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Analysing Urban Heat Island Patterns and simulating potential future changes

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Abstract— This paper analyses the strength of the urban heat island effect in a temperate climate, explains local variation in the observed temperatures and quantifies how this urban heat island effect may develop in the coming 30 years due to projected climatic and socio-economic changes.

Index Terms— climate change, land-use change, UHI

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1 Introduction

Various studies measure the urban heat island (UHI) effect using different data sources such as satellite images (Nichol and Wong, 2009; Döpp, 2011), weather stations (Steeneveld et al., 2011) and mobile devices (Heusinkveld et al., 2010). Yet, few studies exist that explain spatial variation in observed urban temperatures from local urban conditions. This paper analyses the strength of the urban heat island effect in a temperate climate (Amsterdam, the Netherlands) and attempts to explain local variation in the observed temperatures. Based on that, a quantitatitve assessment is made of the potential changes in the magnitude and spatial pattern of the urban heat island effect in the coming 30 years as a result of projected climatic and socio-economic changes. The analysis is based on our own measurement of the UHI effect that we define as UHImax: the maximum temperature difference between local urban temperatures and a rural reference station observed during a 24 hour period (Van Hove et al., 2011). To assess potential future changes we build on existing scenario studies and a land-use simulation model. Using observed relations between average maximum daily temperatures and observed UHI values we are able to assess the impact of global climate change on local UHI values. The land-use change model allows the translation of macro-level socio-economic changes into potential future urbanisation patterns and thus the assessment of increased urbanisation on UHI.

In section 2 the selected methods for this study are discussed. Section 3 then presents the main results, and the final section (4) summarises them.

2 Methodology

2.1 Analysing Current Urban Heat Island Patterns

We describe current urban heat island patterns based on two separate analyses. *Spatial variation* in urban temperatures is measured along a route using mobile measurement devices and then explained using regression analsyis and spatially explicit explanatory variables, while *temporal variation* is described based on local temperature measurements derived from amateur weather stations.

2.1.1 Spatial Variation in Urban Temperatures

Urban temperatures were measured using a GPS Logger and a USB-thermometer fixed to a bicylce while travelling along a circular tour around the city of Amsterdam that passed open areas outside the city, various neighbourhoods with different densities and the historic centre. Measurements were taken every minute during a two-hour period after sunset on an average-temperature summer day. This particular day (June 17 2012) an average maximum daily temperature of 19.7°C was measured at the nearby Dutch Royal Meteorological Institute's weather station (Schiphol Airport) that was considered as the rural reference station in this study. The observed maximum daily temperature corresponds very well to the 30-year average maximum daily temperature of 19.8°C for the same station. The late evening period was chosen because maximum UHI values are known to be highest after sunset when the heat stored in artificial surfaces is slowly released (Van Hoven et al., 2011). The Urban Heat Island-effect was described by comparing the collected urban temperatures with those measured at 10-minute intervals at the Schiphol Airport reference station. The observed variation in Urban Heat Island-effect was explained from local spatial conditions using linear regression. With a geographical information system various explanatory variables (presence of different types of land use, degree of sealed surface, number of houses) were made available for differently sized neighbourhoods surrounding the temperature observation locations. The amount of urban volume in a 500x500 metres neighbourhood turned out to best explain variation in Urban Heat Island-effect (R^2 = 0.569, constant and coefficient significant at 1% level). Additional explanatory variables (e.g. proximity to water and green spaces, local degree of sealed surface) were also incorporated in the regression analysis, but this did not improve the explained amount of variance (R^2). This leads us to believe that urban volume is able to capture similar spatial characteristics as the other variables. As a simple explanatory model allows us to assess potential future changes in a more straightforward way (without requiring too many additional assumptions) we preferred to keep this model for subsequent analysis.

2.1.2 Temporal Variation in Urban Temperatures

Hourly records of air temperature were collected from five amateur weather stations in Amsterdam for a 30-day period in the summer of 2010 (June 15 and July 15). This period was chosen because of the occurrence of relatively high temperatures, calm wind and clear sky conditions, which enhance UHI effects (Arnefield, 2003). Although amateur stations are not fully compliant with the standards of the World Meteorology Organization, they offer the possibility to study long-term temporal weather data in urban areas (Steeneveld et al., 2011). Again, the weather station at Schiphol Airport was considered as reference station. All amateur stations showed a consistent relation between between daily UHI_{max} and daily maximum temperatures in the observed period. For our analysis we selected the Watergraafsmeer station (Fig. 1) because of its proximity to the location where spatial variation in temperatures was analysed.

