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Climatological analysis of the mitigating effect of vegetation on the urban heat island of Milan, Italy

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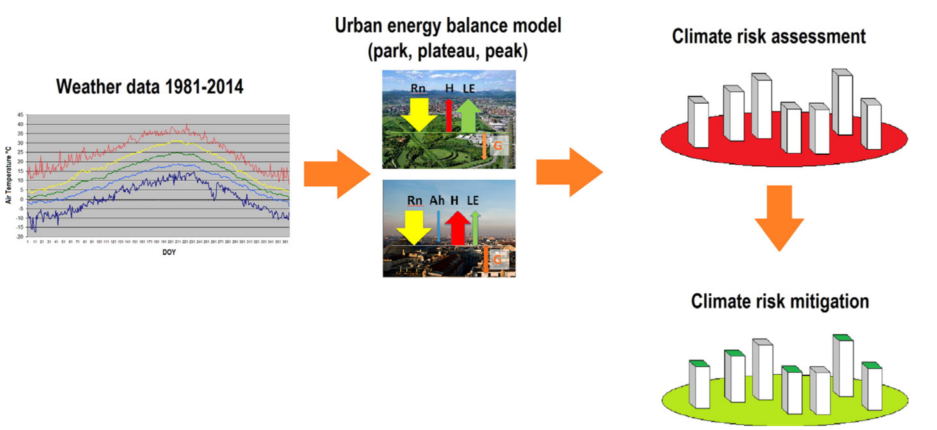
HIGHLIGHTS

- A surface energy balance (SEB) was applied to model the urban heat island of Milan
- Three different levels of UHI impact were considered (urban park, urban plateau, urban peak)
- Three different levels of green management were considered
- The maximum mitigation of UHI was provided by tree shade but irrigation is also effective.
- The SEB approach provide support to evaluate the effect of wide set alternative urban design and green management options.

GRAPHICAL ABSTRACT



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ABSTRACT

The urban heat island (UHI) of Milan (Italy) was analyzed by means of an Energy Balance Model calibrated for four different sites representative of an urban park, the UHI plateau and the UHI peak of the selected town. The model was driven by weather stations data and parameterized as a function of land use, urban morphology, human activities and soil hydrology. A run of the model on the 1981–2014 period was carried out on four hourly datasets. Results provided useful statistics of energy balance terms and the climate risk of extreme thermal events (sensible heat fraction of the total turbulent flux H% exceeding specific thresholds). Results for summer (June–August trimester) show that the mitigation of climate risk of high values of H% given by the urban park is more effective for June than for July and August. We also discuss the relevance of enhanced soil water reservoirs in urban green areas to improve the mitigating effect of urban vegetation on UHI by both the substitution of sensible heat fluxes with latent heat ones and the increase of the shading effect of tree canopies.

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1. Introduction

The urban heat island (UHI) is the result of the significant impact of urbanization (Stewart and Oke, 2012) on surface energy balance (SEB) variables (Geiger et al., 2009; Oke, 2002; Stull, 1997). The primary cause of the UHI phenomenon is the characteristic partitioning between the H flux and LE flux of the total turbulent flux (TTF) (Shashua-Bar et al., 2009). In fact, in urban areas with little moisture available for evapotranspiration H clearly dominates over LE and warms the air near the surface. Consequently, the reduction of H in favor of LE is considered one of the key strategies for mitigating the UHI effect (European Commission, 2015). The analysis of TTF partitioning into H and LE can be accomplished using the latent fraction of the TTF, often referred to as evaporative fraction (EF) (Guillod et al., 2014), or sensible fraction (SF), which is the complement to 1 of EF. Although the SF ratio is similar to the H/LE Bowen ratio (Bowen, 1926; Lewis, 1995), it does not tend toward infinity in the way that LE reaches zero. This problem is quite common in urban microclimates or in arid areas. In mid-latitudes, the partitioning of TTF into H and LE is subject to strong inter-annual variability, which is the result of changes in the frequency and persistence of different weather patterns. For this reason it is important to analyze a time period that is compatible with the period (i.e., last three decades) specified by the World Meteorological Organization (2011) as representative of the climatological standard. Such a time-frame would provide an indication of the current climate within a given site or territory (Arguez et al., 2012).

The UHI phenomenon has been generally assessed by measuring the air temperature in selected sites (Oke, 2002; Geiger et al., 2009) or by using mobile thermometers (e.g., for Brno, Czeck Republic, see Dobrovolný and Krahula, 2015), remote sensing (e.g., for Basel, Switzerland, see Parlow et al., 2014), and by direct measurements of energy balance terms (e.g., for Basel see Christen and Vogt, 2004).

