (UCL). Top UCL site selection allows to assess the city's climate without being influenced by very local situations but taking into account a sum of them. Measuring at top building level (open rooftop terraces, with no physical obstacles around and suitable pavements) is the result of fulfilling requirements of strict siting homogeneity at national level, local scale representativeness for all weather variables, continuity with past weather observations and easy maintenance in the urban context (points a, b, c, f).

Figure 1: Climate Network weather stations (50 AWS). Urban metropolitan networks: Milano (20 stations), Firenze (2 stations), Roma (2 stations).

CN weather stations consist of the same last generation sensors (multi-parameter sensor: Vaisala WXT520), compact and easy to use, without moving parts, ensuring more reliable measures. In every CN station (Figure 2), there is also a redundant temperature sensor (PT100) as a check of the WXT520 thermometer, being temperature the most relevant variable for the network usual applications (points e, f). Each station measures temperature, relative humidity, atmospheric pressure, wind speed and direction - gust included (ultrasonic bi-axial sensor), rain and hail (amount, intensity and duration). Some stations measure solar global and diffuse radiation too.

The compact sensor and redundant thermometer, together with solar panel, battery pack and data logger (Campbell CR800) - modem system, are mounted on enough tall masts (2-4 m).

Daily remote sensors control, data acquisition, validation and archiving are performed by both automatic procedures and experienced meteorologists by means of a specially designed software (named Datamet). Remote control and data transmission could be performed on request too. CN database contains 10 minutes data for each meteorological variable (10 minutes mean, max, min are calculated locally by station data loggers), then aggregated into hourly and daily values in the Data Base. Datamet processes also derived quantities, such as Degree Day or weather data of "virtual" stations (according to tri-dimensional interpolation formula entered by meteorologists case by case). This software also arrange for daily automatic transmission of data reports to users (points i, j).

Figure 2: Some typical CN weather stations in Milano (left), Roma (centre) and Taranto (right).

Thanks to all the features of the network, it is possible to compare different local data, having the confidence of a documented homogeneity of all stations.

3. Operational procedures

Climate Network is entirely managed by Fondazione OMD: once a year, following a scheduled turn-over, every WXT operating for CN is replaced with another WXT previously cleaned and calibrated. This rotation is achievable thanks to the same type sensor installed in every CN station and thanks to the same calibration chain which all WXTs are subject to.

Once per year, every AWS is routinely maintained: the transmitter is disassembled, cleaned and painted with white car paints in case of yellowing of the shelters, in order to avoid a drift in recorded temperature values due to the ageing of the station (Lopardo et al, 2014).

All ordinary and extraordinary maintenance activities (e.g. in the event of damages or anomalies occurred in CN station) are recorded on a dedicated "maintenance database" which contains the past history of every WXT and of each CN station.

Once cleaned, every WXT is calibrated in a climatic chamber, owned by Fondazione OMD, following a strict and defined calibration chain. WXT is a digital sensor, so we don't need to calibrate the sensor together with its datalogger. The calibration process was studied and developed in accordance with UNI EN ISO 9001:2000, a quality management system.

The temperature calibration procedure is carried out in a special climatic chamber using a Secondary Reference Platinum Resistance Thermometer (Fluke 5616), as first line standard, and three Resistance Thermometers (PT100 ohm in Class A according to IEC 751), as transfer standards. The first line standard is periodically (every 5 years) calibrated at a National Institute of Metrology (e.g. INRIM, the National Institute of Metrology in Turin or LMK, Slovenian Institute of Metrology).

The second line standards are calibrated (every year) with the Platinum Resistance Thermometer using a copper block as temperature comparator. Finally, the WXT is calibrated in the climatic chamber, placing it close to the three PT100 (Figure 3).