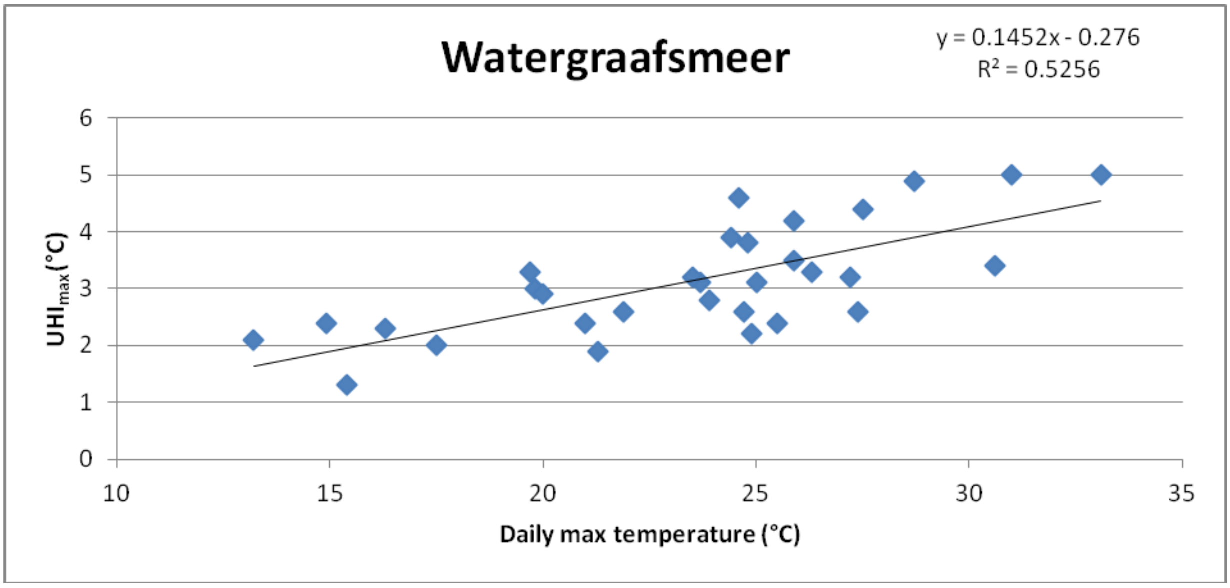

Figure 1: Relation between UHI_{max} and daily maximum temperature at Watergraafsmeer weather station

2.2 Simulating Future Urban Heat Island Patterns

The UHI effect is likely to become stronger in the future as both temperature and amount of urban area are expected to increase. Dutch climate change scenarios indicate an increase of either 1°C or 2°C in the average yearly temperature for 2050 (Van den Hurk et al., 2006). This increase can be translated into a likely UHI increase with the observed relation between daily UHI_{max} and daily maximum temperatures described above: for each degree increase in daily maximum temperature the UHI_{max} is expected to increase by about 0.15°C. This impact is expected to be present within the urban area of Amsterdam (close to the amateur station on which it was based) and will decrease to 0 near the reference station. This relation is used to create a climate change correction factor that can be applied to update the map depicting spatial variation in UHI effect.

To provide an outlook on future urban patterns we apply a land-use simulation model that is well-established in spatial planning and climate adaptation research in the Netherlands and beyond: Land

Use Scanner (Kuhlman et al., 2012; Koomen and Borsboom-van Beurden, 2011; Te Linde et al., 2011). This GIS-based model is rooted in economic theory and integrates sector-specific inputs (e.g. regional demand for residential land) from other, dedicated models. It is based on a demand-supply interaction for land, with sectors competing within suitability and policy constraints. To reflect the inherent uncertainty in future socio-economic changes we have selected the two most diverging scenarios from an existing Dutch scenario study (CPB et al., 2006). The Global Economy scenario is part of the A1-scenario family in the SRES terminology and shows a substantial population growth and strong economic growth. In the Regional Communities scenario (based on the B2-scenario family of SRES) the population remains more or less stable, with modest economic growth and a higher unemployment rate.

