Estimation of the Urban Heat Island for UK Climate Change Projections

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Abstract

Cities are known to exert a significant influence on their local climate, and are generally warmer than their surroundings. However, climate models generally do not include a representation of urban areas, and so climate projections from models are likely to underestimate temperatures in urban areas. A simple methodology has been developed to calculate the urban heat island (UHI) from a set of gridded temperature data; the UHI may then be added to climate model projections and weather data files. This methodology allows the urban heat island to be calculated on a monthly basis and downscaled to hourly for addition to weather generator data. The UHI intensities produced are found to be consistent with observed data.

Practical Application:

There is overwhelming consensus amongst the scientific community that the Earth's climate is warming. In addition to the effects of climate change the urban heat island (UHI) effect can increase air temperatures significantly in urban areas above those of the rural areas around them. The proposed methodology for calculating the UHI from a set of gridded temperature data allows the UHI to be added to climate model projections such as UKCP09 or HadRM3 and weather data files. The methodology also allows for the temporal downscaling of the UHI from monthly values to hourly data for use in building thermal simulation software.

Introduction

Global surface temperatures have been increasing since the beginning of the industrial revolution, and have risen markedly in the last 50 years. The Central England Temperature record[1], which began in 1659, is the longest such record available. Temperatures in central England have risen rapidly since 1980, and 2006 is (at the time of writing) the warmest year in this record. Projections of future climate change indicate that this warming trend is very likely to continue throughout the 21st century[2].

It has long been recognised that urban areas have their own climate and are typically warmer than surrounding non-urban areas[3-5]. Briefly, buildings store heat gained during the day, both from solar radiation and from human-related activity such as traffic exhaust and energy use. This heat is then released during the night resulting in higher night-time temperatures in urban areas. Many buildings are designed in this way to regulate their internal temperatures. The geometry of most urban areas (tall buildings and narrow streets) means that buildings provide large areas for absorption of heat but limit the ease with which the heat can be lost via radiation and convection (the "canyon effect"). Urban areas are usually well drained which limits the cooling effect of evaporation of water from the surface. The temperature difference between an urban area and the non-urban surroundings is referred to as the urban heat island (UHI), and has a maximum value at night. Non-urban areas warm more quickly than urban areas, but also cool more rapidly at night.

There have been several measurements of the UHI effect in London. Temperature data for London in the period 1931-1960 reported a mean annual UHI for central London of 1.4°C (1.6°C in summer and 1.2°C in winter)[6]. Watkins *et al*[7] measured the urban heat island of London during 1999. They found that the urban heat island (UHI) decreased approximately as $1/r^2$, (where r is the radial distance from the thermal centre) and was about 2.8 °C on average, with values as high as 7 °C recorded on some days. The UHI was also shown to follow a distinct sinusoidal shape over the course of a day with the minimum around noon. Further analyses of these data[8,9] has shown the importance of urban morphology, wind speeds and cloud cover on the UHI of London. For summer, the UHI was shown to be controlled mostly by the urban environment itself, whereas in winter the larger-scale climate had the strongest influence.

Van Weverberg[10] found that increasing urbanisation had increased temperatures by between 0.8 and 1.0 °C in Brussels depending on the weather at the time. The UHI was shown to be larger in the summer when there were clear skies and calm conditions compared to rainy and cloudy conditions in the winter. Gedzelman *et al*[11] showed that the diurnal cycle of the UHI for New York City has the form of a truncated sine wave. The maximum UHI occurs at approximately midnight and the minimum around noon. These authors also showed that the UHI effect is greater during clear conditions than in overcast conditions, but there is greater variability in the magnitude of the UHI in clear conditions (shown in Figure 5 of Gedzelman *et al*[11]). The magnitude of the UHI was shown to depend greatly on wind speed and direction and current weather patterns. It has been shown[6, 8,9,12,13] that wind (speed and direction) is the most significant weather variable to affect the UHI intensity, followed by cloud cover. Oke[14] showed that the relationship between wind and UHI is non-linear with an approximate inverse square root dependence and that cloud type as well as amount is important. In the summer the UHI is greatest, owing to the absorption of solar radiation by buildings, and anthropogenic heat release is of less importance. However, during winter the solar radiation intensity is much lower than in summer and anthropogenic heat release has a higher impact on the UHI.

During the very hot summer of 2003 nearly 15,000 people died in Paris from heat related illnesses arising in part from a failure of the buildings to adequately moderate internal air temperatures. It is estimated that there were

~35,000 additional deaths across the whole of Europe caused by this heat wave[15]. Many of these additional deaths were likely to be caused by an enhanced UHI during the heat wave, where the elevated night-time air temperatures prevented people from being able to cool themselves at night. Approximately 50% of the world's population currently live in an urban environment[2] and this number is set to increase over the 21st century. The consideration of the urban climate in building design and simulations of building thermal performance is therefore very important. The exact impact of climate change on the urban heat island is uncertain. If a greater number of and / or longer lasting high-pressure systems occur in summer over the UK, the magnitude of the urban heat island may increase. However, a preliminary analysis of regional climate model simulations which include an explicit treatment of urban areas suggests, to a first approximation, the urban heat island does not increase with climate change[16].

The latest UK Climate Projections (UKCP09)[17] were produced using the regional climate model HadRM3 which was developed by the Met Office Hadley Centre and has a resolution of 25 km. An explicit representation of urban areas was not included in the HadRM3 model, and hence the UKCP09 projections do not include the effect of the urban areas on climate. Urban areas have generally not been represented explicitly in climate models, although some schemes have been developed (Betts and Best[18]). At the scale of global climate models (100's km) the influence of urban areas on the simulated climate is negligibly small. However, at the resolution of the HadRM3 model (25 km), the largest urban areas have some influence on the local simulated climate[16]. A method for calculating the magnitude of the urban heat island, which could then be added to temperature projections from regional climate models, is therefore required.

Weather files, consisting of hourly values of temperature, solar intensity, and many other variables are routinely used in the thermal modelling of buildings to show compliance with building regulations and to influence design. These files have been produced previously from observed weather data. However, it is now recognised that the current weather files need updating to include the impact of climate change, as many buildings will have a life span of at least 50 years. There are two likely routes for the modification of weather files using climate data from the UKCP09 projections. The observed weather data can be mathematically transformed (a procedure called morphing[19,20]) using climate change factors calculated from climate projections. The urban heat islands calculated here could be added to current weather files using the morphing procedure. Alternatively, a synthetic time series of weather variables produced by a weather generator[21] could be modified in a similar way, provided the generator hasn't been calibrated with data from an urban area, although in this latter case the magnitude of the urban heat island included would be unknown.

