Modeling the local urbanization effects on the temperature series of Uccle (Brussels, Belgium): a sensitivity study using the Town Energy Balance (TEB) scheme

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Abstract

This study analyzes impact of change in impervious surfaces in the Brussels Capital Region on trends in extreme temperatures between 1960 and 1999. Specifically, we combine data from remote sensing imagery and a land surface model (LSM) including state-of-the-art urban parameterization, the Town Energy Balance scheme. In order to isolate effects of urbanization on near surface temperature independent of atmospheric circulations, we run the LSM in a stand-alone mode coupled to downscaled ERA-40 reanalysis data. Model simulations show that annual mean urban bias (AMUB) on minimum temperature is rising at a higher rate than on maximum temperature, with a linear trend of 0.14°C and 0.05°C per decade respectively. The 40-year AMUB on mean temperature is estimated to be 0.62°C.

Key words: Urban heat island, temperature trend, urbanization

1. INTRODUCTION

The focus of our study is the Brussels Capital Region, centrally located in Belgium, with a size of 161.78 km^2 and a registered population of 1 031 215 on January 1st 2007, estimated by the National Institute of Statistics (INS). As in the majority of large European cities, it is only during the 19th century that the population strongly increased, exceeding 1 million inhabitants in 2004. This caused a rapid expansion of the capital during the last 150 yr. Compared to some other European capitals, Brussels is, however, a green city. In fact, according to an inventory made in 1999 by the Brussels Institute of Environmental Management (BIM) the city has 8563 hectares of green areas, which is 53% of the total area (Van de Voorde et al., 2008). The area covered by the BCR is quite circular with a diameter of 12 km and the effects of urbanization variability dominate the topographic influence (orography is beneath 150 m). The national recording station of the Royal Meteorological Institute (RMI) of Belgium [World Meteorological Organization (WMO) code 06447] is situated some 6 km south of the center of the capital, in the Uccle suburban, at 50.80°N and 04.35°E, at 104 m above sea level. The temperature time series has a long history, dating to 1833, and was homogenized for different sources of errors (Demarée et al., 2002) but not for urbanization of the station environment. The temperature time series of Uccle has always been used as a rural station, whereas it is actually one of those series suspected of being influenced by urban heat island (UHI) created by the surrounding growing urban areas.

2. EVOLUTION OF SURFACE COVER FRACTION

With the advent of remote sensing methodology, it has become possible to monitor local urban climate changes associated with land use changes over rapidly expanding urban areas like BCR. The evolution of surface cover fractions over the study region was derived from Vanhuysse et al. (2006) study. This study aims to assess the evolution of the fraction of impervious surfaces in the BCR since the 1950s date of the acceleration of urban growth linked to widespread use of car as a new mode of transport.

Figure 1 shows that the increase in impervious surfaces is very important since the 1950s, from 26% in 1955 to 47% in 2006, slightly a doubling. The largest increase (both in absolute and relative terms) occurs between 1955 and 1970. Then a slight decline in the upward trend is observed. Between 1985 and 1993, there was a decline in growth due to a crisis in the real estate market during the 1980s. After 1993, the increase in impervious surface becomes again very important, which remains until now. The results presented here reflect the reality but must be considered keeping in mind that different data information and methods were used, and therefore we should tolerate a margin of error of a few percent over the areas studied (Vanhuysse et al., 2006; Van de Voorde et al., 2008).

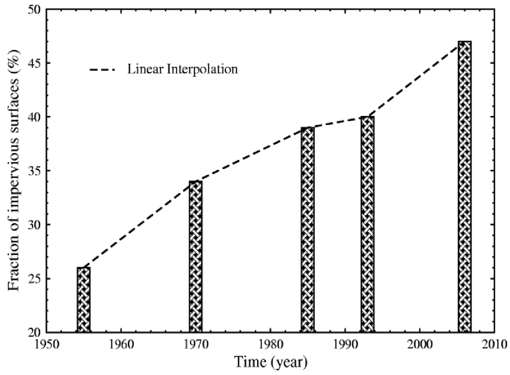

Figure 1: Evolution of the average percent imperviousness of the Brussels Capital Region from 1955 to 2006. Redrawn from Vanhuysse et al. (2006).