Based on the simulated land-use patterns for 2040 we created two updated versions of the 2006 urban volume data set; one for each scenario. These were created according to the following rules: 1) for locations where land use did not change between 2008 (base year for simulation) and 2040, the urban volume values for 2006 were maintained; 2) for locations where land use changed the urban volume value was updated to the average 2006 urban volume value of the corresponding new land-use type. This approach is an obvious simplification of potential future developments, but allows for inclusion of changes in the urban fabric. The updated uban volume values were then used to create a new set of maps depicting spatial variation in UHI effect.

3 Results

Using the statistical relations obtained in our explanatory analysis of local measurements of spatial variation in UHI effect and a data set describing urban volume in Amsterdam we mapped spatial variation in the UHI effect for the entire city (Fig. 2). The results indicate how the UHI effect is thought to be distributed over the greater Amsterdam area on an average June day corresponding to the moment of our measurements.The inner city is clearly distinguishable with values up to 2.9° C. Moving outwards the temperature shows a gradual decrease. In the areas surrounding the old centre, with lower urban density, the UHI effect is found to be between 1.5° C and 2.5° C. Still further from the city the UHI pattern becomes more heterogeneous; with several areas with low UHI values representing open areas and areas with moderate UHI values following the suburban lobes of Amsterdam. A second area with high UHI values represents a dense commercial district. It is interesting to note that the outskirts of Amsterdam still show an UHI effect of around 0,95 °C, which is probably due to the fact that we did not travel out of the uban sphere of influence.