In this paper, a simple method for calculating the monthly average urban heat island for the major towns and cities in the UK at a resolution of 5 km (to match that of the UKCP09 weather generator) is described. The urban heat islands may then be transformed onto the regional climate model 25 km grid and added on to the temperature projections from the 11 member RCM data. A method for adding the UHIs to hourly climate data is also briefly described.

Data Sources

The temperature data (temperatures at 1.5 m above local ground level) used in this study were taken from the set of monthly minimum values for the period 1961-2006, and have coordinates on the UK national grid at a resolution of 5 km (these data can be obtained free of charge from the Met Office[22]). A brief description of the data creation is given here for completeness but full details are given by Perry and Hollis[23,24]. The number of stations reporting daily minimum temperatures in the UK is ~540 and this did not vary significantly during the period 1961-2006. These observed temperature data were normalised with respect to the 1961-1990 climate mean using an existing 1 × 1 km gridded minimum temperature data set[23]. Climate data are often strongly influenced by geography and topography so it is important to incorporate these influences in the gridding process. A regression model relating the normalised temperatures to latitude, longitude, altitude, coastal influence, urban fractions (average proportion of land within each 5 km grid classed as urban) and many other topographical variables was used to calculate a series of residuals, which are the difference between the temperatures calculated from the regression model and the observed temperatures at meteorological stations. Inverse-distance weighting was used to interpolate in space the residuals onto the regular

5 km grid. Finally, the same regression model was used to restore the interpolated residuals back to actual minimum temperature values for each cell of the 5 km grid. Henceforth “temperatures” and “temperature data” will refer to this data set.

Urban areas in the UK were mapped using a very high resolution (~1 km) global land cover characteristics database[25], generated as part of the International Geosphere-Biosphere Programme (IGBP). This data set was produced using AVHRR (advanced very high resolution radiometer) satellite data collected between 1992 and 1993. The relevant part of this dataset for the UK was extracted and transformed onto the UK national grid at 5 km resolution, to match that of the temperature data. The proportion of land classed as urban within each 5 km cell was then calculated, and is referred to as the urban fraction in this paper. This definition is slightly different to that used by Perry and Hollis[23,24] in constructing the gridded temperature data.

Temperature Transects

A north – south transect of urban fractions and temperatures across London for each season of 2003 is shown in

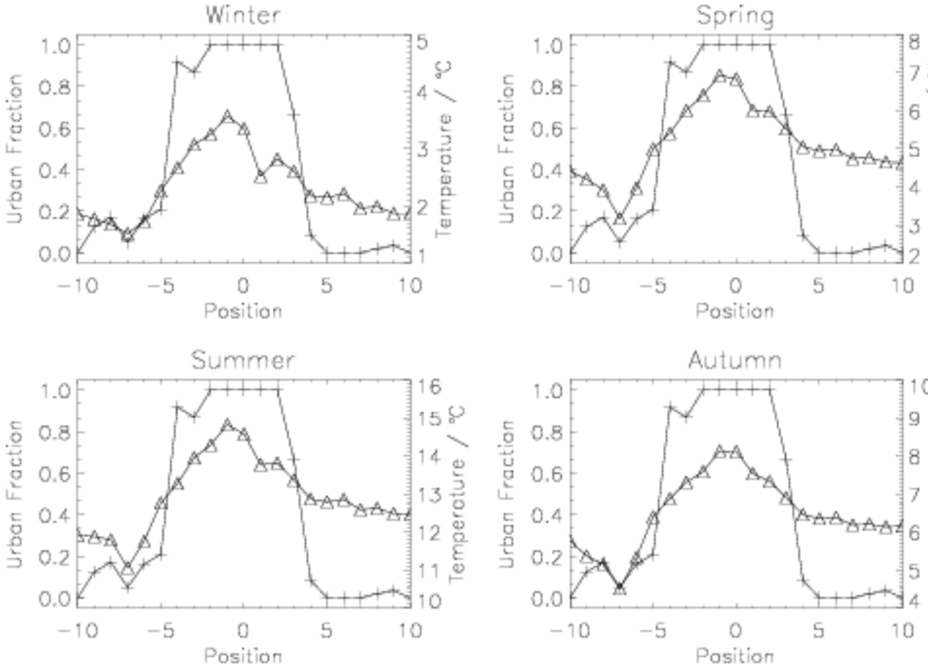

Figure 1. Here, the four seasons are defined as: Winter (December, January and February), Spring (March, April and May), Summer (June, July and August) and Autumn (September, October and November). The temperatures shown in Figure 1 are mean values each of the three-month periods. The abscissae are in units of 5 km cells. The urban centre used here is marked as position ‘0’ on each panel of

