

A new method for fine-scale assessments of the average urban Heat island over large areas and the effectiveness of nature-based solutions

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Abstract

People living in cities experience extra heat stress due to the so-called Urban Heat Island (UHI) effect. To gain an insight into the spatial variability of the UHI for the Netherlands, a detailed map (10 m horizontal resolution) has been calculated that shows the summer-averaged daily maximal UHI situation. The map is based on a relationship between the UHI, mean wind speed at 10 m height and the number of people living within a distance of 10 km, derived from simulations of over 100 European cities with the extensively validated urban climate model UrbClim. The cooling effect of green and blue infrastructure is also taken into account in the map, based on these simulation results. The presented map will help local authorities in defining target areas for climate adaptation measures and estimate the impact of nature-based solutions.

Keywords

Urban Heat Island, Netherlands, nature-based solutions, UrbClim model, Ecosystem services mapping

Introduction

High population density and rapid urban growth increase the vulnerability of cities to extreme weather (Rosenzweig et al. 2015). Heat extremes are amongst the most important weather-related health hazards in cities, where the presence of the urban heat island (UHI) is likely to exacerbate the effects of extreme heat. This UHI is caused by the increased heat capacity of cities, anthropogenic heat sources and the imperviousness of urban surfaces, which inhibit evaporative cooling (Oke et al. 1991, Lynn et al. 2009). Due to the

UHI increment, cities are particularly vulnerable to heat waves, with an excess of heat-related mortalities (Gabriel and Endlicher 2011).

In this context, nature-based solutions as urban greenery and water features have been proposed as an effective measure to mitigate the UHI and improve the urban microclimate (Demuzere et al. 2014, Tan et al. 2016). Observational studies revealed that green areas are usually cooler than their surrounding built-up areas, with instantaneous air temperature differences of 1°C up to 7°C (Bowler et al. 2010, Jamei et al. 2016). Similar to parks, water features have the potential to alleviate high urban temperatures through enhanced evaporation and reduced sensible heat fluxes (Nishimura et al. 1998, Coutts et al. 2012).

Since climate change will further increase the risks of morbidity and mortality in urban areas due to greater frequency of weather extremes, there is increasing interest for detailed maps of the UHI effect covering large areas (regions or countries). To accomplish this, two types of methodologies are currently used. The first type of models use empirically derived relationships between land use/vegetation indices and the UHI (e.g. van Hove et al. 2015) to create high-resolution maps over large areas (e.g. Shi et al. 2018). The advantage of this methodology is that it is simple and computationally very cheap to perform. The drawback is that the relationships are based on just a few measurements and extrapolated to locations outside the observational reach. The second type of models are physically based mesoscale atmospheric models or local climate models (e.g. Wouters et al. 2013, Tan et al. 2016). These type of models calculate the UHI for all types of locations in a physically consistent way, but are computationally expensive and struggle to deliver very high horizontal resolution (<100 m) results for large areas.

In this paper, we present a GIS-based methodology that combines both the advantages of physically based model results with the fast and simple regression methodology to deliver a very high resolution (10 m) daily maximal UHI map in which the effectiveness of existing green and blue infrastructure can be assessed for all locations.

Methodology

The methodology is based on a large ensemble of physically based model simulations of 100 cities and their surroundings all over Europe. These simulations have been performed with the urban boundary layer climate model UrbClim (De Ridder et al. 2015), designed to cover agglomeration-scale domains at a high spatial resolution, taken as 250 m for this study. The model has been successfully validated regarding its calculated air temperatures and urban-rural temperature differences for a large number of cities throughout Europe (De Ridder et al. 2015, García-Díez et al. 2016, Lauwaet et al. 2015, Lauwaet et al. 2016). These simulations have been performed in the framework of the European FP7 project RAMSES (www.ramses.eu).

A statistical analysis of the simulation results revealed that the summer (June-August) average daily maximal UHI value of a given city can be estimated based on only two

explanatory variables: the mean wind speed at 10 m height ($wind_{10m}$) and the total number of people living within a radius of 10 km ($population_{10km}$) (Fig. 1).

The resulting regression is as follows:

$$\text{Daily maximal UHI} = -1.605 + 1.062 * \log(x) - 0.356 * y$$

with

x is the total number of people living within a radius of 10 km

y is the mean wind speed at 10 m height

the lower boundary set to 0.

Subsequently, detailed land use and soil sealing maps are used to calculate the local daily maximal UHI value. UHI values are only assigned to a pixel when there are sealed surfaces in the neighbourhood. Since data analysis showed that the maximum UHI value of a city is only reached in pixels that are surrounded by large sealed areas, we scale the daily maximal UHI value of a location by multiplying it by the average soil sealing % of all the grid cells (10 m x 10 m) in a 1 km radius. In this way, we introduce realistic local variations of the UHI within a city.

