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Numerical study of the urban heat island over Athens (Greece) with the WRF model

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HIGHLIGHTS

► The urban heat island in Athens, Greece, is studied with a meteorological model.
► The model shows a global satisfactory performance.
► The canopy-layer heat island is strongest during the night (up to 4 °C).
► The city surface is cooler than its surroundings during the day.
► The assimilation of skin temperature data slightly improves model performance.

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ABSTRACT

In this study, the Weather Research and Forecasting (WRF) model coupled with the Noah land surface model was tested over the city of Athens, Greece, during two selected days. Model results were compared against observations, revealing a satisfactory performance of the modeling system. According to the numerical simulation, the city of Athens exhibits higher air temperatures than its surroundings during the night (>4 °C), whereas the temperature contrast is less evident in early morning and mid-day hours. The minimum and maximum intensity of the canopy-layer heat island were found to occur in early morning and during the night, respectively. The simulations, in agreement with concurrent observations, showed that the intensity of the canopy-layer heat island has a typical diurnal cycle, characterized by high nighttime values, an abrupt decrease following sunrise, and an increase following sunset. The examination of the spatial patterns of the land surface temperature revealed the existence of a surface urban heat sink during the day. In the nighttime, the city surface temperature was found to be higher than its surroundings. Finally, a simple data assimilation algorithm for satellite-retrieved land surface temperature was evaluated. The ingestion of the land surface temperature data into the model resulted to a small reduction in the temperature bias, generally less than 0.2 °C, which was only evident during the first 4–5 h following the assimilation.

1. Introduction

Urbanization induces significant changes in land surface properties that, in turn, modify the surface energy balance. The well-documented urban heat island (UHI), characterized by the excess warmth of urban areas compared to the surrounding non-urbanized areas, is one prominent urban effect that influences air quality (e.g. Rosenfeld et al., 1998), energy consumption (e.g. Konopacki and Akbari, 2002), heat-related mortality (e.g. Conti et al., 2005) and local- and regional-scale atmospheric circulations (e.g. Miao et al., 2009). In addition, although heat islands in themselves do not influence global temperatures (Houghton et al., 2001), they do have an impact on local temperatures used for assessing climate change (Van Wevenberg et al., 2008).

Heat islands develop primarily due to differences in the surface energy budget (SEB) of urban and rural areas (Oke, 1982). During the day, urban areas store more heat than do rural areas due to the

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surface enlargement provided by canyon-like geometry and the thermal properties of urban fabric. Following sunset, urban and rural temperatures begin to diverge, generating the heat island in the canopy-layer. The rural environment starts cooling quickly after sunset due to its open exposure and generally unobstructed sky view. Conversely, the cooling rate of the urban environment is significantly reduced due to the decreased sky view factor and the increased release of storage heat from the urban surfaces (Grimmond and Oke, 1995). Normally, the canopy-layer heat island persists overnight, until shortly after sunrise the daily solar radiation cycle begins and the rural area starts warming quickly.

During the past few decades, significant progress has been recorded with regards to the understanding and modeling of the complex processes that take place in the urban boundary layer (UBL), contributing to the formation of the UHI (Martilli, 2007; Masson, 2006). The development of sophisticated atmospheric models along with experimental campaigns has contributed notably towards this direction. Especially during the past decade, several parameterizations have been proposed for representing the mesoscale impact of cities (e.g. Kanda et al., 2005; Kusaka et al., 2001; Liu et al., 2006; Martilli et al., 2003).

The representation of the UHI effect in mesoscale meteorological models is thought to be of great importance for the successful simulation of the urban boundary layer (UBL) and, consequently, air pollutants' dispersion and transport. This is because the thermodynamic properties of the UBL can be significantly modified by the UHI effect. For instance, Pal et al. (2012) recently showed that the spatio-temporal variability of the boundary layer over Paris, France, is closely related to the intensity of the UHI. Martilli et al. (2003) also concluded that the parameterization of the thermodynamic impact of cities, induced by the heat island formation mechanism, can significantly modify pollutants' distribution.

Land surface temperature (LST) lies at the heart of the SEB and is considered to be an important variable in meteorological models. It influences the sensible and latent heat fluxes, through which it affects the development of the UHI. Accurate LST specification is therefore significant for improving the accuracy of heat island simulations. In the past few years, satellite-retrieved LST data have been widely assimilated into weather and climate models to either improve the initialization of soil moisture (e.g. Lakshmi, 2000) or account for the overall model biases (e.g. Bosilovich et al., 2007).