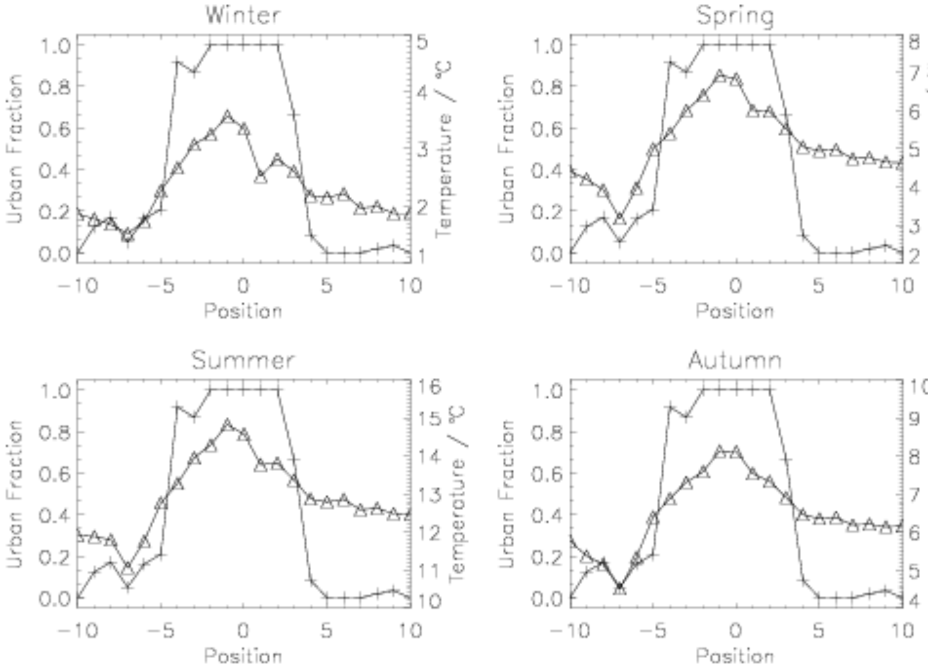

Figure 1 and in this case corresponds roughly to Kensington (although others could have been chosen). It can be seen that the temperatures of cells close to the urban centre are warmer than the surrounding areas. Generally there is a trend of increasing temperature with urban fraction. Within the urban area, where the urban fraction is 1.0 or close to 1.0 (completely urban), temperatures are larger in the centre than at the edges. This indicates there are other factors affecting the UHI intensity other than the urban fraction, such as the street widths and building type and the materials used in its construction. Anthropogenic heat release (from heating and cooling buildings, vehicle exhaust and even human metabolism) may also increase the urban heat island. Advection of cooler air (e.g. by sea breezes) can reduce the UHI. The magnitude of the UHI indicated in Figure 1 is between 2 and 3°C in the summer and between 0.5 and 1.5 °C in winter. Further analysis of the measurements of Watkins et al[7] has shown that, on average, the UHI for London lies between about 2.5 and 3 °C in summer[9] and 1.0 and 3.2°C during winter[20]. The UHIs from the transects in Figure 1 are in good agreement with the summer values but underestimate the winter UHI.

Methodology

The urban heat islands of the major towns and cities could be estimated from the gridded temperature dataset using several transects. However, the positions of the transects are arbitrary, and many cells around the cities would not be used in the analysis. Instead, the average temperatures and urban fractions of concentric circles around the major urban centres were used. This method has the advantage of using all temperatures and urban fractions around the city, while minimising the influence of other factors such as the altitude and topography of surrounding areas.

First, a method to identify the major urban centres in the UK was devised. A cell is defined as an ‘urban centre’ if it has an urban fraction greater or equal to some limit F_c, In addition, the average urban fraction of the 8 cells surrounding each urban centre was calculated, and if it was less than a limit F_s that urban centre was discarded. Maps showing the locations of areas marked as urban centres were generated for a range of values of F_c and F_s and were inspected by eye. Optimal values found for F_c and F_s were 0.5 and 0.1 respectively. These values allowed large towns and cities to be identified while excluding smaller towns which cannot be resolved adequately at the resolution (5 × 5 km) used here. The major urban areas identified in the UK are shown in Figure 2. The black box around each town contains all cells that were considered to be part of that urban area.

The urban heat island for each town and city shown in Figure 2 was then calculated as follows. Each cell within the boxed areas in Figure 2 is treated individually; as mentioned earlier those cells with an urban fraction greater than or equal to the limit F_c (= 0.5) were classed as urban centres. The average urban fraction and temperatures of the cells in concentric areas around the urban centre were calculated. The cells within the concentric areas were defined for a radius r (where r has units of number of cells) using standard Cartesian co-ordinates such that:

eqn. 1 $$r^2 \le \left(\Delta x^2 + \Delta y^2\right) < (r+1)^2 \text{ and } -r \le \Delta x, \Delta y \le r,$$

where Δx and Δy are the offsets (in cells) from the urban centre. The cells which form part of the concentric area with radius r are identified by finding all combinations of Δx and Δy which meet the criteria in eqn.1.

For each urban centre, the average urban fractions and temperatures were calculated for radii $1 \leq r \leq 10$. The maximum radius $r = 10$ (corresponding to a distance of 50 km from the urban centre) was found to use adequate data around each urban centre, but not extend into other urban areas. The proximity of Liverpool and Manchester for instance meant that using a larger radius would have resulted in the inclusion of some of Liverpool's urban areas in the analysis of Manchester's UHI and vice versa. Given $1 \leq r \leq 10$, 11 data points are created; one for the urban centre and one for the average of each surrounding radius. Plotting the average temperatures against the average urban fraction for each value of r allows any relationship to be identified and the magnitude of the UHI intensity for that urban centre to be calculated. The full process is illustrated in Figure 3.

Results

Scatter plots of temperature and urban fraction for the major cities of London, Birmingham, Glasgow and Plymouth are shown in Figure 4 for the summer of 2003. These data are the average temperatures and urban fractions of a randomly chosen urban centre and the surrounding concentric areas. These results indicate that the relationship is approximately linear. For the larger cities (London and Birmingham), there are a wide range of different urban fractions and temperatures around the urban centres and the correlation coefficients are high ($R^2 > 0.9$). However, for the smaller cities (Glasgow and Plymouth) there is less variation, and most of the points have urban fractions closer to zero. The correlation coefficient of the linear trends is smaller but still significant with $R^2 > 0.7$.

A linear fit to the data using a simple least squares method allows the urban heat island (ΔT) for each urban centre to be calculated as follows:

eqn. 2
$$\Delta T = m \times U_0,$$

where m is the gradient of the straight line fit and U_0 is the urban fraction of the urban centre. The calculation of the average UHI (ΔT_{ave}) for each of the towns and cities shown in Figure 2 is:

eqn. 3
$$\Delta T_{ave} = \frac{\sum\left[m(i) \times U_0(i)\right]}{n} \qquad 1 \le i \le n,$$

where n is the total number of urban centres associated with each town, $m(i)$ is the gradient of the linear fit and $U_0(i)$ is the urban fraction of urban centre i. The associated errors in the average UHI, $\sigma(\Delta T_{ave})$ can be estimated using a standard propagation-of-error formula:

eqn. 4
$$\sigma\left(\Delta T_{ave}\right) = \frac{\sqrt{\sum\left[\sigma_m(i) \times U_0(i)\right]^2}}{n},$$

where $\sigma_m(i)$ is the error in the gradient from the linear fit.