The expansion of the built-up area was found to be the main factor in long-term changes in air temperatures (Shouraseni and Fei, 2009). Therefore, in this study we will update previous research by analyzing the local impact of change in impervious surfaces in the BCR on long-term trends in extreme temperatures between 1960 and 1999. Specifically, we combine data from remote sensing imagery and the newly developed surface scheme of Météo-France SURFEX (SURFace Externalisée) (Martin et al., 2007) including the most advanced urban parameterization of Masson (2000), the Town Energy Balance (TEB) scheme. In the present study: (i) we use SURFEX in a stand-alone mode, coupled to downscaled ERA-40 reanalysis data, in order to isolate the local effects of urban growth on near surface temperature independent of atmospheric circulations, (ii) we consider BCR as a lumped urban volume with the underlying assumption that the entire BCR is composed of one homogeneous material comprised of uniform thermophysical properties, irrespective of spatial variability.

3. MODELING STRATEGY

We selected a small heterogeneous domain, (10 km x 10 km) over the BCR, centered at the city center of Brussels. We overlaid that domain over a 1-km resolution land cover classification provided by the ECOCLIMAP database (Masson et al., 2003). The land cover types contained in this domain are then aggregated into 4 tiles (Sea, Lake, Vegetation, and Urban) with the corresponding fractional coverage (0%, 0%, 53%, 47%) to be used as the contemporaneous land cover setting. We run the model in an offline single column mode from 1^{th} January 1950 to 31 December 1999 (40 years). This mode of running reduces errors due to the atmospheric forcing and makes it possible to run long term simulations. The forcing parameters necessary to run the model are derived from a downscaling of the ERA-40. The atmospheric data consist of 3-hourly: air temperature, specific humidity, atmospheric pressure, incoming global radiation, incoming long-wave radiation, precipitation rate and wind speed. These drivers are taken at a height of 50 m above ground level (AGL) to ensure that they are representative of the local scale (10^2-10^4 m). SURFEX calculates the meteorological variables from this forcing level down to the ground. The integration time step is 300 s. To isolate effects of urbanization on local near surface climate conditions, we performed model simulations according to two scenarios, which correspond to different states of urbanization:

(i) the "rural" scenario represented a hypothetical situation with no urban areas inside the domain during the 40 years. Radiative and thermal properties of the vegetation cover (albedo, roughness length, emissivity, thermal inertia, leaf area index, etc.) are taken from the ECOCLIMAP database (Masson et al., 2003) and remained fixed through the simulation. Changes of these properties due to vegetation dynamics were not included in the present study.

(ii) the "urban" scenario represented the climate in the presence of urban areas using the evolution of surface cover fractions (see Fig. 1). For this run, the surface cover fractions are updated each year using a linear interpolation. In this study, geometrical, thermal, and radiative properties of roofs, walls, and roads were averaged over available data (Hamdi and Schayes, 2008) and were set to values representing a typical midsize European city. These properties remained fixed through the simulations. Another important urban-related aspect is the anthropogenic heat. This term includes all heat emitted by human activities: traffic, release from industry, and release from residential buildings. Over the area presented in this study, releases from buildings have been shown to be the dominant component of the anthropogenic heat (Van Weverberg et al., 2008). In SURFEX, to mimic space heating, a fixed minimum internal building temperature of 19 °C is specified (Masson, 2000). During fall or winter, internal wall and roof surface temperatures often have values below this threshold, and the heat flux between the internal volume of the building and the wall (or the roof) is directed out of the buildings. An evaluation of this parameterization of anthropogenic heat sources against an inventory of energy consumption for the city of Toulouse (France) was performed in Pigeon et al. (2008).