Many authors have addressed the UHI phenomenon using empirical models. For example, Landsberg (1981) described UHI intensity in relation to city diameter and population, while Morabito et al. (2016) described the UHI of some Italian cities in relation to built-up surfaces. Furthermore, Mihalakakou et al. (2004) investigated the UHI of Athens by simulating meteorological variables within a neural network. Other authors (Grimmond, 1992; Kawai et al., 2007) described the UHI in a mechanistic way by means of SEB models founded on the law of energy conservation applied to surfaces affected by the four main fluxes of net radiation (Rn), sensible heat (H), latent heat (LE), and ground heat (G). Grimmond et al. (2010) reviewed the SEB approaches in the context of the International Urban Energy Balance Models Comparison Project. SEB models are also useful for providing a quantitative assessment of the effects of green areas and urban parks on UHI (Parisi et al., 2013). For example, Bowler et al. (2010) observed the urban greening effects on UHI in different macroclimates, and Mirzaei (2015) analyzed the impact of different urban-scale policies on UHI adopting SEB models working at different scales.

A SEB approach was also applied in our study that investigated long time series of atmospheric data with the following objectives: (1) to describe the behavior of the SEB in the city of Milan with reference to typical urban environments, specifically urban parks, UHI plateaus and areas registering UHI peaks; (2) to establish a climatology of the frequency distribution of the SF index to describe the characteristics of the urban settings in point 1; and (3) to shed light on the likely occurrence of extreme events that are typically associated with summer heat waves in terms of H predominance in the turbulent exchange processes between surface and atmosphere.

From a more general perspective, the results of this study are intended to provide useful information to guide the management of urban green areas with the aim to mitigate the UHI and increase attractiveness for citizens.

2. The case study and the selected approach

The metropolitan area of Milan is located in the upper plain of the Po river and is characterized by a humid subtropical climate (type Cfa; see Koeppen and Geiger, 1936) with cold winters, hot summers and summer drought conditions mitigated by significant thunderstorm activity. The city and entire metropolitan area boast one of the highest economic outputs in Europe, promoted by continual urban expansion, which enhances the UHI effect.

The history of Milan's urban parks is closely related to that of the city itself. Sempione Park was constructed at the end of the 19th century on a military area surrounding Sforzesco Castle. Pallavicino Park and Don Giussani Park were constructed in the 1930s on areas formerly occupied by the railway station of Scalo Sempione, while Monte Stella Park was built in the suburban area used as storage for city ruins after the World War II bombings. Parco Nord Milano (PNAR) (Marziliano et al., 2001; Sanesi et al., 2007; Sanesi et al., 2016) was developed on the former military airport and Breda factory brownfield areas.

Among previous studies that have investigated the UHI effect, worth mentioning is the work by Bacci and Maugeri (1992), in which the UHI was addressed by analyzing different time series and by comparing the Milan Brera observatory (Buffoni et al., 1996) with Milan airport and other European and Northern Hemispheric series. The modeling approach by Borghi et al. (2000) applied the urban canopy layer model developed by Mills (1997) to Milan and its hinterland to describe UHI behavior in relation to different radiative and dynamic forcings. More recently, Poli et al. (2009) analyzed the impact of Milan's UHI on the energy demand of buildings, and Pichierri et al. (2012) obtained a phenomenological description of Milan's UHI by means of MODIS data from Terra and Aqua satellites.

We assessed UHI behavior by calibrating an hourly energy balance using data collected by weather stations and parameterized them as a function of land use, urban morphology, and soil hydrology, based on soil moisture and remote sensing data. The SEB model was applied to a long time series of weather data (1981–2014) for five sites of the metropolitan area of Milan that represent different UHI intensities to highlight the effects of different urban microclimates on SEB components. An analysis was conducted on the mitigating effect of urban vegetation on the UHI due to both the substitution of the H flux with LE and the increase of the shade effect caused by increased tree canopy cover. In this context, the key role of large soil water reservoirs to ensure temporal continuity of the mitigating effect was also highlighted.

3. Data and methods

3.1. Surface measurements and methods for data reconstruction

Although a number of studies have quantified the impact of urban structures and patterns on the UHI effect (Hamada et al., 2013), a systematic characterization of the UHI in time and space is difficult to obtain, since each urban area is a collection of microclimates and is prone to rapid and influential transformation processes. In this context, a useful theoretical approach would be to subdivide concentric urban belts (from the city center toward the suburbs and rural areas), which are homogeneous in terms of UHI (Oke, 2002; Stewart and Oke, 2012). However, a limitation of this approach is the variability of urban texture, which is often enhanced by the presence of urban green areas and parks creating consistent discontinuities in the urban network (Lafortezza et al., 2009). To overcome this limitation, a taxonomic approach based on Local Climate Zones was recently proposed by Stewart and Oke (2012). Following the approach laid out by Oke (2002), Milan's UHI can be ideally subdivided into the following concentric belts: (1) an outer rural area, affected only marginally by the UHI's urban plume advected from the city; (2) a peripheral area