Table 1 shows the monthly and seasonal UHI for 2003 and their estimated errors for the cities shown in Figure 2. Generally, the UHIs are largest in the summer, but not for every city. The UHIs are very small for some of the smaller cities (Leicester and York), and show little variation with season. The results for London are consistent with those found by direct observation of the UHI[6]. The method for calculation of the effect of urbanisation on the UHI used here seems to work better when applied to larger cities and towns. This is likely to be due to the 5 × 5 km resolution of the temperature data, which will favour larger urban areas. Interestingly, the UHIs calculated for Newcastle-upon-Tyne and Portsmouth are the largest. This could be due to local topography or other climate effects which are beyond the scope of this paper.

The UHI results discussed above used temperature data for 2003. To test the consistency of these results, UHI intensities were also calculated for all years between 2002 and 2006. For most cities the UHI intensities were similar in all years. For example, in central London, the UHI was consistently between 1.6°C and 1.9°C for summer, which is similar to the nocturnal UHI values calculated by Kolokotroni and Giridharan[8].

If desired the 5 km urban heat islands could be regridded to the 25 km resolution of the regional climate model. This would allow the addition of an UHI to the publicly available 11-member ensemble HadRM3 data which were used to compile the UKCP09 climate projections. This would be beneficial for anyone wishing to use the RCM data as they include the effect of topography but not urbanisation.

Sub-daily variation of the UHI

It is necessary to add the UHI to the hourly temperature data in weather files used for thermal modelling of buildings, or the hourly data produced by the UKCP09 weather generator. In order to create a diurnal variation of the UHI several assumptions are made. First, the diurnal variation follows a sinusoidal pattern. This is a reasonable assumption as the observed diurnal variation of the UHI[4,7-11] has been found to be approximately sinusoidal. More complex functions could be used but a simple sinusoid was deemed adequate for the purposes of the methodology described in this paper. Secondly, the UHI is periodic and has a period of 24 hours. There is some discrepancy in the literature about the position of the minimum UHI but several sources support a cyclic function with extrema at approximately noon and midnight[4,7,11]. Here we assume that the UHI is greatest at the daily temperature minimum and that the UHI minimum occurs at the peak daily temperature. Using the CIBSE timings for daily maximum and minimum temperatures[26] we see that during the summer months these occur just after noon and midnight respectively, which is consistent with observations[4,7,11]. Thirdly, that the minimum UHI is 0°C (or close to zero) which is supported by several sources[4,8-11]. Cool islands (where the urban area is cooler than surrounding rural areas) can occur and could be included by simply shifting the minimum value of the sinusoidal function. Fourthly, we ignore the effects of other weather variables on the diurnal cycle. To accurately predict the variation in the diurnal cycle would require not only detailed observations of the effect of different weather variables (for example, wind speed and direction, cloud cover and cloud type) on the UHI but also knowledge of how these variables will change in the future. UKCP09 does not include any information about wind speed or direction or any information about cloud type; therefore it would be difficult to include the effect of these variables on the UHI.

A function describing the hourly variation of the UHI (δT_{hourly}) may be constructed using the CIBSE monthly timings for daily maximum and minimum temperatures[26]. The wavefunction is constructed from two sinusoids that vary between T_{min} (typically 0°C) and a maximum ΔT_{ave} (example values given in Table 1). The inclusion of T_{min} allows for cases where the minimum UHI is not 0°C or where cool islands (negative UHI) have been observed. The example function is given in eqn. 5.

eqn. 5
$$\delta T_{hourly} = \frac{\Delta T_{ave} - T_{min}}{2}\left[\frac{1+\cos\left(\pi(t_i - t_{max})\right)}{t_{min} - t_{max}}\right] + T_{min} \qquad t_{max} \le t_i \le t_{min}$$

and
$$\delta T_{hourly} = \frac{\Delta T_{ave} - T_{min}}{2}\left[\frac{1-\cos\left(\pi(t_i - t_{min})\right)}{24 + t_{max} - t_{min}}\right] + T_{min} \qquad t_{min} \le t_i \le t_{max},$$

where t_i is the hour of the day and t_{max} and t_{min} are the times of the maximum and minimum UHI. A plot of the output of eqn. 5 is shown in Figure 5 using CIBSE timings for the month of April. This estimation of δT_{hourly} should be sufficient to allow addition of the UHI to hourly climate data, such as that output by the UKCP09 weather generator, or to downscaled hourly RCM data. While the morphing procedure for creation of future climatic data adjusts temperatures by shifting and stretching the observed historical data, the magnitude of the UHI is not expected to change as a result of climate change, simple addition of the UHI onto the values of daily temperature should be sufficient.

Alternatively the quarter-sine method developed by Chow and Levermore[27] could be adapted to create sub-daily variation of the UHI. However, it is uncertain whether the extra complexity of this method will yield sufficiently improved results.

Uncertainties and Limitations

Uncertainty in the results can originate from many areas. The gridded temperature data used in this study did include the impacts of urban areas when they were constructed. However, very few urban areas have (or had in the past) a meteorological station located within them. It is therefore possible that the urban temperatures for towns and cities have been over- or underestimated in the gridded temperatures. Additionally, all urban areas were treated identically in the construction of the gridded temperatures and in the present work, whereas in reality they differ considerably in building types and sizes, and green areas. A potential improvement would be to use high density temperature measurements (such as those made by Watkins *et al.*[7]) and to take the urban morphology into consideration. However, some recent work attempting to model the UHI of London as a function of different urban characteristics has only been partially successful[8,9]. High-density temperature data for urban areas are scarce and are not available for most cities and are not routinely collected. It is beyond the scope of this paper to include other climate effects on the UHI, such pooling of cold air at night, and advection by winds and sea breezes.

