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Evaluation of albedo enhancement to mitigate impacts of urban heat island in Rome (Italy) using WRF meteorological model

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ABSTRACT

The extreme effects of urban heat island (UHI) on energy consumption, air quality, and human health are significantly detrimental. Increasing the albedo of urban surfaces has been proposed as a potentially efficient mitigation strategy. In this study the Weather Research and Forecasting (WRF) mesoscale model has been used to simulate the urban climate of Rome (Italy).Four different scenarios have been analyzed: the Base Scenario as control case; the Base-ALB Scenario, in which the albedo of roof, walls and road have been increased; the Morph Scenario in which the morphology of urban area has been parameterized more accurately; the Morph-ALB Scenario in which the urban albedo of the improved model has been increased.

This study demonstrates that a more accurate parametrization of the urban morphology leads to a more accurate representation of UHI phenomenon. The simulation results show that albedo increase leads to the decrease of the 2-m air temperature at day-time and at night-time. Albedo increase offers very promising results in terms of UHI mitigation, reducing the temperature in the urban area by up to 4 °C at daytime and a little increased (up to 1 °C) in some locations at night time, compared to the control cases.

1. Introduction

Since 753 BCE (the year of the founding of Rome) the land-use and the land-cover has undergone substantial changes in the region where the city is located. Today, Rome is one of the largest and most populated cities in Italy and the human settlements have replaced rural, natural areas with urban, concrete areas. As proved by several researches, human-induced landscape changes have many impacts on local and regional-scale climate (Kaufmann et al., 2007; Golden, 2010; Morini, et al 2017a). The most documented effect linked to urbanization is the urban heat island (UHI) phenomenon, that characterizes the air above the urban canopy that is usually warmer than the air in the rural surroundings.

The UHI appears in almost every urban area, no matter whether the specific city is small or large, or whether it is situated in a warm or a cold climate (Stewart and Oke, 2012). One major effect of UHIs on human health is the increase of human discomfort because of urban heat stress. UHIs increased temperatures can potentially increase the magnitude and duration of heat waves within cities (Tan et al., 2010). The relationship between the heat island and “death island” has been introduced by Buechley et al. (1972) that found the mortality rate during a heat wave increases exponentially with the maximum temperature; an effect that is enhanced

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by the UHI. In summer 2003, the Local Health Authority of Rome assessed the negative impact of heat waves on mortality: 1094 excess deaths occurred during three major heat wave periods in 2003, an increase of 23% compared with the average annual number of deaths during 1995–2002 (Centers for Disease Control and Prevention, USA, 2004).

Discomfort situations that lead to the risks to human health and the increase in mortality have been discussed by Sakka et al. (2012). Indoor thermal field measurements showed how the heat wave emphasized by UHI made people exposed to hot spells above 33 °C for 6 days continuously, provoking not only low indoor comfort issues, but also increasing the risk of non-negligible health disease for the most vulnerable households (Sakka et al., 2012). To mitigate the mortality rate, (Rossi et al., 2015c) investigated integrated aspects of comfort conditions of people in urban public environments and proposed solutions to reduce the effect of UHI.

Several studies have assessed the impact of the UHI on other aspects such as energy consumption and air quality. Elevated temperatures in fact lead to an increase in energy demand for cooling. Akbari and Sezgen (1992) found that the increase of energy demand for summer cooling is increased by 1.5–2% each 0.54 °C of temperature. According to Santamouris (2016), energy consumption for cooling represents about 2.9% to 6.7% of the total world energy consumption to date. Energy consumption for cooling will increase in the near future for combination of many factors: the global climate change, the higher temperatures in the built-up environment due to the UHI, the expected population increase and the economic development. Many researches assess that in the future cooling energy demand of buildings will very likely become the dominant energy component. At the same time the increase of energy consumption will lead to a higher amount of energy production by fossil-fueled power plants (Akbari, 2005) and systems (Rossi et al., 2015b) which lead to higher emissions of heat-trapping greenhouse gases such as carbon dioxide, as well as other pollutants such as sulfur dioxide, carbon monoxide and particulate matter that in turn worsen the UHI phenomenon (Fallmann et al., 2016).

