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Interdecadal variations and trends of the Urban Heat Island in Athens (Greece) and its response to heat waves

D. Founda [a,*], F. Pierros [a], M. Petrakis [a], C. Zerefos [b]

[a] National Observatory of Athens, Institute for Environmental Research and Sustainable Development, P. Penteli, Athens, GR-15236, Greece
[b] Research Center for Atmospheric Physics and Climatology, Academy of Athens, Athens, Greece

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ABSTRACT

The study explores the interdecadal and seasonal variability of the urban heat island (UHI) intensity in the city of Athens. Daily air temperature data from a set of urban and surrounding non urban stations over the period 1970–2004 were used. Nighttime and daytime heat island revealed different characteristics as regards the mean amplitude, seasonal variability and temporal variation and trends. The difference of the annual mean air temperature between urban and rural stations exhibited a progressive statistically significant increase over the studied period, with rates equal to + 0.2 °C/decade. A gradual and constant increase of the daytime UHI intensity was detected, in contrast to the nighttime UHI intensity which increases only in summer, after the mid 1980s. UHI phenomenon was found to be related to higher increasing rates of hot days frequency at the urban stations. It was found that the interaction between heat waves and heat island in Athens, results to pronounced amplification of nocturnal UHI intensity under exceptionally hot weather.

1. Introduction

Urbanization of an area includes developments of different types such as commercial, residential, industrial and others. Urban structures increase air temperature at urban environment in comparison to surrounding less urbanized areas, by consuming and re-radiating solar radiation The phenomenon is known as the urban heat island (UHI) and is quantified through the difference of the air temperature between urban and surrounding rural/suburban environment (Oke, 1973; Roth, 2007). The extra warmth of built-up environments is actually the result of processes related to surface energy balance such as the exchange of short and long wave radiation but also latent, sensible and conductive heat flows. Urban surfaces such as dark asphalt roads and rooftops have a lower albedo than natural ones and absorb efficiently short wave radiation during daytime. But reduced sky view at street level in cities impedes cooling through long wave radiative processes. Moreover, high heat capacities of urban surfaces result to heat storage and release during nighttime. The urban geometry decelerates wind and reduces ventilation and urban heat cooling. Latent heat cooling is also reduced in urban areas through the reduction of evapotranspiration compared to areas with vegetation or natural soil.

Anthropogenic heat emission through human activities in the city (e.g. exhaust gases from traffic, heating and cooling of buildings, human metabolism) has been also considered as a major factor impacting urban heat islands in developed countries (Ohashi et al., 2007) while atmospheric pollution (e.g. aerosols) can not only reduce incoming solar radiation but also reduce radiative cooling due to elevated levels of carbon dioxide (Blake et al., 2011).

The magnitude of the UHI intensity is determined by many factors and exhibits pronounced variability with the type of climate (latitude, longitude, elevation, proximity to the sea), the meteorological conditions (cloud cover, wind speed, near surface temperature lapse rate), the season, time of the day, but also the geometry, morphology and size of a city (Goldreich, 1984; Chow and Roth, 2006; Camilloni and Barrucand, 2012). But quite local conditions can also affect the magnitude of UHI. Local and microscale are believed to be more important than mesoscale (size of a city) in the determination of UHI (Peterson, 2003).

UHI phenomenon is documented in many cities of the world, however, distinct differences are reported between UHIs of cities in temperate and tropical or subtropical regions. Such differences concern mainly the magnitude of UHI (which is in general larger in temperate regions) but also the time of occurrence of the maximum UHI intensity (Chow and Roth, 2006). The reason why the maximum UHI intensity appears during daytime or nighttime (or during winter or summer) is mainly determined by the thermal balance of the city, related to solar radiation, albedo of surfaces, anthropogenic heat release, latent and sensible heat release and storage and heat advection. For instance, in warm and very humid climates, the heat which is stored in the humid soil during the day dampens the cooling during night. Cities with high population density and increased human activities experience higher UHI intensity during daytime.

* Corresponding author.
E-mail address: founda@noa.gr (D. Founda).

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It is reported that heat island intensity at several European and Mediterranean cities is more important at night and varies between 1.5 °C and 12 °C, while in other cities (e.g. Athens and Parma) maximum of heat island intensities occur during the day (Santamouris, 2007). Other cities experience higher UHI intensity in summer (e.g. Rome, Madrid) and others in winter (e.g. Lisbon). Giannaros and Melas (2012) report higher UHI intensity during the night and during the warm period of the year at Thessaloniki (Greece). Maximum intensity of the daytime UHI in summer is reported in other non European cities with subtropical or tropical climate, e.g. in Shanghai (Tan et al., 2010), Muscat (Charabi and Bakhit, 2011) as well as in large cities of Korea (Kim and Baik, 2004). It is concluded that reported UHI varies considerably by existing studies in terms of its maximum intensity and season/time of occurrence. In addition to the aforementioned reasons related to different climatic features and thermal balance of the cities, other reasons such as the application of different monitoring protocols or the selection of reference stations could largely influence UHI estimations. UHIs estimated from standard fixed stations can be very different from those derived from non standard fixed stations or mobile traverses. Oke (2009) stresses the need for the adoption of common protocols in urban heat island (UHI) research and its use in applied climatology. Strict attention to issues of scale, experimental design, site classification, instrument exposure and metadata are believed to greatly improve UHI studies.

Although most research studies concern the spatial distribution of UHI, a few studies focus on the temporal variability of UHI intensity over long periods (e.g. Camilloni and Barrucand (2012) for Buenos Aires, Lee (1992) and Wilby (2003) for London). The knowledge of the temporal variability and trends of UHI intensity is very important in climatic change studies, since urban effect has an additive effect on long term air temperature trends. This is usually the case of historical stations which are traditionally located in urban areas (Stone, 2007; Parker, 2010). It must be stressed however, that the multiyear variability of UHI intensity is very sensitive to the history of reference station, since many rural or suburban stations have experienced urbanization over time and exhibit warming trends as well.