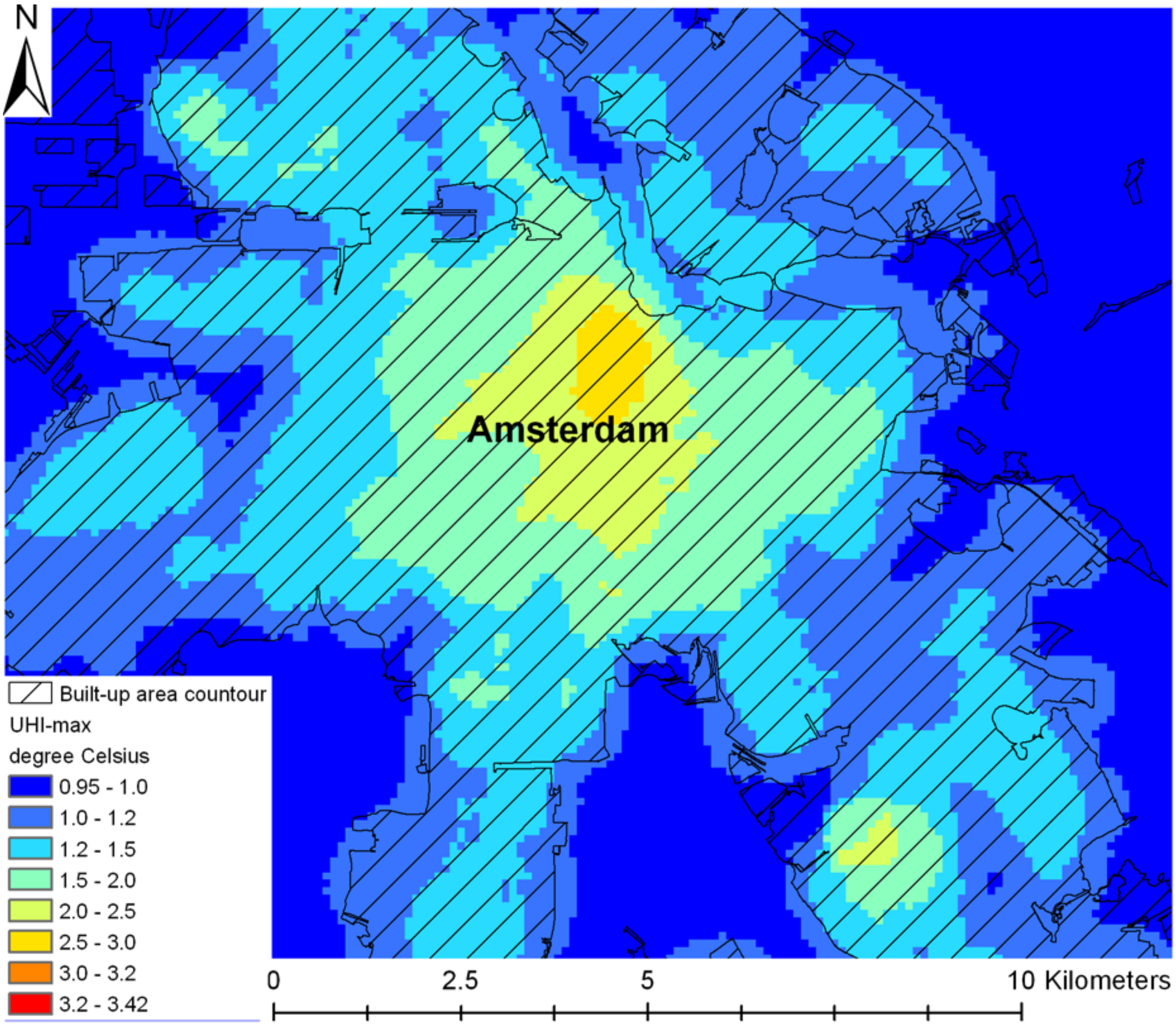

Figure 2: Spatial variation in UHI values the greater Amsterdam area

The simulated future UHI patterns are shown in Fig. 3-8. The legends for these maps are the same as in Fig. 2. From these maps it can be observed that the UHI effect increases in both scenarios. This is because of the increase in urban volume in both scenarios compared to the situation in 2006. The RC scenario shows a concentrated UHI increase in areas with high urban volume values in the centre, whereas the GE scnenario shows a more dispersed spread of the UHI. This follows from the stronger focus on concentration of activity in the RC scenario, while the GE scenario allows more urban development at the edges of town. The increases in temperature following the climate scenarios result in more extreme UHI values with maximum UHI valus in the centre rising to about 3.4° C.This may not seem much, but one has to consider that we base our depictions on an average June night. On hot summer days the UHI will be much larger.