The gridded temperature data have a resolution of 5 × 5 km and so represent an average over this area. Real temperatures at specific points within each 5 km cell could be hotter or cooler than expected. The resolution of the data means that calculation of the UHI for larger cities will be more accurate than that calculated for smaller ones. This is illustrated in the discrepancy between the values given in Table 1 and the data shown in

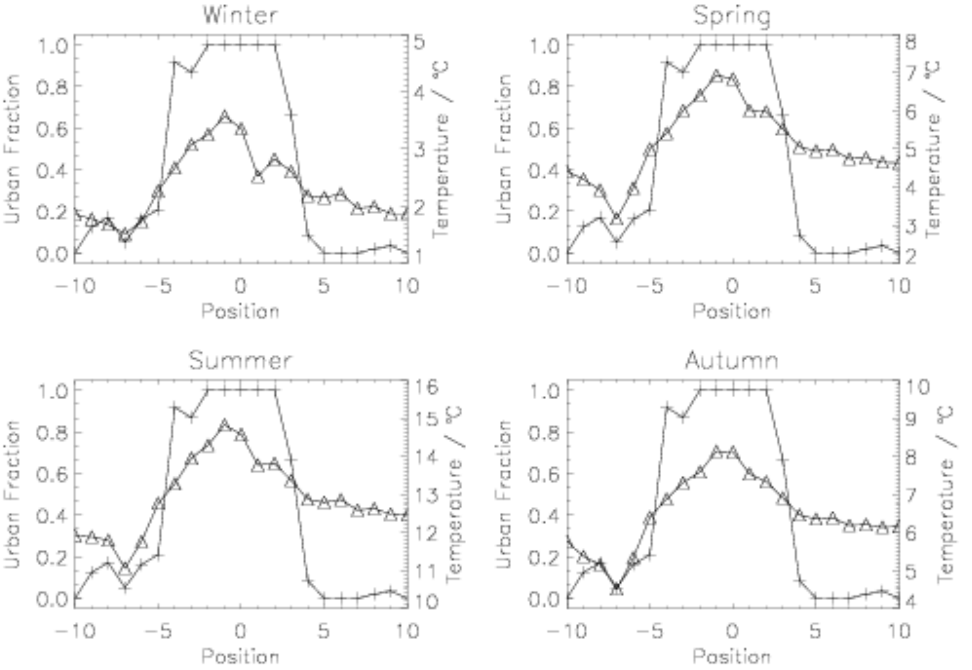

Figure 1.

The IGBP dataset distinguishes between many different land types and each 1 x 1 km cell is allocated to just one of those land types. However, even at this scale small parks, gardens and other green areas will be missed which would mean the urban fractions used here are too high. Similarly, some small urban areas on the edges of cities will be missed and the area classified as rural (i.e. grassland, crops etc) resulting in an urban fraction which is too low. Both of these factors will affect the urban fractions used and hence the UHIs calculated.

Towns and cities have a tendency to change in size and density with time. The methodology described in this paper could be used to estimate an UHI for new towns and enlargements of existing ones. However, it would be necessary to regenerate the 5 km gridded temperature data using a modified land use map. The current tendency is for new housing developments to be denser than older ones (as a result of increased land value and for an improved localised infrastructure), which contain fewer green areas[28]. Such developments may experience an enhanced UHI by comparison with older developments, which tend to have larger green areas. Urban areas are generally very heterogeneous and consist of many different shapes and types of buildings with very different uses made from different materials.

Summary

We have produced monthly, seasonal and annual UHI estimates which may be added to the 11-member ensemble RCM data released by UKCP[17] and also to weather files for the major towns and cities in the UK. We have also proposed a methodology for the addition of hourly UHI data to the output of a weather generator or for addition to existing hourly weather files for locations where a new city is planned or a current one has changed in size or density since the creation of the weather file. The methodology described in this paper allows estimation of the UHI intensity for urban centres and areas in the UK using gridded minimum temperatures at a 5 km resolution and corresponding land cover data. The formulae produced here to calculate the UHI may also be used to estimate how the UHI may change with urban expansion. However, incorporating the effects of new building design, orientation of buildings and streets, and climate change on the UHI is beyond the scope of this paper. The UHI intensities produced are found to be consistent with those reported previously[6-9]. The methodology can be summarised as:

- Calculate the average urban fraction and the surface minimum temperatures of concentric areas around an urban centre.
- Fit a straight line to the data, using the urban fractions as the independent variable and the temperature is the dependent variable.
- Calculate the UHI from the product of the urban fraction at the urban centre and the gradient of the straight-line fit.
- Repeat for many urban centres within an urban area (city) to produce an overall UHI intensity.
- Estimate the hourly variation of the UHI if required using a simple sinusoidal function.
- Re-grid the UHI intensities produced to 25 km, to match the Met Office's RCM resolution if required, and then add to simulated temperatures so that the urban impact on climate is included. This can be done just as monthly adjustments to the daily minimum and maximum temperatures or for downscaled sub-daily RCM data.