The WXT is not directly compared with the first line standard: three reference sensors placed around the weather station could be able to better detect temperature differences occurring around the WXT within the climatic chamber.
The calibration range is between −20°C and +50°C, with 10°C steps. The entire calibration procedure is automatically handled by a personal computer, using a specially designed Labview tool. In this way, the calibration process is standardized and the error due to the operator is minimized. The calibration curve obtained is interpolated with a polynomial second degree function. Their coefficients are inserted into the AWS acquisition software to correct the measured data.
At each calibration process, a specialized register is compiled with the following information: WXT serial number, calibration coefficients, and estimated uncertainty curve. In addition, the operating parameters of the climatic chamber, and temperature and pressure conditions of the room containing the climatic chamber are registered: in case of extreme conditions, the climatic chamber could not work properly, causing some errors or anomalies in the calibration procedure.
The datalogger corrects the raw WXT data with the calibration parameters and provides 10 minutes averages transmitted via GSM to the DataMet server. Each 10-minute record therefore contains time stamp, WXT serial number, and also the parameters of the calibration correction curve used. This ensures total traceability of the data for a possible back-correction (for further details see Poster P3_10).

Figure 3: Fondazione OMD Climatic chamber (left), and WXT520 Calibration using three PT100 as transfer standards (right).

4. Measurement representativeness

It is well known that urban measurements are strongly affected by the complex environment. As any other meteorological measurement their representativeness is first of all a question of spatial scale, where usually the environment roughness is taken as an important indicator (Davenport et al. 2000; WMO, 2014). On the other hand, more specific factors as the 3-dimensional structure of the Urban Boundary Layer (UBL) and some typical urban phenomenon as the Urban Heat Island (UHI) must be taken into account in evaluating urban meteorological data. Therefore, it is not meaningful to measure meteorological variables in cities without an exact definition of the specific application: measurements at ground level in street canyons are important for air quality aspects, but cannot be directly compared with

others taken in large urban green areas or at building top heights. This is a typical problem of station siting, which is strongly dependent on the scope of the measuring network and is also affected by UHI. Furthermore, very local effects as radiation from heated walls or roofs, shielding effects by nearby buildings and similar ones must be reduced to a minimum by a correct choice of the exact position of the AWS or of the individual sensors: the last one is the problem of correct sensor exposure. Only if station siting and sensor exposure are correctly and homogeneously chosen, urban measurements could be considered representative of a definite urban area and of one specific aspect of the urban atmosphere.
In line with goals of our monitoring network, CN stations have been placed mainly on building tops, with the most possible attention paid to both siting and exposure and with the main criterion of homogeneity, as explained in section 2. On the base of this careful project, Climate Network can be considered to measure consistently the part of the UBL at the mean building top height and being therefore representative of the Urban Canopy Layer. Differences among stations are then caused primarily by the horizontal variations produced by the urban environment on the mean meteorological fields (controlled by greater synoptic or meso-synoptic scales) and secondary by more local effects induced by the urban structure. One typical phenomenon to be studied by this type of network is namely the UHI: in Figure 4 is represented, as example, an UHI episode, measured by CN in Milano. Intensity and structure of UHI are clearly visible both in the afternoon and during the night.