Athens is the largest city of Greece, both in terms of population and area extend. Although the UHI in Athens is well documented since decades (Katsoulis, 1987), the number of relevant modeling studies is rather limited. Several meteorological studies over the greater Athens area (GAA) have been conducted in the past, but mostly focusing on either air quality (e.g. Kotroni et al., 1999; Moussiopoulos et al., 1995) or local-scale atmospheric circulations (e.g. Grossi et al., 2000; Melas et al., 1998a,b). Only the numerical studies of Martilli et al. (2003) and Dandou et al. (2005, 2009) focused on the urban effect of Athens, by incorporating explicitly modified boundary layer parameterizations.

In the summer of 2009, the THERMOPOLIS2009 campaign (Daglis et al., 2010b) took place in Athens. The campaign was funded by the European Space Agency (ESA) as part of the "Urban Heat Islands and Urban Thermography" (hereafter "the UHI project") Data User Element (DUE) project. One of the key objectives of the campaign was to combine concurrently acquired airborne, spaceborne and ground-based measurements to generate spectrally and geometrically representative datasets with the purpose to address the observational requirements of the UHI project (Daglis et al., 2010a). The spatially and temporarily rich observational dataset collected during THERMOPOLIS2009 provided us with a unique opportunity to implement and evaluate a mesoscale modeling system comprised of the numerical weather prediction (NWP) Weather Research and Forecasting (WRF) model coupled with the advanced Noah land surface model (LSM). The collected observational data were also exploited for evaluating a simple data assimilation scheme for satellite-retrieved LST data.

The present study aims to fill the gap of modeling studies focusing explicitly on the UHI effect, by combining numerical simulations and observations to investigate the spatio-temporal structure of Athens' heat island. The key objective is to examine the degree to which the WRF/Noah modeling system can capture the major features of the heat island phenomenon, which are of importance for a successful simulation of the UBL. Further, a simple data assimilation algorithm for LST is evaluated, focusing on the potential impact on air temperature simulation.

2. Data sources

2.1. Description of the study area

Athens (37°58′N, 23°43′E) is located in a small peninsula situated in the south-eastern end of the Greek mainland (Fig. 1a). The GAA covers about 450 km^2 and the urban zone sprawls across the central plain of a basin that is often referred to as the Attica Basin. The city is bound by Mount Aigaleo to the west, Mount Parnitha to the north, Mount Penteli to the north-east, Mount Hymettus to the east, and the Saronic Gulf to the south-west (Fig. 1b). The industrial zone of Athens is located in the western part of the basin (Thriassion Plain), while the Mesogeia Plain dominates in the south-east part of the peninsula (Fig. 1b).

2.2. THERMOPOLIS2009

During the period from July 15 to July 31, 2009, the THERMOPOLIS2009 campaign took place in Athens. In the frame of this campaign, a significant number of researchers and institutes were deployed in the GAA, conducting ground-based and airborne measurements. These measurements were scheduled to coincide with specific satellite overpasses (Daglis et al., 2010a,b). This section aims to describe only the part of the experimental campaign that is relevant to the present study; that is a subset of the ground-based and satellite remote sensing observations.

The locations of the ground-based measurement sites that were deployed during THERMOPOLIS2009 are shown in Fig. 1c. Table 1 summarizes the characteristics of each measurement site. Air temperature and relative humidity were measured by a network of stations operated by the Democritus University of Thrace (DUTH), the National Observatory of Athens (NOA), the Hellenic National Meteorological Service (HNMS) and the National and Technical University of Athens (NTUA).

Besides in situ observations, the campaign included remote sensing data from the Terra and Aqua satellites, both part of NASA's Earth Observing System (EOS). In particular, the campaign included data from MODIS (Moderate Resolution Imaging Spectroradiometer), a key instrument on board Terra and Aqua. MODIS has twenty infrared bands; however, only two of them are suitable for LST retrievals, namely bands 31 and 32 at 11.0 μm and 12.0 μm, respectively. The spatial resolution of these thermal infrared (TIR) bands is approximately 1 km. Two MODIS images were used for validating the model LST in this study: one acquired at 09:15 UTC and one at 20:20 UTC on July 25, 2009.

3. Numerical simulation setup and evaluation methods

3.1. Meteorological model configuration and physics

The meteorological model used in this study is the WRF-ARW (Advanced Research Weather), version 3.2 (Skamarock et al.,