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City	Nº. UC	J	F	M	A	M	J	J	A	S	O	N	D	Winter DJF	Spring MAM	Summer JJA	Autumn SON	Ann
Newcastle-upon-Tyne	10	1.8,0.1	1.9, 0.1	2.1, 0.1	1.7, 0.1	1.9, 0.1	2.1, 0.1	1.9, 0.1	2.0, 0.1	1.9, 0.1	2.0, 0.1	1.5, 0.1	1.6, 0.1	1.8	1.9	2.0	1.8	1.9
Portsmouth	3	1.2, 0.1	1.4, 0.2	1.5, 0.2	1.8, 0.2	1.8,0.2	1.9, 0.2	2.1, 0.2	2.1, 0.2	2.3, 0.3	1.9, 0.2	1.6, 0.2	1.6, 0.2	1.3	1.73	2.0	2.0	1.8
Central London	16	1.3	1.4	1.7	1.8	1.7	1.9	1.8	1.9	1.8	1.5	1.5	1.4	1.3	1.7	1.9	1.6	1.6
Liverpool	12	1.1	1.1, 0.1	1.2, 0.1	1.2, 0.1	1.7, 0.1	1.7, 0.1	1.7, 0.1	1.6, 0.1	1.7, 0.1	1.4, 0.1	1.4, 0.1	1.2, 0.1	1.1	1.4	1.7	1.5	1.4
Glasgow	9	1.0, 0.1	1.2, 0.1	1.3, 0.1	1.6, 0.1	1.6, 0.1	1.6, 0.1	1.5, 0.1	1.5, 0.1	1.3, 0.1	1.1, 0.1	1.1, 0.1	1.0, 0.1	1.0	1.5	1.5	1.2	1.3
Edinburgh	1	1.1, 0.2	1.1, 0.2	1.4, 0.3	1.5, 0.3	1.3, 0.2	1.5, 0.3	1.4, 0.3	1.4, 0.3	1.4, 0.3	1.2, 0.2	1.1, 0.2	1.2, 0.3	1.1	1.4	1.4	1.3	1.3
London Suburbs	46	0.9	1.0	1.1	1.2	1.2	1.4	1.3	1.4	1.2	1.0	1.0	1.0	0.9	1.2	1.4	1.1	1.1
Plymouth	1	0.8, 0.3	1.0, 0.3	1.2, 0.3	1.3, 0.4	1.1, 0.4	1.3, 0.4	1.1, 0.3	1.2, 0.3	1.0, 0.3	1.2, 0.3	0.9, 0.3	0.9, 0.3	0.9	1.2	1.2	1.1	1.1
Sheffield	4	1.0	0.7, 0.1	0.9, 0.1	0.9, 0.1	1.0, 0.1	1.1, 0.1	1.1, 0.1	1.1, 0.1	1.0, 0.1	0.9, 0.1	1.0	0.9	0.9	0.9	1.1	0.9	1.0
Manchester	21	0.8	0.9	1.0	1.1	1.2	1.2	1.2	1.1	0.8	0.8	0.7	0.6	0.8	1.1	1.2	0.8	0.9
Bristol	3	0.6, 0.1	0.6, 0.1	0.9, 0.1	1.0, 0.1	1.0, 0.2	1.1, 0.2	1.3, 0.2	1.2, 0.2	1.0, 0.2	0.9, 0.2	0.8, 0.1	0.7, 0.1	0.6	1.0	1.2	0.9	0.9
Middlesbrough	3	0.8, 0.1	1.0, 0.2	1.0, 0.2	1.0, 0.2	1.0, 0.2	1.0, 0.2	0.9, 0.2	0.8, 0.2	0.8, 0.2	0.8, 0.2	0.7, 0.2	0.7, 0.2	0.8	1.0	0.9	0.8	0.9
York	3	0.9, 0.1	0.7, 0.1	0.8, 0.1	0.7, 0.1	0.9, 0.1	1.1, 0.1	0.9, 0.1	1.0, 0.1	1.0, 0.1	0.9, 0.1	0.9, 0.1	0.8, 0.1	0.8	0.8	1.0	0.9	0.9
Cardiff	3	0.5, 0.1	0.6, 0.1	0.9, 0.1	0.9, 0.1	1.0, 0.1	1.1, 0.1	1.2, 0.1	1.0, 0.1	0.7, 0.1	0.6, 0.1	0.4, 0.1	0.5, 0.1	0.5	0.9	1.1	0.6	0.8
Leeds-Bradford	15	0.5	0.6	0.7	0.7, 0.1	0.7, 0.1	0.8, 0.1	0.8, 0.1	0.7	0.8,0.1	0.7	0.7	0.8, 0.1	0.6	0.7	0.8	0.8	0.7
Nottingham	4	0.6, 0.1	0.5, 0.1	0.5, 0.1	0.8, 0.1	1.0,0.1	0.9, 0.1	0.8, 0.1	0.9, 0.1	0.7, 0.1	0.7, 0.1	0.5, 0.1	0.5, 0.1	0.5	0.7	0.9	0.6	0.7
Bournemouth	4	0.4	0.7, 0.1	0.7, 0.1	0.9, 0.1	0.7 , 0.1	0.9, 0.1	0.9, 0.1	0.7, 0.1	0.6, 0.1	0.5, 0.1	0.5, 0.1	0.7, 0.1	0.6	0.8	0.8	0.5	0.7
Birmingham	23	0.4	0.3	0.5	0.5	0.6	0.8	0.7	0.7	0.7	0.5	0.5	0.6	0.4	0.5	0.7	0.6	0.6
Coventry	3	0.3	0.4, 0.1	0.4, 0.1	0.5, 0.1	0.7, 0.1	0.7, 0.1	0.6, 0.1	0.7, 0.1	0.5, 0.1	0.3, 0.1	0.5, 0.1	0.4, 0.1	0.4	0.5	0.7	0.4	0.5
Belfast	2	0.4, 0.1	0.4, 0.1	0.3, 0.1	0.6, 0.1	0.6, 0.1	0.7, 0.1	0.5, 0.1	0.5, 0.1	0.4, 0.2	0.2, 0.1	0.3, 0.1	0.4, 0.1	0.4	0.5	0.3	0.3	0.4
Leicester	3	0.0, 0.1	0.1, 0.1	0.1, 0.1	0.2, 0.1	0.3, 0.1	0.2, 0.1	0.1, 0.1	0.1, 0.1	0.0, 0.1	0.1, 0.1	0.1, 0.1	0.1, 0.1	0.0	0.2	0.1	0.1	0.1

Table 1 Monthly, seasonal mean and annual mean urban heat islands for the towns and cities shown in Figure 2. The monthly average UHI and the estimated error are given in the first 12 columns. If no error is given, the actual error is less than 0.05 °C. Also listed are the number of urban centres considered for each urban area (see text for definition of ‘urban centre’). The seasons are defined using continuous three-month periods: Winter (December, January, February), Spring (March, April, May), Summer (June, July, August), and Autumn (September, October, November). For the winter average value, data for December are taken from the previous year. Central London is defined as the central 20 × 20 km area in the centre of the boxed region around London shown in Figure 2, and London suburbs is the remaining area.