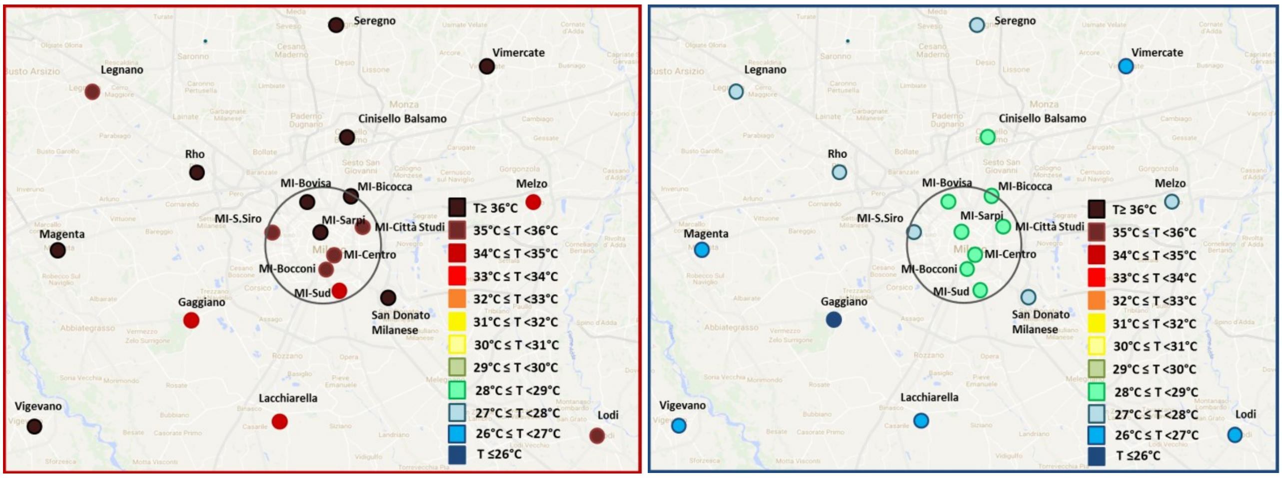

Figure 4: Urban Heat Island (UHI) in Milano as observed by CN. On the left: 03 August 2017, 17:00-18:00; on the right: 04 August 2017, 02:00-03:00.

5. Measure uncertainties

One other important aspect in measurement theory is the uncertainty associated to the value: it is essential for climatology purposes. Considering the good and homogenous characteristics of the CN in Milano, used as a test-bed, the uncertainty associated with urban measurements has been investigated in the framework of the EURAMET-MeteoMet (Merlone et al., 2015). A method has been developed to obtain a better uncertainty estimate for temperature (Curci et al., 2017), which is based on:

- the mean differences of hourly data measured in respect to a suitable reference for very homogeneously sited stations (only the 8 inner stations of the Milano metropolitan network, in a radius of about 7 km from city centre, were used);

- well selected weather situations, when horizontal gradients due to larger scale effects (synoptic and meso-synoptic ones), and to UHI effects are reduced to a minimum.

This method is valid only for a very homogenous network measuring the UCL at top building height. The analysis has been extended more recently to measures of relative humidity: the results are qualitatively similar to temperature ones. The results for both variables are summarized in Table 1 for each CN station downtown Milano at a coverage factor k=2 (2σ or 95% confidence level). An upper limit of about 1°C for temperature and of about 7% for relative humidity are found from a selected subset of data obtained by CN in almost 5 years of continuous operation. For temperature the result is significantly larger than the calibration uncertainty of about 0.2°C (Curci et al., 2011), but well under the maximum uncertainty of 5°C stated for urban stations in the CIMO Guide classification (WMO, 2014). For insights on the results, and specifically for daily and seasonal trends, refer to Curci et al, 2017.

$U_{exp\ (k=2)}$	MI Sud	MI Centro	MI Bovisa	MI Bicocca	MI Sempione	MI S.Siro	MI Città Studi	MI Bocconi
T [°C]	0.7	0.3	1.0	0.9	0.8	0.9	0.7	0.3
UR [%]	5.0	2.0	6.6	5.9	4.6	4.2	5.6	2.0

Table 1: Added measurement uncertainties for temperature and relative humidity (at coverage factor k=2, or 2σ or 95% confidence level) of CN AWSs in Milano, due to the combined effect of station siting and (mainly) sensor exposure.

In order to better understand the effects of siting and exposure, uncertainties obtained were studied in term of stations metadata. For each CN station, an extended metadata set was established since the early set-up, similar to the Birmingham network (Muller et al, 2013; Chapman et al, 2015), including mapping and photographic documentation of siting at different scales, detailed measurements of sensor exposure and albedo measurements of the underlying surface, as shown in Figure 5.