Each simulation starts from the same initial conditions and runs forward for 40 years using the same climate drivers so that the model responses are exclusively attributable to land cover change. The use of the land surface model in an offline mode does not account for atmospheric feedback and therefore allows isolation of the effects of landscape difference on local near surface climate conditions. The difference in simulated temperature of both model integrations is assumed to be the local urbanization contamination in the local observed temperature record. It should be noted that since in this study the effect of urban growth is treated in isolation to climatic change of the general circulation, the local temperature change can either be exacerbated or diminished by the effects of large-scale circulation.

4. RESULTS AND DISCUSSIONS

4.1. Analysis of the simulations

To evaluate model performance, a comparison is made between the urban run and the routine observations of the Uccle ground station. The temperatures predicted by the urban run are consistent with meteorological observations, with a correlation coefficient of 0.96 and an index of agreement of 0.97 for T_{MAX} and T_{MIN}. The systematic root mean square error ($RMSE_{SYS}$) which should account for physical processes that the model does not routinely simulate well is small compared to the unsystematic root mean square error ($RMSE_{UNSYS}$). The proportions of systematic errors in the model are 26% and 11% for T_{MAX} and T_{MIN} respectively. The minimum temperature is better simulated by the model with a minor negative bias of 0.43 °C and $RMSE_{SYS}$ of 0.66 °C against 1.12 °C and 1.38 °C for maximum temperature. It is expected that a change in the land use forcing should have an imprint on long-term near-surface temperature records. This effect was first detected via significance test of the differences in 2-m temperatures between the urban and rural scenarios. The statistical filter Mann-Whitney U test was applied to the time series of the monthly means (the term "monthly" refers to the average of daily data in that month) maximum and minimum temperature and to the diurnal temperature range (DTR=maximum-minimum temperature). Both T_{MIN} and DTR have high Mann-Whitney z values (4.00 and 7.30 respectively), which indicate that the difference between the urban and rural scenarios is highly significant at 95% (1.96) confidence level. T_{MAX} has a positive value (0.68) but it is not significant at 95% confidence level. The effect on minimum temperature seems to be more important than on maximum temperature. This is to be expected, since the UHI is best observed at night when radiative cooling differences are maximized between urban and surrounding rural areas (Hamdi and Schayes, 2008).

4.2 Urbanization effect on near-surface temperature trend

As indicated by the spacing between the curves in Fig. 2, annual mean urban bias (AMUB) on minimum temperature is shown to be rising at a higher rate (slightly 3 times) than on maximum temperature, with a linear trend of 0.14°C and 0.05°C per decade respectively.

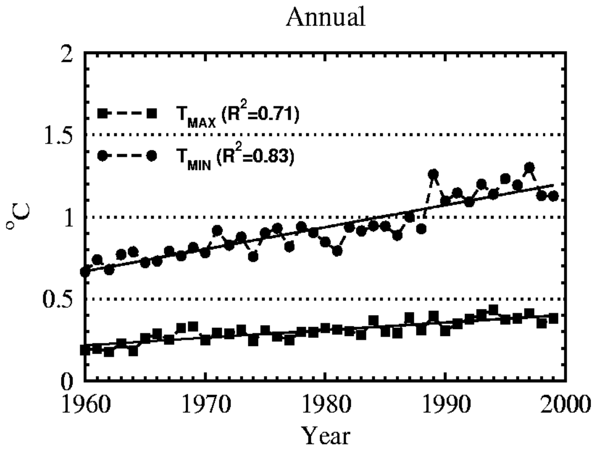

Figure 2: Annual mean urban bias on maximum (T_{MAX}) and minimum (T_{MIN}) temperature with the linear trends, 1960-1999. R^2 is the coefficient of determination. The annual mean is the average of the 12 monthly data of the year.

This result is consistent with previous work suggesting that the maximum temperature is substantially less affected by urbanization than the minimum temperature (Landsberg, 1981). The increase of AMUB on minimum temperature may be attributed to: (i) the higher thermal inertia, which, in combination with lower albedo of urban surfaces (0.08-0.25), delays the cooling of the cities at nights compared to rural areas. (ii) it can also be attributed to the limited evapotranspiration which prevents evaporative cooling of urban areas. (iii) during night hours, the contribution of anthropogenic heat can also influence long-term trend of temperature.

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