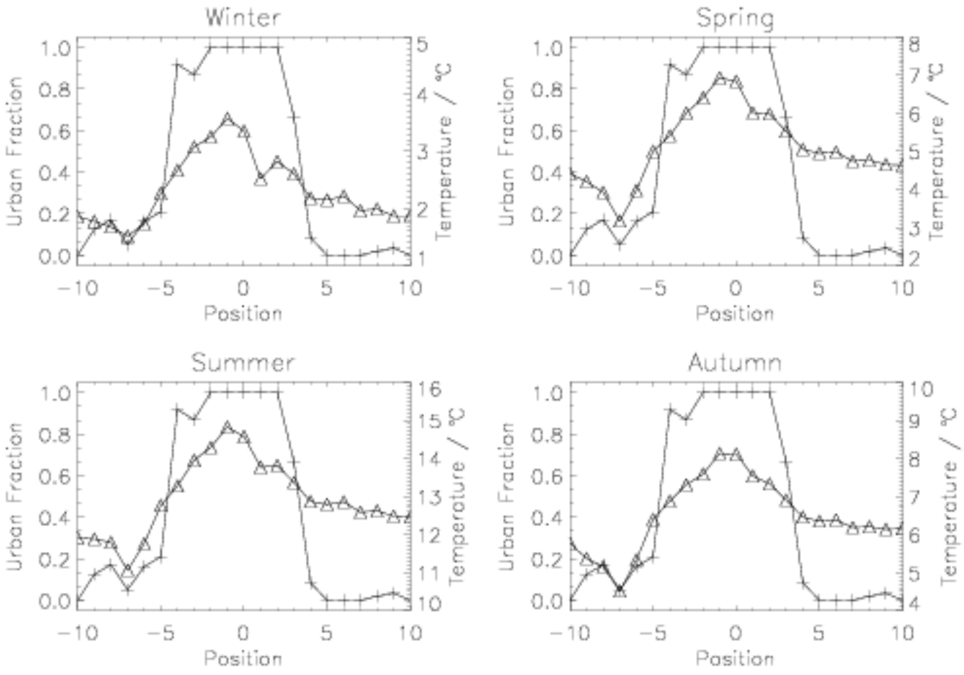

Figure 1. Seasonal plots of 1.5 m temperature (triangles) and urban fraction (crosses) for a 100 km north - south transect through London. For the position shown on the *x*-axes, positive and negative values indicate cells to the north and south of the urban centre respectively.

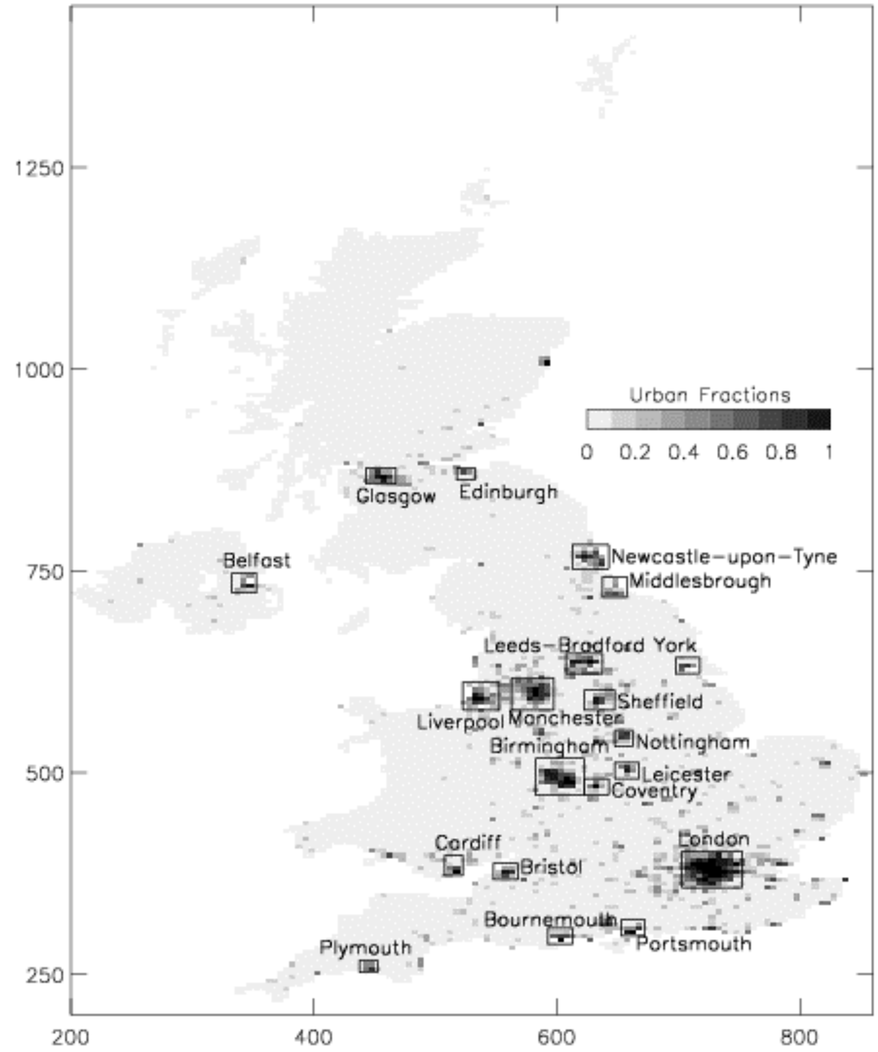

Figure 2. Map showing major towns and cities in the UK at 5 × 5 km resolution. The urban heat islands were calculated using all cells within the boxed areas around each city. The grey scale indicates the fraction of the surface of each 5 x 5 km cell which is classed as urban. The axes show the distance from the national grid origin in km.