Since the extreme effects of this phenomenon are significantly detrimental, many researchers have been focusing on proposing solutions to weaken the phenomenon itself or the related causes. Several researches use meteorological simulation tools to understand and analyze the UHI, such as Weather Research and Forecasting (WRF) mesoscale model, incorporating the urban canopy model (UCM) to consider multi-reflections between urban surfaces and to estimate the energy budget of the canopy (Ramamurthy et al., 2015; Touchaei and Akbari, 2015; Kondo et al., 2005; Kusaka and Kimura, 2004a, 2004b; Kusaka et al., 2001). Urban canopy models (UCMs) account for the exchange of energy and momentum between the urban surface and the atmosphere. 1D, 2D, and 3D UCMs are available for WRF. 1D model considers buildings and streets as a roughness of the surface; 2D model considers one directional infinitely-long street canyons, delimited by lines of buildings of equal width; 3D models recognizes the three-dimensional nature of urban surfaces and the fact that buildings vertically distribute sources and sinks of heat, moisture, and momentum through the whole urban canopy layer (Chen et al., 2011). Urban trees, soils and short vegetation have also been integrated into the urban canyon by Wang et al. (2013) and Ryu et al. (2016), whose models allow the development of the urban heat island mitigation strategy of enhancing urban greening.

Another worthy of investigation and potentially efficient mitigation strategy that is also implemented in WRF UCMs is based on the increase of the average albedo of urban surfaces throughout highly reflective materials for roofs, pavements and walls (Rosenfeld et al., 1995, 1998; Akbari et al., 2016; Morini et al., 2016). Researchers have also introduced, studied and tested at local scale innovative high albedo solutions including thermochromic materials (Doulos et al., 2004), directional materials (Hooshangi et al., 2015) and retro-reflective materials (Rossi et al., 2015a, 2016; Morini et al, 2017b) for UHI reduction.

In this paper, the effect of increasing urban surfaces reflectivity in Rome is simulated by using Weather Research and Forecasting (WRF) mesoscale model. The model is used to reproduce the circulation in the urban area of Rome in Pichelli et al. (2014). The configuration that better reproduced the dynamics of the urban area is chosen as physics parameters in this work. A multi-layer UCM is coupled to the mesoscale model to better estimate the momentum, heat, and turbulent kinetic energy budget of the urban canopy.

The objective of the paper is twofold: 1) Quantify the effectiveness of albedo increase in the urban area of Rome to reduce UHI and 2) Quantify the sensitivity of urban energy model to urban parametrization. The first objective is to prove the effectiveness of UHI mitigation strategies, focusing in particular on urban albedo increase, that allows a decrease of absorbed heat by urban surfaces, and decreases the surfaces and air temperatures.

The second objective is to provide a realistic estimation of morphologic characteristics of the investigated urban area to represent more accurately the geometry of urban canopy in the UCM and thus the fluxes from urban area to the atmosphere in the simulation model.

For this purpose four different simulations were carried out during four cloudless summer days in Rome during summer 2013. The simulations start on the 2nd of August at 00:00. The first 12 h are considered as initialization time to allow the model to reach stability.

Four scenarios are implemented: the control case is the Base Scenario. Results from numerical simulations at the highest resolution domain (260 m) are compared to measurements in 9 weather stations that cover a large area inside and around the urban area of Rome to validate the model. Temperatures in some urban points are also compared to temperatures in rural points to quantify the relevance of the UHI in Rome during the simulated days. In the Base-ALB Scenario the countermeasure to UHI is adopted and the reflectivity of urban surfaces is increased. Results from this simulation allow to verify the effectiveness of albedo increase strategy for the UHI reduction. A more accurate urban parametrization is provided in the Morph Scenario, where data in UCM describe more accurately the morphologic characteristics of the urban area. In the Morph-ALB Scenario the reflectivity of urban surfaces is increased in the improved parametrization scheme.