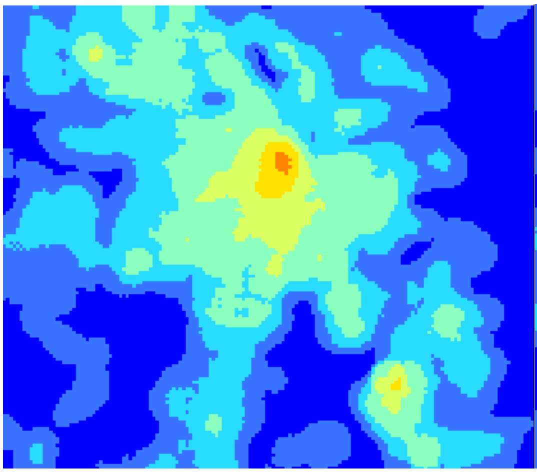

Figure 3: scenario RC with current temperature

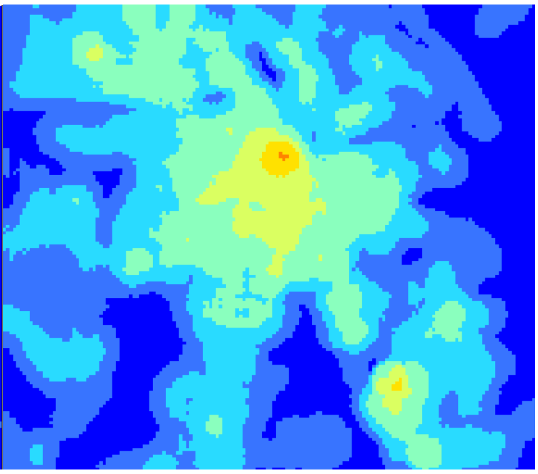

Figure 4: scenario GE with current temperature

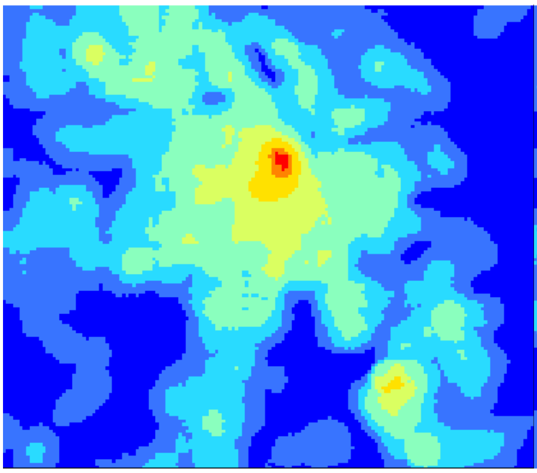

Figure 5: scenario RC with 1C° increase

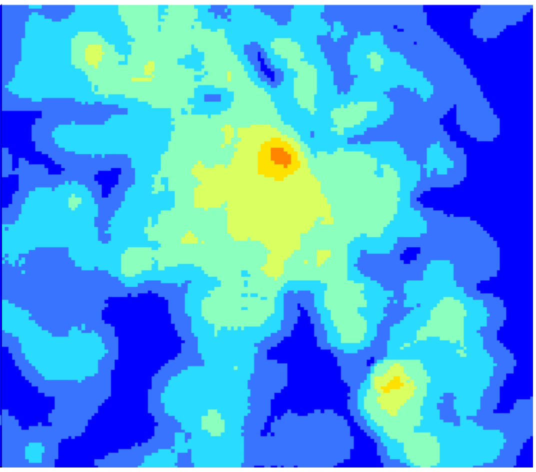

Figure 6: scenario GE with 1C° increase

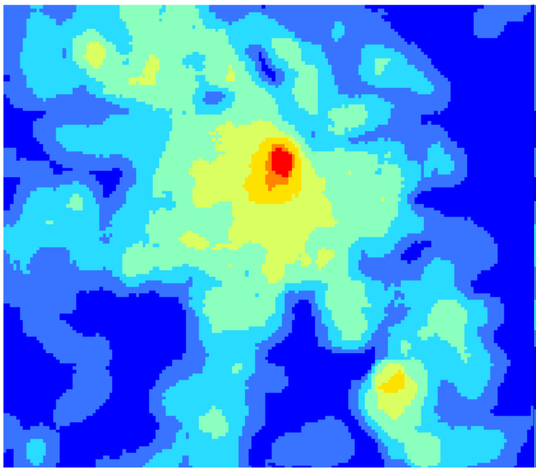

Figure 7: scenario RC with 2 C° increase

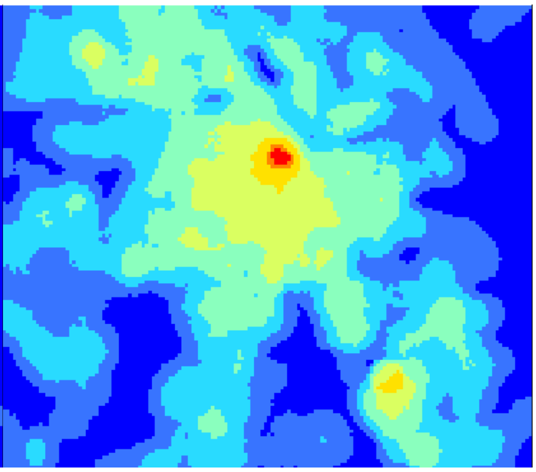

Figure 8: scenario GE with 2 C° increase

4 Conclusion

Our measurements for the Amsterdam region in the Netherlands show that the urban heat island effect induces maximum temperature differences with the surrounding countryside of over 3° C on moderately warm summer days with a maximum daytime temperature of 20° C. The observed temperature difference between urban and rural areas increases by about 0.15° C for each degree increase in maximum daytime temperature. The simulations of potential future changes in urban heat island patterns indicate that strong local temperature increases are likely due to urban development. Climate change will, on average, have a limited impact on these changes. Large impacts can, however, be expected from the combination of urban development and potentially more frequent occurrences of extreme climatic events such as heat waves.

5 References

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