Stone (2007) reports that UHI intensity has increased on average by 0.05 °C/decade at large cities of USA from 1951–2000, with a clear division in the trends between northeastern and southern cities. Using historical air temperature data for New York, Gaffin et al. (2008) report that 33% of the observed warming in the city is attributed to UHI strengthening and 66% to regional/global warming. However, in other rapidly growing cities, the contribution of the UHI in the warming rates is much larger. Ren et al. (2007) report that up to 80% of the local warming in Beijing since 1961 might be due to UHI intensification. Although enhancement of UHI with time has been documented in cities with increasing urbanization, e.g. in Seoul, Korea (Kim and Baik, 2004), Camilloni and Barrucand (2012) found a negative trend in the nocturnal UHI at Buenos Aires over a 48-years period, despite the population growth in the city. According to another research study, daytime UHI in London has decreased over time and nighttime UHI has increased (Lee, 1992).

The reaction of the UHIs under extremely hot weather has also received some attention recently. Tan et al. (2010) report on the additive effect of UHIs on the frequency, intensity and duration of heat waves in Shanghai. Using a combination of observational and modeling analysis, Li and Bou-Zeid (2013) found a stronger impact in large cities under extremely hot weather and support the argument of a synergistic interaction between heat waves and urban heat island. It is also reported that the extreme heat wave of 2003 in central Europe, increased only nighttime UHI intensity in London (McGregor et al., 2006). Studying UHI in Bucharest from satellite data, Cheval et al. (2009) found that extreme high temperatures in July 2007 induced significant modifications of the features of the diurnal heat island, dissipating it in some spots, but enlarging it and creating shifting heat island in other spots. It is therefore concluded that the interaction between heat waves and UHI is not clear yet.

The present study focuses on the city of Athens, a large urban area of Eastern Mediterranean, which experiences regional warming but also urbanization effects (Founda, 2011).

As in other Mediterranean areas (e.g. Iberia) (Fernández-Montes et al., 2013), Athens experiences strong warming during the last decades (Founda et al., 2004; Founda, 2011). Based on the climatic archives of the National Observatory of Athens (NOA), located on a small hill in the center of the city, Founda (2011) reports warming rates of the order of 1 °C/decade since the mid 1970's, as regards the summer daily maximum air temperature (Tmax). Similar trends are also observed in the summer mean air temperature (Tmean) while summer daily minimum air temperature (Tmin) was found to increase at similar rates only after the mid 1980s. Warming in winter is not statistically significant. It is also notable that other stations in the city, e.g. the coastal station of Hellinikon (HEL) to the SW coast, experiences warming rates of the same order (+0.9 °C/decade in summer Tmax since the mid 1970s (Founda et al., 2013). The positive trend of the mean air temperature in Athens has been reported to be accompanied by a simultaneous increase in the frequency of hot days, but also in the frequency, duration and intensity of heat waves in the area (Founda et al., 2004; Theoharatos et al., 2010; Founda, 2011). The observed increase in Athens air temperature is possibly the combined effect of a regional warming in the area of Eastern Mediterranean and Greece and urbanization (Founda, 2011). Kostopoulou et al. (2014) report a warming rate of 0.4–0.5 °C/decade in many areas of Eastern Mediterranean and Nastos et al. (2011) report warming trends in most of Greek areas during summer.

Moreover, Regional Climate Models (RCMs) suggest a further air temperature increase in the area for the future, which varies by the selected model, scenario, assumptions and future period. Using the regional climate model PRECIS,based on the intermediate IPCC SRES scenario A1B, Lelieveld et al. (2012) found a continual, gradual and rather strong warming in the future for Eastern Mediterranean and Middle East. The mean air temperature is expected to be 1–3 °C higher in the near future (with respect to 1961–1990), 3–5 °C by mid century (2040–2069) and of about 3.5–7 °C by the end of the century (2070–2100). It is also noted that the projected warming of maximum daytime temperature was found to be more rapid in the Balkans and Turkey than in the south. Moreover, hot summer conditions that rarely occurred in the reference period may become the norm by the middle and the end of the 21st century (Founda and Giannakopoulos, 2009; Lelieveld et al., 2012).

Similarly, using an ensemble of nine RCMs based on A2 scenario, Zanis et al. (2009) report an increase of 3.4 °C in winter and 4.5 °C in summer over Greece by 2071–2100 (compared to 1961–1990), with increases being larger in continental areas.

The possible impact of the urban effect on the climate of Athens had been introduced at very early studies concerning air temperature trends in the city (e.g. Karapiperis, 1954). Katsoulis and Theoharatos (1985) estimated the magnitude of the nighttime UHI in Athens to be of the order of 2–3 °C, while other studies report that the urban effect on the climate of Athens is larger in the summer daytime air temperature (Philandras et al., 1999).

Numerous studies have shown now that the heat island is a very well documented phenomenon in Athens (Santamouris et al., 1999, 2001; Livada et al., 2002; Mihalakakou et al., 2002; Kassomenos and Katsoulis, 2006). The results however differ, depending on the selected sites, the season and the used method. Santamouris et al. (2001) report a pronounced intensity of UHI in Athens that can reach up to 10 °C between rural areas and the central zone of the city as regards the summer maximum temperature, while Livada et al. (2002) report a UHI intensity of 4–5 °C between urban and suburban areas. A dominant feature of UHI highlighted by most studies, is its local character, resulting to pronounced spatial variability of its intensity. Zoulia et al. (2008) report that the beneficial effect of a park in the center of Athens, disappears at a distance of just few meters outside the park.