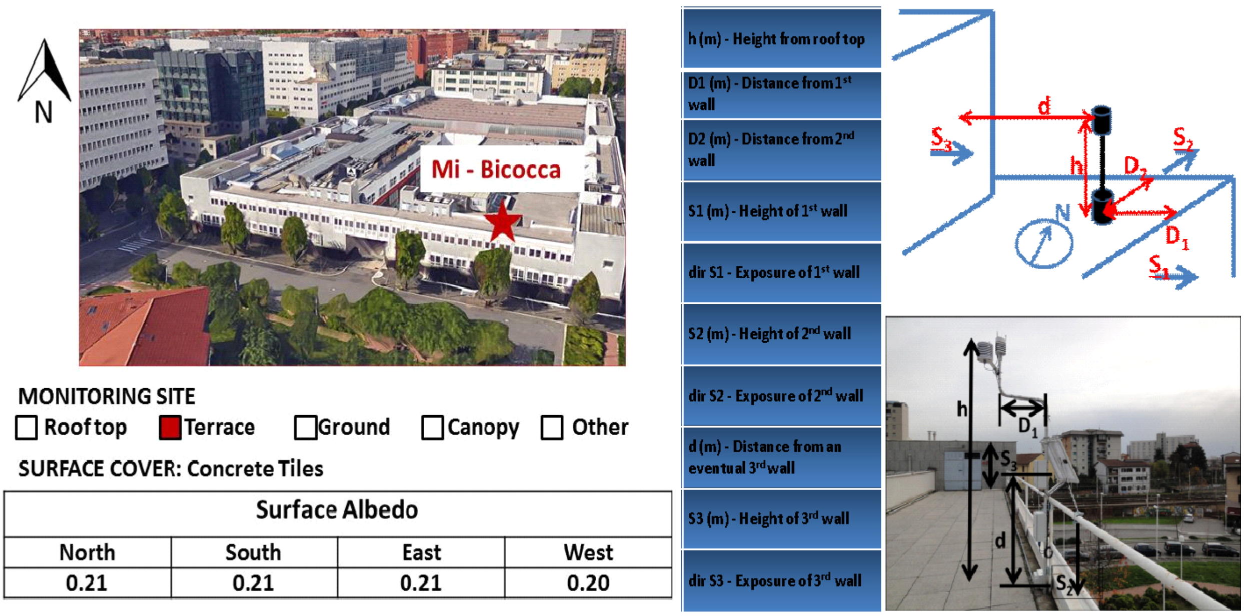

Figure 5: Extended metadata for MI Bicocca, with albedo measurements of the underlying surface.

The lowest uncertainties are obtained for MI Centro and MI Bocconi and they are supported by metadata similarity, especially concerning sensor exposure and environmental characteristics. Both of the stations are located in the centre of a terrace, with same albedo values of the underlying surface.
Differently, MI Bovisa and MI Bicocca stations showed larger uncertainties values, due to the particular exposure of the two stations. Both AWSs are sited on the edge of a terrace at South. During the day the underlying wall is directly irradiated by the sun (Figure 6), thus inducing an upward flow of warm air that reaches sensors.

Figure 6: Upward flow of warm air from underlying wall in MI Bovisa station

6. Conclusions

The Italian urban Climate Network® has been described in its technical and procedural characteristics, based on homogeneous AWSs, strict metrological criteria and the best possible fulfilment of WMO specifications for meteorological urban measurements.
Continuous and regular operation, maintenance and data validation, detailed and quantitative metadata are further key strengths of CN, which contribute to create a high quality meteorological database. Climatology series are the CN finale goal. The network, especially its Milano sector, is a useful and reliable tool to describe the complex UCL and the urban induced meteorological phenomena, first of all the UHI.
CN has been recently used also to investigate (in the framework of the EURAMET-MeteoMet Project: Metrology for Meteorology) the added uncertainties due to specific station siting and different sensor exposures in a typically very inhomogeneous urban environment. The results obtained in almost 5 years of continuous operation in downtown Milano set upper uncertainty limits well under the maximum added uncertainty estimated by WMO for urban measurements: 1°C instead of 5°C for temperature, and less than 7% for relative humidity.
These encouraging results and the experience gained during CN operation represent a valid start point toward the definition of an urban meteorological reference automatic weather station. Furthermore, they demonstrate the necessity of a classification of urban stations and networks based on their specific targets, to avoid using inhomogeneous data in applications (i.e. modelling), where uncertainties must be known and kept to a minimum.
Current CN development is related to data transmission, from GSM System to GPRS. All raw data will be sent directly to the server, where they will be analysed (data processing will no longer be at station level in the datalogger) and users could be have data in near real time.

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