Finally, we take the cooling effect of neighbouring green/blue areas into account based on the average UHI reduction effect for all non-urban types of land uses (assigned to a limited amount of categories) from the model simulations of the 100 European cities (Table 1). Since observations have shown that the cooling effect of green/blue infrastructure is spatially limited (e.g. Chen et al. 2009), we have assigned a cooling radius of 30 m to the non-urban land use types. This 30 m radius is an estimated value, based on experimental studies on the extent of the cooling effect of urban green and water (Spronken-Smith and Oke 1998, Nishimura et al. 1998). So the final daily maximal UHI value of a pixel is calculated by subtracting the fractional cooling contributions of all the grid cells within a 30 m radius. The fractional cooling contribution of a grid cell is equal to the UHI reduction effect of the grid cell, divided by the total number of grid cells within the 30 m radius.

Results and discussion

The methodology described above is used to calculate the summer-average daily maximal UHI map for the entire Netherlands at a spatial resolution of 10 m (Fig. 2). The population density map was available at a spatial resolution of 1 km and a climatological mean 10 m wind speed map was available at a spatial resolution of 50 m. The final UHI map is calculated by using 10 m resolution land use and soil sealing maps. The overall UHI map looks realistic and contains a lot of detail (e.g. see Fig. 3 for a detailed map of Amsterdam).

This map shows only the average UHI situation in a region, which can look drastically different for real-time situations (e.g. during heat waves, the UHI effect is typically much

larger). Another drawback of the methodology is that it is only suited for populated areas. Remote industrial complexes where no-one is living, which are known to produce a large UHI effect, will not appear on the map. In addition, since the Netherlands is very flat, we did not take terrain effects into account in our methodology in order to keep it simple. These should certainly be included when working in more accidental areas, which is easy to do.

Comparing our methodology to existing literature and reported case studies is not straightforward, since it is based on a very large and unique dataset of high-resolution urban climate simulations of 100 cities over a full summer period. Related studies are mainly based on either measurements on a few locations and/or for short time periods (e.g. van Hove et al. 2015) or ENVI-met-like model simulations for small areas and short time periods (e.g. Tan et al. 2016). The results of our methodology are certainly not contradictory to these studies, but cannot be compared one-to-one.

Taking all this into account, we believe our methodology is suited to deliver a good first-order estimate of the local UHI situation and the effect of green/blue infrastructure over large areas.

Conclusion

In this paper, a GIS-based methodology is presented to calculate very high resolution (10 m) maps for the average urban heat island situation in large regions, taking the cooling effect of green/blue infrastructure into account. The method is based on a large dataset of urban climate simulations for cities all over Europe and needs only 4 input maps: population density, mean wind speeds at 10 m height, soil sealing and land use. When mapping areas with a lot of topographical variation, the terrain height effect should also be included. The methodology is applicable for all locations in Europe and delivers a detailed first-order estimate of the average UHI situation in a region, given the listed limitations.

Grant title

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Conflicts of interest

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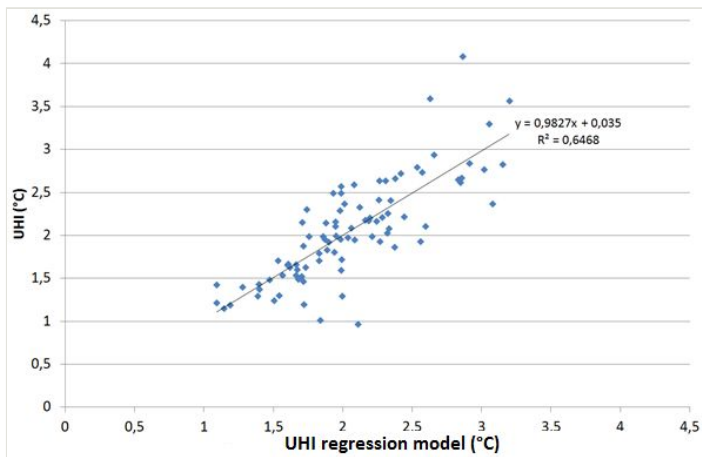


Figure 1.
Relationship between the regression model and the actual simulated daily maximal UHI effect for the 100 European cities (De Ridder et al. 2015)

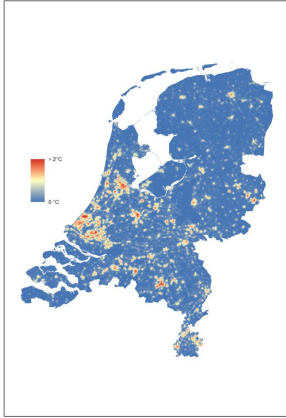


Figure 2.
Average daily maximum UHI map for the Netherlands.

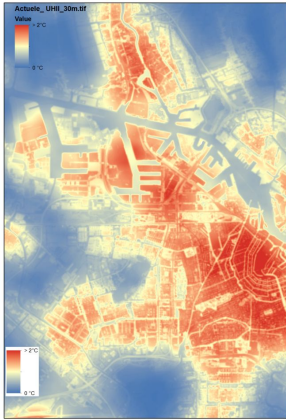


Figure 3.
Average daily maximum UHI map for a part of the city of Amsterdam.

Table 1.

Estimated Urban Heat Island reduction effect of non-urban land use classes.

Non-urban land use class	UHI reduction effect (%)
Trees	50%
Shrubs/cropland	30%
Grassland	20%
Inland water	30%
Sea water	100%