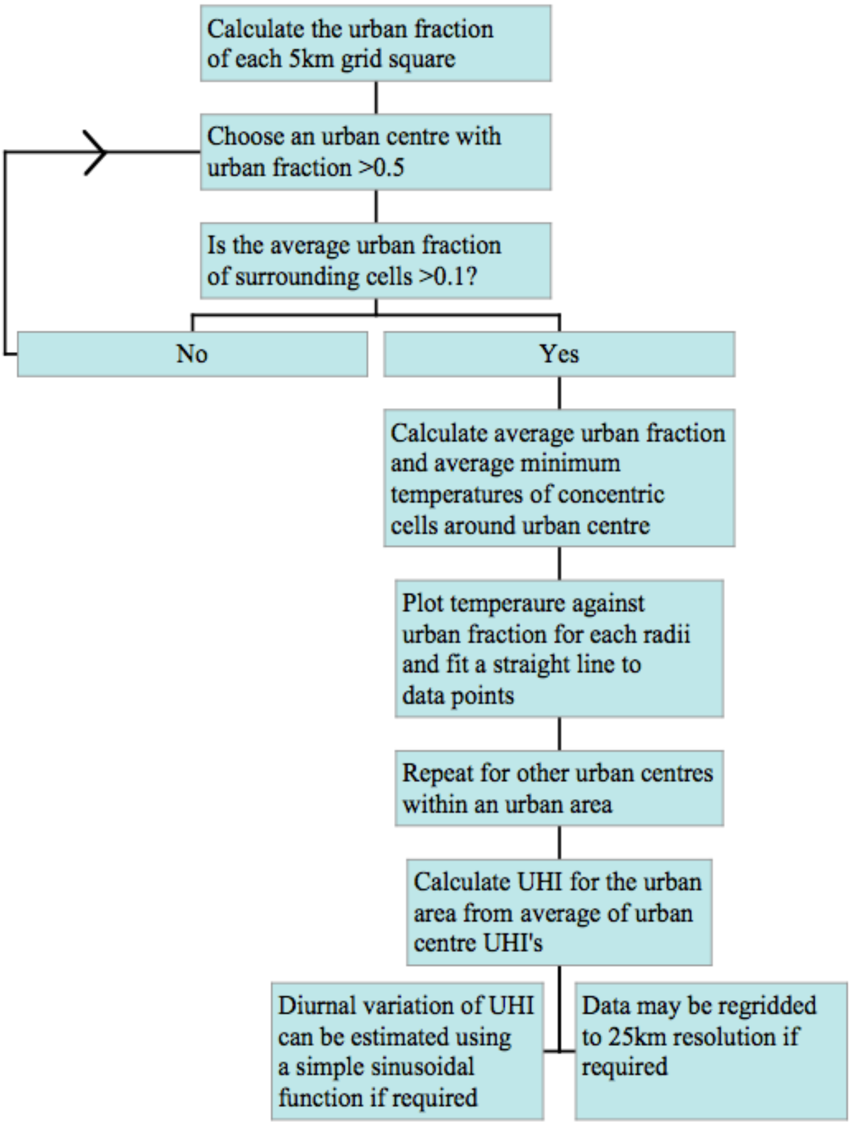

Figure 3. Flow chart of the methodology described in this paper for the estimation of the UHI of an urban area.

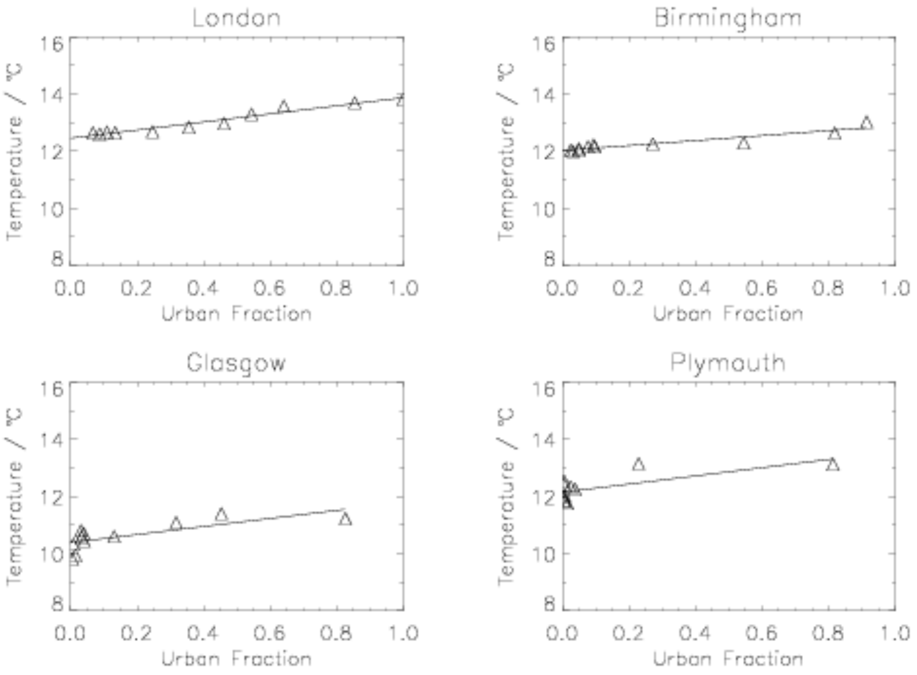

Figure 4. Examples of the relationship between temperature and the urban fraction for radii $1 \le r \le 10$ for four cities in the UK. The temperatures were calculated using the averages for each cell for July 2003. The straight lines are a least squares fit to the data.

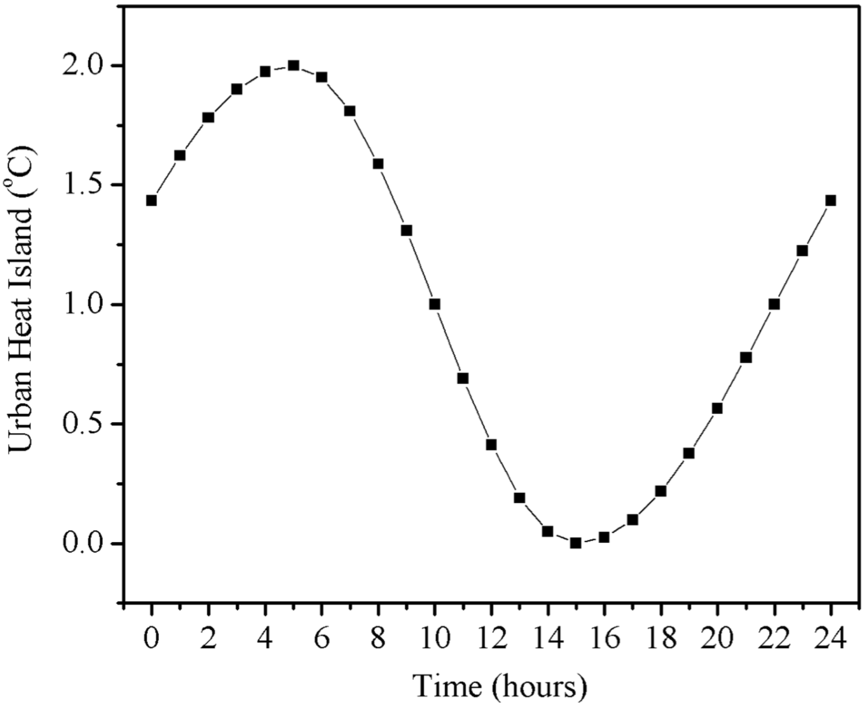

Figure 5. Plot of the diurnal variation of the UHI (δT_{hourly}) as given by eqn. 5, t_{max} and t_{min} are taken to occur at 5:00 and 15:00 respectively for ΔT_{ave} = 2°C and T_{min} = 0°C.